NNT : 2016SACLE021

THESE DE DOCTORAT
DE
L'UNIVERSITE PARIS-SACLAY
PREPAREE A
"L'UNIVERSITE D'EVRY VAL D'ESSONNE"

ECOLE DOCTORALE N° 580
Sciences et Technologies de l'Information et de la Communication

Spécialité de doctorat : Automatique

Par

Camila Freitas Salgueiredo

Biomimétisme et Véhicule Décarboné : génération de concepts innovants bio-inspirés à partir de la théorie C-K

Thèse présentée et soutenue à Paris, le 25 octobre 2016 :

Composition du Jury :

M., VANDAMME, Henri	Directeur de recherche, CNRS,	Président
M., BASSET, Michel	Professeur, Université de Haute-Alsace,	Rapporteur
M., REICH, Yoram	Professeur, Tel Aviv University,	Rapporteur
M., MAMMAR, Saïd	Professeur, Université d'Evry,	Examinateur
M., GLASER, Sébastien	Directeur de recherche, IFSTTAR,	Directeur de thèse
M., DONCIEUX Stéphane	Professeur, ISIR, UPMC,	Co-directeur de thèse
M., ORFILA, Olivier	Chargé de recherche, IFSTTAR,	Co-encadrant
M., SAINT PIERRE, Guillaume	Chargé de recherche, IFSTTAR,	Co-encadrant
M., HATCHUEL, Armand	Professeur, Mines ParisTech,	Invité
M., DOUBLET, Philippe	Consultant, RENAULT,	Invité

Valeu a pena? Tudo vale a pena
Se a alma não é pequena.
Quem quere passar além do Bojador
Tem que passar além da dor
Deus ao mar o perigo e o abismo deu,
Mas nele é que espelhou o céu.

Fernando Pessoa, Mar português.

à ma famille
à Jacques

Remerciements

Je tiens tout d'abord à remercier les membres du jury de thèse pour avoir accepté de participer à l'évaluation des travaux présentés dans ce manuscrit de thèse: le Professeur Henri Van Damme, président du jury, les Professeurs Michel Basset et Yoram Reich, rapporteurs, le professeur Saïd Mammar, examinateur, les professeurs Sébastien Glaser et Stéphane Doncieux, directeurs de thèse, le professeur Armand Hatchuel, Philippe Doublet, tuteur en entreprise et les Dr. Olivier Orfila et Guillaume Saint Pierre, co-encadrants au LIVIC.

Je remercie particulièrement le Dr. Sébastien Glaser, mon directeur de thèse au sein de l'IFSTTAR-LIVIC et le Pr. Stéphane Doncieux, mon co-directeur de thèse au sein de l'ISIR pour ses conseils et orientations au long de cette thèse.

Je tiens à remercier les professeurs Agnès Guillot de l'ISIR et Henri Van Damme de l'IFSTTAR pour avoir accepté de participer au comité de suivi de cette thèse.

Cette thèse a été initialement portée au sein de Renault par Philippe Doublet. Je le remercie très sincèrement pour m'avoir confié cette mission. Ses commentaires et suggestions m'ont permis d'avancer vers une meilleure compréhension des enjeux environnementaux et économiques de l'industrie automobile. Il m'a honorée avec sa confiance pendant ces années pour la réalisation de ces travaux et j'en suis très reconnaissante.

Je remercie très sincèrement le professeur Armand Hatchuel du Centre de Gestion Scientifique de Mines ParisTech pour m'avoir orientée dans l'étude de la conception et de la bio-inspiration. Nos réunions, discussions et tout ce que lui et son équipe m'ont appris ont été essentiels pour la réussite de ces travaux de thèse. Je suis également très reconnaissante de l'accueil que j'ai eu auprès de toute l'équipe du CGS et de la chaire Théories et Méthodes de la Conception Innovante. Je garde un très bon souvenir de mes discussions avec Sophie Hooge qui m'a beaucoup appris sur les champs d'innovation et sur le fonctionnement de la recherche chez Renault. Je me rappellerai aussi de la conférence Design2014 à Dubrovnik avec Akin Kazaçi et de la passionnante soutenance de thèse de Marine Agogué. Je suis aussi très reconnaissante de l'aide que les professeurs Pascal le Masson et Benoît Weil m'ont apporté pendant les cours sur la conception et lors de l'organisation des séminaires sur la bio-inspiration et C-K.

Je tiens à remercier très sincèrement le professeur Véronique Billat, qui avec sa passion pour la recherche, la science et la performance sportive a été mon guide dans l'exploration de ce nouveau monde "de la Nature". Nos échanges ont aussi été très importants pour l'accomplissement des travaux décrits dans ce mémoire.

J'adresse mes remerciements également aux Drs. Olivier Orfila et Guillaume Saint-Pierre, pour avoir encadré et suivi ces travaux de thèse au quotidien et pour avoir cru en ce projet depuis son origine. Je tiens à remercier également Benoît Lusetti pour tout son aide lors de la réalisation des essais sur piste.

Pendant ces années passées au sein de Renault, j'ai pu rencontrer des personnes qui possédaient une maîtrise technique et une passion pour le monde de l'automobile remarquables. Je remercie très sincèrement Rémi Bastien, pour m'avoir accueilli au sein de sa direction et Dominique Levent, pour m'avoir pleinement intégrée à son équipe. Je tiens à remercier Lomig Unger, pour son aide avec les idées biomimétiques. J'aimerais remercier également Gonzalo Hennequet, pour les cours sur les véhicules (dynamique, boîtes de vitesse, électriques et hybrides). Je remercie sincèrement Amin El-Bakkali, pour ses explications sur les calculs de consommation de carburant d'un véhicule. Je remercie très sincèrement Valérie Boch, pour m'avoir fait confiance pour le développent d'un arbre de concepts dans son domaine d'expertise. Je remercie sincèrement Frédéric Canal pour l'intérêt porté sur mes travaux et les échanges sur les analogies entre coureurs et les batteries. Je tiens à remercier également Stéphane Morel, pour nos échanges sur les impacts environnementaux des matériaux et sur l'arbre de concepts sur le véhicule bas-impact environnemental. Je remercie très sincèrement Damien Le Guen, Ali Ercan et Alain Daumard pour leur aide avec les véhicules hybrides. Je remercie vivement Benoît Chagniot, pour m'avoir encouragé à présenter mes travaux à d'autres groupes de travail de l'entreprise. Je remercie Philippe Schulz et Rodrigo Guizoni, pour les échanges sur les les impacts de l'introduction des nouvelles technologies sur le marché et l'évolution du parc automobile. Je remercie très sincèrement Sylvie Autor, pour sa gentillesse et pour m'avoir ouvert les portes de sa bibliothèque. Je remercie vivement aussi l'ensemble de l'équipe de la Créativité et Promotion de l'Innovation de Renault, Jean-Marc Postic, Mickael Desmoulins, Philippe Flegel, Pascale Nays, Suvi Kallio, Elise Layec et Cécile Amar, pour leur amitié et leur pêche au quotidien. Il me serait vraiment impossible de citer tous les experts et ingénieurs avec lesquels j'ai échangé pendant cette thèse, mais je tiens à leur adresser mes plus sincères remerciements.

Grâce à cette thèse j'ai pu faire connaissance avec le monde du Biomimétisme, qui se développe à toute vitesse en France. Je tiens à remercier chaleureusement Kalina Raskin-Delisle pour son soutien et nos échanges sur le biomimétisme. Je voudrais remercier Tarik Chekchak du Comité Français de Biomimicry Europa ainsi que à tous ces membres pour tous nos échanges au long de ces années de thèse. Je remercie également Pierre-Emmanuel Fayemi et Giacomo Bersano pour nous échanges et pour l'intérêt qu'ils ont toujours porté à mes travaux.

Je tiens à remercier les responsables du Master Transport et Développement Durable, Emeric Fortin et Marie-Laure Le-Naire pour leur encouragements au démarrage de cette thèse et pour leur amitié. Laure Guilbard et Barbara Forrière, les tutrices de mon stage de fin de master, comptent aussi parmi les personnes qui ont été essentielles pour que cette thèse puisse voir le jour.

Au Technocentre, j'ai rencontré des personnes avec qui j'ai partagé des bons moments et qui ont toujours su apporter de la gentillesse et de l'amitié à nos journées de travail: Christine Alabarbe, Max Vérité, Yves Lebfevre, Nathalie Sourdille, Chantal Le-Guillou et Michèle Godefroid, un grand merci pour ces années ensemble. Je tiens à remercier Maud Guy-Coquille pour son amitié et le partage que nous avons construit pendant nos thèses respectives. Je remercie également Sophia El-Kerdini et Kenza El-Qaoumi, pour leur soutien inconditionnel même dans les moments plus inattendus. J'aimerais aussi remercier Meriem Lafou et Milena Klasing Chen, Redouane Adda Ahmed-Bacha, Nicolas Gimonnet, Vincent Judalet et Steve Pechberti, et tous les autres collègues du LIVIC et de l'ISIR pour nos bons moments partagés pendant nos années de thèse. Les stagiaires TRADD et MVE, avec qui j'ai pu échanger pendant leurs stages au Technocentre comptent aussi parmi les personnes avec lesquelles j'ai partagé des très bons moments, je pense à Helena, Felipe, Cansu, Noriko, Kan, Jinsoo et Juan. Je remercie aussi Thibaud du Rosel, stagiaire du master MISE, qui m'a fait confiance pour l'encadrement de son sujet de mémoire.

Je ne pourrais pas ne pas remercier le RER C, mon compagnon de déplacements journalier, pour les moments de réflexion et de lecture que les retards et les incidents m'ont permis d'apprendre à apprécier.

Sur un plan plus personnel, eu gostaria de agradecer a Jacques, pela força que me deu todos os dias e por seus conselhos valiosos. Também gostaria de agradecer a minha família, especialmente ao meu pai e a Valéria, a minha mãe, aos meus avós, aos meus padrinhos e aos meus tios, que ajudaram tanto da minha criação e permitiram que eu estudasse e me desenvolvesse em ótimas condições. Meu irmão Guilherme também me ajudou muito durante todos esses anos de estudos, mesmo quando ele ainda nem sabia o que significava estudar. Meus amigos: Erika, Monica, Camille, Gaëlle, Pierre, Philippe, Olga S., Fernando T., Adriano, Ariane, Annelise e Mariana, lhes agradeço pela companhia mesmo com toda a distância que nos separa. A saudade é grande, mas o mais importante é continuarmos avançando...

Résumé

Le biomimétisme ou conception bio-inspirée est une approche qui propose l'utilisation du vivant en tant que source d'inspiration pour améliorer ou concevoir de nouvelles technologies. D'une part, s'inspirer du vivant pourrait aboutir à des technologies plus innovantes, grâce à la diversité et à la multifonctionnalité rencontrées même chez les systèmes vivants les plus simples. D'autre part, s'inspirer du vivant pourrait aboutir à des technologies plus durables car chez le vivant, le recyclage de ressources à tous les niveaux, une chimie avec des matériaux abondants et à température ambiante sont déjà pratiqués depuis 3,8 milliards d'années. Ces processus du vivant ont également été évalués par la sélection naturelle, et seulement les organismes les plus adaptés survivent. Intégrer la conception bio-inspirée au processus d'innovation des entreprises pourrait ainsi permettre la génération de concepts à la fois innovants et durables.

La diversité des formes, structures, processus et systèmes du vivant peut rendre le processus de recherche « d'une bonne analogie biomimétique », permettant de résoudre un problème ou de concevoir un nouveau produit bio-inspiré, très difficile. La littérature sur le biomimétisme propose quelques approches pour guider ce processus d'inspiration du vivant, comme l'utilisation de bases de données avec des connaissances biologiques, la recherche par mots-clefs dans les textes écrits en langage naturel ou encore l'identification des principes dans le vivant pour résoudre des contradictions. Cette thèse, réalisée au sein de Renault avait deux objectifs : comprendre les mécanismes de la conception bio-inspirée et les appliquer à un cas concret dans l'automobile pour stimuler la génération de concepts en rupture.

Pour comprendre les mécanismes de la bio-inspiration, nous nous sommes appuyés sur la littérature scientifique ainsi que sur les inventions et concepts bio-inspirés. Ces exemples montrent que la conception bio-inspirée peut effectivement être le fruit de découvertes accidentelles, mais qu'un processus plus systématique et guidé pouvait aussi conduire à des résultats intéressants. Pour analyser le raisonnement de conception de ces exemples, nous avons choisi une théorie de la conception, qui

décrit le cheminement depuis la conception des idées jusqu'au prototypage. La théorie C-K a été choisie comme base permettant d'expliquer le cadre usuel de la conception biomimétique (la résolution de problèmes), tout en ouvrant la voie à d'autres possibilités, comme la génération de « crazy concepts » ou de concepts en rupture. Le cadre issu de la théorie C-K nous a permis de proposer un modèle général pour la conception bio-inspirée en quatre étapes: la première est l'identification de chemins de conception pour lesquels la bio-inspiration pourrait apporter des ruptures potentielles, la deuxième est l'identification de bases de connaissances biologiques avec des propriétés intéressantes permettant de former une partition de ces chemins de conception « bloqués ». La troisième étape consiste en une exploration et révision des connaissances traditionnelles à partir de cette partition, activant des connaissances qui ne seraient pas spontanément activées. Enfin, la quatrième étape consiste en un retour vers les connaissances traditionnelles : une fois que la voie bio-inspirée est caractérisée et devient une connaissance, son développement est réalisé selon les expansions traditionnelles de connaissances.

Nous avons appliqué ce modèle au champ d'innovation du véhicule décarboné. Ce champ traite des questions liées au développement d'innovations permettant aux véhicules de réduire leur empreinte environnementale, principalement par la réduction des émissions de dioxyde de carbone, un puissant gaz à effet de serre qui contribue également au phénomène du changement climatique. La recherche de solutions innovantes se justifie par les nouvelles réglementations sur les émissions de dioxyde de carbone qui sont de plus en plus contraignantes. L'identification des voies où la rupture serait nécessaire a débuté par la réalisation d'un arbre des concepts, à l'aide des connaissances internes disponibles en entreprise auprès des experts leaders. Un travail de réorganisation de ces concepts et la création d'une base de connaissances rassemblant articles scientifiques et expertises sur le sujet des émissions de gaz à effet de serre ont été effectués. Ce travail a permis de cartographier le champ d'innovation du véhicule décarboné. Les véhicules multi-énergies ont été la voie choisie pour la recherche de concepts bio-inspirés. Ils utilisent de façon combinée plus d'une source d'énergie. Cette combinaison permet d'améliorer les rendements individuels des chaînes de traction thermiques ou électriques. La flexibilité dans les usages est aussi améliorée avec ces véhicules, car ils ne sont plus dépendants d'une seule source d'énergie. Leur potentiel de réduction des émissions de gaz à effet de serre est considérable en utilisation (plus de 50% pour les hybrides rechargeables) par rapport à un véhicule traditionnel avec moteur à allumage commandé ou diesel.

Une recherche générale sur l'énergie dans le vivant nous a conduits à identifier l'énergie dans les cellules animales et particulièrement chez les humains comme une base de connaissances biologiques particulièrement intéressante. L'énergétique humaine possède un certain nombre de propriétés qui pourraient permettre une révision des connaissances sur les véhicules multi-énergie : ces cellules ont également plusieurs types de stockage d'énergie, ont au moins deux métabolismes énergétiques, et ces métabolismes peuvent être utilisés pour recharger une source d'énergie. La performance sportive humaine s'est aussi révélée être une base de connaissances intéressante par les différentes techniques utilisées pour les entrainements et en course afin de mieux mobiliser des sources d'énergie.

L'application du modèle du processus de bio-inspiration avec C-K nous a conduit à formuler un concept inspiré des observations réalisées sur des coureurs pendant des courses supérieures à 1 500 m. En effet, les profils de vitesse enregistrés pour des athlètes indiquent qu'une variation de vitesse est choisie par le coureur pour lui permettre de mieux utiliser ses réserves anaérobies limitées. Pour un véhicule, ceci pourrait impliquer qu'une variation de vitesse pourrait conduire à des meilleurs résultats en termes de consommation de carburant qu'une vitesse stabilisée. Pour un véhicule avec deux sources d'énergie, comme un hybride, ce concept revient à utiliser une source d'énergie pour recharger une autre source. Pour un véhicule conventionnel, ce concept de variations de vitesse peut aussi être interprété comme une manière de réduire la consommation d'énergie. Ce concept avait été exploré dans la littérature sur le fonctionnement des automobiles. Dans cette thèse, il a été exploré de manière plus approfondie avec la réalisation d'essais sur piste qui complètent les simulations réalisées avec des modèles numériques. Ces explorations montrent le potentiel de ce concept pour des véhicules conventionnels et aussi ses limitations.

Ces travaux ouvrent des perspectives pour la gestion d'énergie des véhicules considérant la façon dont l'énergie est produite, stockée et utilisée chez le vivant. Les systèmes énergétiques étudiés par la physiologie humaine représentent un terrain intéressant pour le développement de véhicules adaptables à différents cas d'utilisation, ville, autoroute ou les nouvelles mobilités. De plus, l'étude du processus de la bio-inspiration a permis d'éclairer les raisons de faire appel à cette démarche et les conditions qui permettraient une application plus systématique de cette démarche dans les processus d'innovation en entreprise. La poursuite des recherches autour d'un modèle dynamique de gestion de l'énergie humaine basé sur les mêmes principes que les modèles multi-énergies des véhicules développés dans le cadre de notre recherche permettrait d'optimiser les stratégies de course qui reposent encore essentiellement sur des approches empiriques.Cette étude sur le processus de la bio-inspiration a permis d'éclairer les raisons de faire appel à cette démarche et les conditions qui permettraient son application plus systématique dans les processus d'innovation en entreprise.

Abstract

Biologically inspired design, also called bioinspired design, biomimetics or biomimicry proposes the use of Nature, or biological knowledge, as a source of inspiration to improve or conceive new designs. On one hand, this inspiration from nature could lead to more innovative designs, as Nature has a great variety of systems with different properties and living in different conditions. On the other hand, this inspiration could also lead to more sustainable solutions, as living systems are included in cycles, where everything is recycled, the chemical reactions take place at room temperature and these cycles evolved during more than 3.8 billion years. Integrating the biologically inspired design approach into the innovation process of companies could then allow the generation of more innovative and sustainable concepts.

The diversity of natural systems, in terms of forms, structures and process can render the process of finding "a good biomimetic analogy" a very difficult task. Literature on bioinspired design proposes some approaches facilitating this process of finding biological inspiration, such as databases with biological knowledge, research with keywords in natural language written biology texts, and the identification of the principles used by the living systems to solve contradictions. This thesis, realized during three years at a French automaker (Renault) research and development department had two objectives: to understand the mechanisms of the biologically inspired design and to apply this approach to a case belonging to an innovation field of the automotive sector. In order to understand the mechanisms of biologically inspired design we studied the literature about bio-inspired concepts and inventions. These examples show that the bioinspired design can be indeed the result of serendipity, but it also indicates that systematizing bioinspiration can lead to interesting results. We have chosen a design theory, the C-K theory, to analyse the design process of these literature examples. This allowed us to propose a model for bio-inspiration. This model explains the usual interpretation of this activity, as a problemsolving activity and the other possibilities opened with the use of biological knowledge during the design process, such as the generation of "crazy" and disruptive concepts. This model proposes four steps for biologically inspired design: (i) the identification of design paths for which

concept partitioning is required, (ii) the activation of biological knowledge related to the initial concept, (iii) expansions in both biological and traditional knowledge bases and (iv) return to traditional knowledge bases in order to develop the design using the usual knowledge expansions.

We applied this model inspired by the C-K theory to the low carbon vehicle innovation field. This field includes the development of innovations allowing passenger cars to reduce their environmental footprint, mainly the reduction of carbon dioxide (CO_2) emissions. The carbon dioxide is a greenhouse gas, contributing to the climate change phenomena. The new regulations have targets that are increasingly more difficult for automakers to meet without the use of disruptive technologies, such as the electrification of the powertrain. The identification of the path where concept partitioning is required in this field began with the construction of a concepts space, using knowledge of company experts on the subject. Reorganizing these concepts and building a knowledge base on the strategies for reducing CO_2 emissions allowed us to map this innovation field. The vehicles with more than one energy source, such as electrified internal combustion engine vehicles and hybrid vehicles were the path chosen for the research of bio-inspired concepts. These vehicles combine more than one energy source, allowing an improvement of the individual efficiencies of the powertrains. These vehicles can allow a reduction on emissions superior to 50% during the use phase when compared to a traditional vehicle using an internal combustion engine only. A research about energy in nature led us to identify the energy in animal cells, particularly those in humans as an interesting biological knowledge base. Human energy properties such as cells with more than one kind of energy storage, with at least two metabolic pathways to recharge these stores are interesting to revise the knowledge about energy store and conversion in multi-energy vehicles. Besides, the human sportive performance has appeared to be an interesting knowledge base, as the training techniques and the running techniques during a race can influence the way athletes use their energy.

These two biological bases have led us to formulate a bio-inspired concept based on the running patterns observed in runners during races superior to 1500 m. The speed profiles recorded show a spontaneous speed variation chosen by the runner, in order to better use its limited anaerobic energy stores. For a vehicle, this could mean that varying its speed could allow a lower fuel consumption than using a constant speed. This bio-inspired concept was already known to automotive engineers, although not deeply explored despite its promises for emissions reductions. We have explored this concept with the realization of tests in a dedicated test track, demonstrating the potential of this concept for conventional vehicles and its limitations.

This work opens the way for analyzing the vehicle energetics in the light of human energetics. The versatility of human activities could help on the development of vehicles adapting to different use cases: urban, extra-urban and new forms of mobility. Further research could also use the knowledge about the dynamic modeling of energy in vehicles to complete the empirical approaches used to model the human energy management, allowing a better optimization of running strategies. The study of the bio-inspiration process using a design theory also allowed a better comprehension of the reasons for using this approach and of the conditions for successfully applying it in the innovative process of a company.

Table of contents

List of Figures

List of Tables

List of Symbols

Symbol	Description	Units ([1])
α, $grade$	road grade	rad
a	vehicle acceleration	m.s^{-2}
	Treiber model acceleration parameter	
A_f	vehicle frontal area	m^2
C_d	aerodynamic drag coefficient	-
C_{fuel}	total fuel consumption	L/100km
$C_{fuel_{avg-speed}}$	total fuel consumption obtained for a constant speed profile at average speed	L/100km
C_{RR}	rolling resistance coefficient	-
δ	Treiber model exponential parameter	-
EC	engine capacity	L
E_{fuel}	fuel energy consumed during the speed profile	W
$F_{add_{res}}$	additional resistance force	N
F_{aero}	aerodynamic resistance force	N
F_g	gravitational force	N
F_{RL}	road load force	N
F_{roll}	rolling resistance force	N
F_{TR}	tractive force	N
FC_{idle}	fuel consumption at idle	L.s^{-1} (*mL.s^{-1})
FC_{var}	fuel consumption variation	%
g	acceleration of gravity	m.s^{-2}
G	vehicle weight	N

. . . continued

Symbol	Description	Units ([1])
$gear$	gear ratio	
$H_{fuel-lcv}$	fuel lower calorific value (also called lower heating value)	J.kg^{-1}
I_{engine}	inertia of the engine	kg.m^2
I_d	inertia of the transmission	kg.m^2
I_w	inertia of the wheels	kg.m^2
$\dot{m}_{fuel}$, M_{fuel}	fuel mass flow	kg.s^{-1}
m_v	vehicle mass	kg
N_f	final drive ratio	-
N_t	transmission ratio	-
N_{tf}	numerical ratio of the final drive and transmission	-
η_{tf}	final drive and transmission efficiency	-
ω_{gb}	rotational speed of the crankshaft	rad.s^{-1}
ω_{engine}	engine speed	rad.s^{-1} (*rpm)
ω_{idle}	engine speed at idle	rad.s^{-1} (*rpm)
ω_{wh}	rotational speed of the wheels	rad.s^{-1}
P_{eff}	available power	W
P_{fuel}	fuel power consumed by the engine	W
P_{aux}	fuel power required by the auxiliaries	W
$\dot{Q}$	fuel energy flow	W
ρ_a	air density	kg.m^{-3}
ρ_{fuel}	fuel density	kg.m^{-3}
r_w	wheel radius	m
T_{drag}	engine drag torque	N.m
T_{engine}	engine torque	N.m
T_{gb}	torque at the clutch side of the gearbox	N.m
T_{wh}	wheel torque	N.m

…continued

Symbol	Description	Units ([1])
v	vehicle speed	$m.s^{-1}$
x	distance made by the vehicle	m

[1]SI units, in case no SI unit is defined, the usual unit is indicated

List of Acronyms

ACC adaptive cruise control

ADAS Advanced Driving Assistance Systems

ADP adenosine diphosphate

ANOVA analysis of variance

ANRT Association nationale de la recherche et de la technologie

ATP adenosine triphosphate

AWC anaerobic work capacity

BEV battery electric vehicle

BID biologically inspired design

bmep brake mean effective pressure

CAFE Corporate Average Fuel Economy

CIFRE Convention industrielle de formation par la recherche

C–K theory Concept-Knowledge theory

CO carbon monoxide

CO_2 dioxyde de carbone

CO_2 carbon dioxide

CP critical power

EDAS Ecological Driving Assistance Systems

ESA European Space Agency

EV electric vehicle

E–W direction east-to-west of the experimental test track

FCV fuel cell vehicle

FCW forward collision warning

FSS Full System Simulation

GWP global warming potential

H_2O water

HC unburnt hydrocarbons

HEV hybrid electric vehicle

ICCT International Council on Clean Transportation

ICE internal combustion engine

ICEV internal combustion engine vehicle

IDM Intelligent Driver Model

IEA International Energy Agency

MoMo International Energy Agency Mobility Model

IFSTTAR Institut français des sciences et technologies des transports, de l'aménagement et des réseaux

ISIR Institut des systèmes intelligents et de robotique, UMR7222 de l'Université Pierre et Marie Curie

LCA life cycle assessment

LED light-emitting diode

LIVIC Laboratoire sur les interactions véhicule-infrastructure-conducteurs

NEDC New European Driving Cycle

NMHC non-methane hydrocarbon

NO_x nitrogen oxides

NRC National Research Council

PCr phosphocreatine

PM particulate matter

PSO particle swarm optimization

SAE Society of Automotive Engineers - SAE International

THC total hydrocarbons

TTW tank-to-wheel

$\dot{V}O_2$ oxygen uptake

W–E direction west-to-east of the experimental test track

WLTC Worldwide Harmonized Light Vehicles Test Cycle

WTT well-to-tank

WTW well-to-wheel

Résumé de la thèse : Biomimétisme et véhicule décarboné : génération de concepts innovants bio-inspirés à partir de la méthode C–K

Ce document s'organise autour de 6 chapitres. Chaque chapitre présente une des étapes du travail de recherche effectué au sein de Renault, un constructeur automobile français, du Laboratoire sur les interactions véhicule-infrastructure-conducteurs (LIVIC) de l'Institut français des sciences et technologies des transports, de l'aménagement et des réseaux (IFSTTAR) et de l'Institut des systèmes intelligents et de robotique, UMR7222 de l'Université Pierre et Marie Curie (ISIR). Ce travail de thèse a été soutenu par l'Association nationale de la recherche et de la technologie (ANRT) dans le cadre d'une Convention industrielle de formation par la recherche (CIFRE) avec Renault.

Table des matières

Chapitre 1 Introduction générale : la conception bio-inspirée et les questions de recherche

S'inspirer des systèmes du vivant, de leurs formes, matériaux ou modes d'organisation pour innover est l'objectif de l'approche de **conception bio-inspirée**. La science des matériaux, l'intelligence artificielle et de nombreux domaines ont des exemples réussis de conception bio-inspirée. Ces exemples stimulent la recherche de solutions permettant de systématiser le recours au vivant comme source d'inspiration pour les processus de conception.

Un des principaux avantages d'utiliser la conception bio-inspirée est la grande variété de problèmes que le vivant « a résolu ». Les principes que le vivant met en œuvre pour la résolution de problèmes sont très différents de ceux utilisés par les humains pour concevoir des « machines » ou des « matériaux ». En outre, les produits avec des principes bio-inspirés peuvent être mieux intégrés à leurs écosystèmes et plus durables.

Cette thèse propose une application de l'approche de conception bio-inspirée (appelée également **biomimétisme**). Nous avons appliqué le biomimétisme au champ de la réduction des émissions de gaz à effet de serre produits par les véhicules particuliers. Ce champ de recherche est un des plus actifs au sein du département de recherche du constructeur automobile au sein duquel cette thèse a été réalisée.

La problématique qui adresse cette thèse peut être formulée comme :

> *La conception bio-inspirée peut-elle être utilisée pour stimuler l'innovation dans l'industrie automobile ?*

Cette problématique est analysée sous deux aspects :

- L'activité de conception bio-inspirée et sa valeur en tant que stimulus pour l'innovation.
- L'application de cette conception bio-inspirée à un domaine précis, l'industrie automobile.

Deux objectifs de recherche sont ainsi définis pour cette thèse :

- Améliorer la compréhension de la conception bio-inspirée. Cette amélioration comprend un cadre pour l'appliquer à un champ d'innovation.

- Identifier et évaluer des stratégies bio-inspirées pour un champ d'innovation spécifique au constructeur automobile.

Une méthodologie de recherche a été élaborée pour étudier la conception bio-inspirée et pour l'appliquer à un cas concret dans le domaine de l'automobile. L'analyse d'exemples de conception bio-inspirée retrouvés dans la littérature avec une théorie de la conception, la théorie C-K fait partie de cette méthodologie. Une fois les exemples de bio-inspiration analysés, le processus de bio-inspiration est appliqué à un champ d'innovation pour générer des concepts bio-inspirés. Ces concepts sont évalués par une modélisation théorique des phénomènes en jeu et par des expérimentations. L'analyse des exemples de biomimétisme avec une théorie de la conception et l'application de la conception bio-inspirée sont deux processus complémentaires. Le socle pour la mise en place du processus permettant la génération de concepts bio-inspirés pour un cas concret a été l'analyse des exemples de biomimétisme.

Les deux questions de recherche liées à la problématique définie précédemment et traitées dans cette thèse sont :

RQ1*: Comment la bio-inspiration stimule la génération de concepts en rupture pendant les processus de conception ?*

RQ2*: Les concepts bio-inspirés permettent-ils une réduction des émissions de* CO_2 *des voitures particulières ?*

La Figure 1 résume le contenu et les contributions des différents chapitres qui constituent cette thèse.

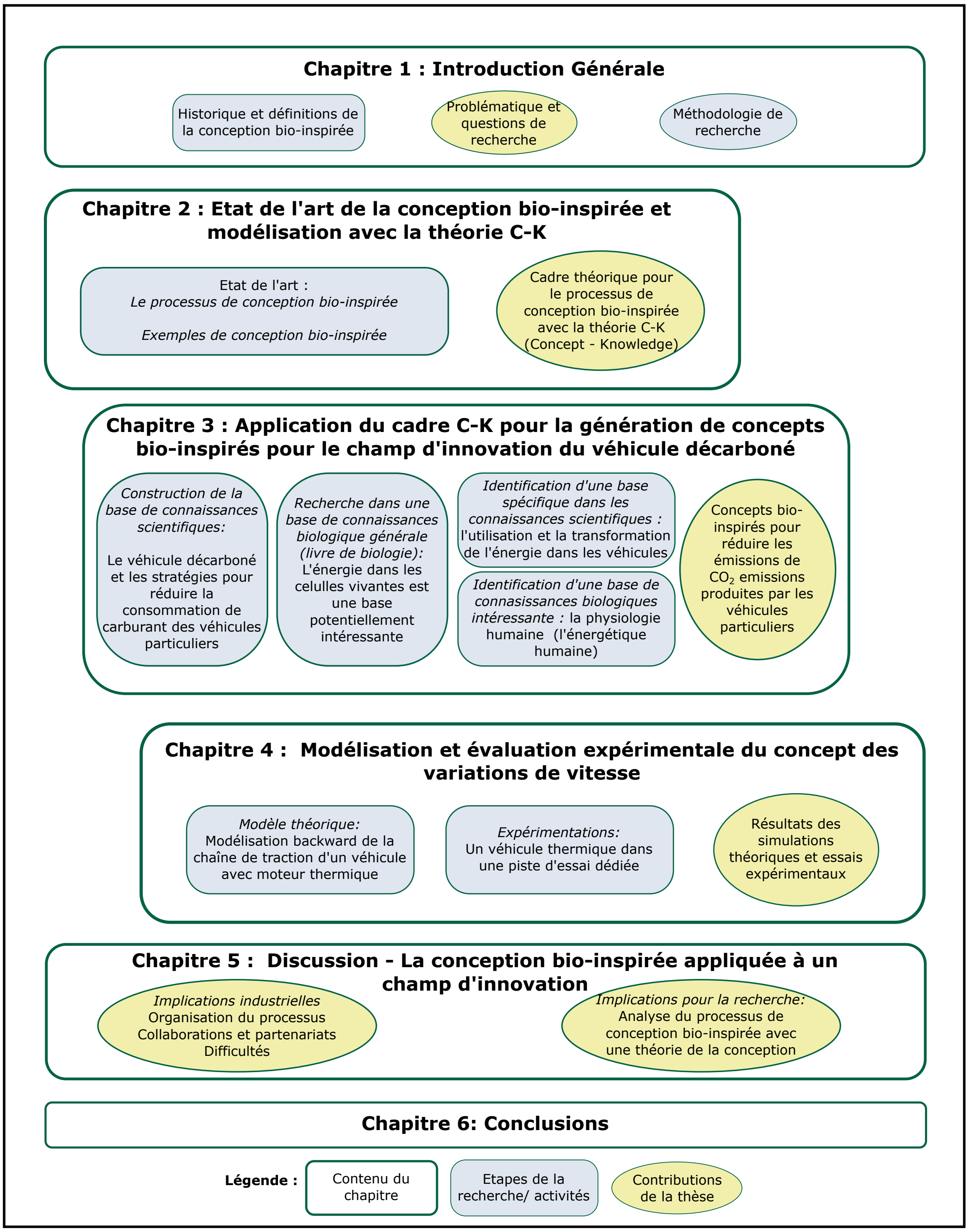


Figure 1: Vue d'ensemble des différents chapitres : contenu, activités et contributions.

Chapitre 2 État de l'art de la conception bio-inspirée et modélisation avec la théorie C–K

La littérature scientifique traitant la conception bio-inspirée est analysée dans ce chapitre sous deux aspects :

- La caractérisation de ce processus de conception, identifiant les étapes, les processus mis en œuvre, les théories de la conception qui peuvent l'expliquer.
- Les méthodes pour mettre en œuvre ce processus de conception. Les bases de données, analyses fonctionnelles, TRIZ etc.

Plusieurs méthodes et outils sont décrits dans la littérature pour appliquer la conception bio-inspirée de manière plus systématique dans les processus de conception :

- Bases de données comme *AskNature*[2].
- Ontologies (Vincent, 2014).
- Recherche par mots-clés dans des textes écrits en langage naturel (Shu, 2010).
- Recherche sur internet (Vandevenne et al., 2013).
- Consultations avec des experts.
- Outils permettant une analyse fonctionnelle plus ciblée (Nagel and Stone, 2012; Helfman Cohen et al., 2014) ou une meilleure description des problèmes et des solutions biologiques (Vincent et al., 2006; Sartori et al., 2010; Wiltgen et al., 2011).

Le processus de bio-inspiration est décrit dans la littérature avec les étapes usuelles de la conception systématique de Pahl and Beitz (1988) et comme un processus de transfert analogique entre la biologie et l'ingénierie. La conception systématique est basée sur un système de règles fixes pour la conception, et ne permet pas de modéliser les activités liées à la créativité, surtout celles qui ne sont pas dans le design dominant (Agogué et al., 2014a). Par ailleurs, si l'activité de conception bio-inspirée est un simple transfert analogique entre deux domaines différents, comment expliquer la nécessité d'acquérir des connaissances nouvelles notamment avec l'analyse de plusieurs systèmes

[2] AskNature est une base de données en ligne gratuite et en libre accès, disponible sur : http://www.asknature.org/ (Site internet consulté le 06/03/2016).

biologiques ? ou encore que la conception bio-inspirée peut ne pas avoir des attributs transférés à partir de la source d'inspiration (Wilson et al., 2010) ?

Pour analyser ces questions, une théorie formelle de la conception, la théorie C–K (Hatchuel and Weil, 2003) est employée. Cette théorie possède des propriétés permettant de décrire les activités de conception en dehors du « dominant design ». Elle a aussi été utilisée comme cadre pour décrire les activités d'autres théories et méthodes de la conception comme TRIZ (Reich et al., 2012), l'analyse paramétrique (Kroll et al., 2014) et pour expliquer les effets de fixation (Hatchuel et al., 2011; Agogué et al., 2014b).

L'analyse du processus de bio-inspiration avec la théorie C–K a procédé par l'analyse d'exemples de bio-inspiration retrouvés dans la littérature scientifique. Quatre exemples ont été analysés avec C–K :

- *Flectofin*®, une innovation dans le domaine des systèmes d'ombrage des bâtiments.
- La technologie *Whalepower*, utilisée dans les pâles de ventilateurs et éoliennes pour augmenter leur efficacité énergétique et aérodynamique.
- Les surfaces *auto-nettoyantes* inspirées de la feuille de lotus.
- Les surfaces *adhésives* inspirées par le Gecko.

Les bases de connaissances activées et mobilisées pendant le processus de conception, ainsi que les concepts formulés au long du processus de conception et qui ont permis la conception du produit final ont été identifiés pour chacun de ces quatre exemples. Cette analyse avec C–K permet de décrire le processus de conception bio-inspirée en 4 étapes (Figure 2) :

1. Identification de chemins de conception pour lesquels la bio-inspiration pourrait apporter des ruptures potentielles.
2. Identification de bases de connaissances biologiques avec des propriétés intéressantes. Ces propriétés contribuent à partitionner des chemins de conception « bloqués ». Cette étape peut être la première étape dans les cas où les connaissances biologiques sont à l'origine du processus de conception bio-inspirée.
3. Exploration et révision des connaissances traditionnelles et des connaissances biologiques.
4. Retour vers les connaissances traditionnelles pour le développement du chemin de conception

bio-inspirée.

Ce processus est plus général que l'analyse traditionnelle de l'état de l'art de la conception bio-inspirée. Il ne décrit pas seulement une recherche de fonctionnalités spécifiques dans le vivant. Il précise que le vivant peut avoir des propriétés (qui peuvent être liées à une fonction ou pas) qui permettront d'explorer les connaissances différemment et ainsi générer des concepts en rupture.

Par ailleurs, le modèle C–K de la bio-inspiration montre que les deux bases de connaissances sont révisées et étendues : la base de connaissances biologiques et les connaissances scientifiques (non-biologiques). La collaboration en place entre biologistes et ingénieurs désireux d'appliquer la bio-inspiration n'est pas ainsi un simple transfert de connaissances. Elle nécessite une réinterprétation des connaissances apportées par chacune des parties en fonction des bases de connaissances existantes. Dans la conception bio-inspirée, la biologie peut inspirer l'ingénierie en activant des bases de connaissances et l'ingénierie peut indiquer des bases de connaissances à explorer en biologie ou à explorer différemment avec des techniques issues de l'ingénierie.

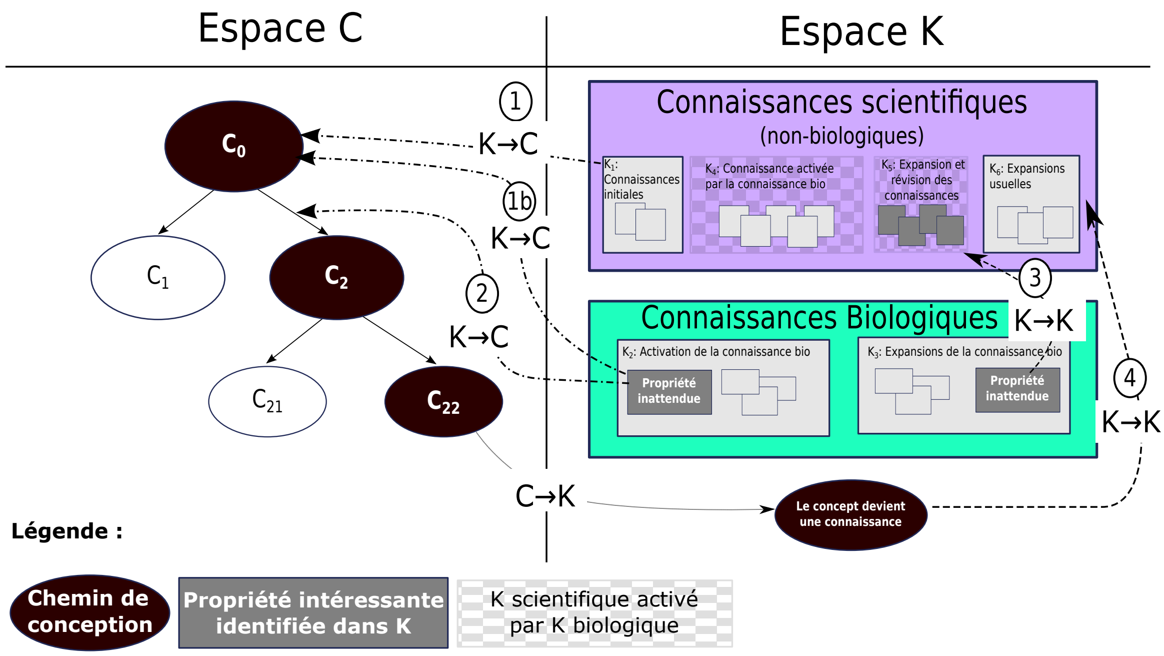


Figure 2: Modèle général C–K pour la conception bio-inspirée. Cette figure est une adaptation du modèle présenté dans Freitas Salgueiredo and Hatchuel (2014, 2016).

Chapitre 3 Application du cadre C–K pour la génération de concepts bio-inspirés pour le champ d'innovation du véhicule décarboné

Le modèle C–K du processus de la bio-inspiration est le cadre utilisé dans ce chapitre pour l'application de la conception bio-inspirée à un champ d'innovation spécifique. Ce champ d'innovation est le « véhicule décarboné » ou la réduction des émissions de dioxyde de carbone (CO_2) produites par les voitures particulières.

Le CO_2 est un gaz à effet de serre qui contribue au phénomène du réchauffement climatique. Il est émis par les véhicules thermiques (avec un moteur à allumage commandé ou à compression) car ils utilisent des combustibles fossiles comme l'essence ou le gasoil comme source d'énergie. Pour l'industrie automobile, la réduction des émissions de CO_2 est une priorité pour lutter contre le réchauffement climatique. Par ailleurs, l'utilisation d'énergies alternatives non issues du pétrole peut aussi avoir un deuxième effet bénéfique, celui de réduire la dépendance vis-à-vis du pétrole. Cette ressource n'étant produite que par un nombre réduit de pays sur le globe.

La première étape pour la génération de concepts bio-inspirés pour le champ d'innovation du « véhicule décarboné » a été la construction d'une base de connaissances et l'identification des concepts existants dans ce champ d'innovation. Ce processus a commencé avec un stage réalisé au sein du constructeur automobile Renault, au cours duquel les experts de l'entreprise ont été mis à contribution pour construire un arbre des concepts autour du concept initial (C_0) « véhicule décarboné » (Amsterdamer and Molin, 2011). Nous avons ensuite consolidé ce premier travail avec la construction d'une base de connaissances autour de ces concepts, ce qui nous a permis d'identifier quelques chemins de conception pour lesquels la bio-inspiration pourrait être appliquée. Cette étape correspond à la première étape du modèle de la bio-inspiration avec C–K : identification des chemins de conception pour lesquels la bio-inspiration pourrait apporter des ruptures potentielles.

Les chemins de conception de ce champ d'innovation ainsi identifiés pour la recherche de rupture avec la bio-inspiration sont :

- La séquestration de CO_2 dans les véhicules (*on-board*) ou à l'extérieur (*off-board*). Des concepts en rupture pourraient venir de l'étude des organismes vivants comme les algues ou les plantes photosynthétiques qui captent le CO_2 de l'air. Elles le transforment en composés organiques. D'autres organismes peuvent aussi avoir des propriétés intéressantes à explorer comme les coraux qui minéralisent les carbonates dissouts dans l'eau.

- Les systèmes d'aide à la conduite pour optimiser le trafic. Dans ce cas, des systèmes de déplacement en banc comme les poissons ou essaims d'insectes pourraient être utilisés pour inspirer le développement de capteurs ou algorithmes d'optimisation en rupture. Cette voie a été explorée par le constructeur automobile Nissan dans le développement de robots avec des capteurs inspirés du comportement des bancs de poisson (Abidin et al., 2015).

- L'aérodynamisme des véhicules pourrait être amélioré avec l'observation des modèles du vivant. Le constructeur automobile Mercedes a utilisé le poisson-coffre comme source d'inspiration pour améliorer l'aérodynamisme de son concept-car « Bionic car » (Daimler, 2011). D'autres modèles de propriétés intéressantes en termes d'aérodynamisme existent chez le vivant.

- Les matériaux ultralégers existants chez le vivant pourraient être source d'inspiration pour l'allégement des véhicules.

- Une meilleure efficacité de l'utilisation de l'énergie dans le véhicule (meilleure efficacité du moteur, possibilité de récupérer ou réutiliser l'énergie). Les différents exemples d'utilisation et de transformation de l'énergie chez le vivant pourraient apporter quelques concepts en rupture pour explorer cette voie.

La voie choisie pour une recherche plus approfondie de connaissances dans le monde du vivant est celle de l'*utilisation et de la transformation d'énergie*. A notre connaissance cette voie n'a pas été explorée sous cet angle en termes de bio-inspiration, ce qui n'est pas le cas de l'aérodynamisme, des systèmes d'aide à la conduite pour optimiser le trafic ou des matériaux ultralégers. La capture de CO_2 a été étudiée d'un point de vue des connaissances traditionnelles pour les véhicules, mais pas sous l'angle de la bio-inspiration. Cependant, les connaissances disponibles lors de la réalisation de cette thèse ne nous ont pas permis d'explorer cette voie également avec la bio-inspiration.

Une recherche avec des mots clés dans les textes écrits en langage naturel, notamment le livre de Sadava et al.[3] a été la première étape de la recherche de connaissances biologiques pour explorer ce chemin de conception. Une base de connaissances plus spécifique a été choisie suite à cette première exploration générale : la **physiologie humaine**. Les similitudes entre systèmes humains et les automobiles quant à l'utilisation de l'énergie (source d'énergie limitée, besoin de ravitaillement, gestion d'énergie) et la possibilité de consulter un expert en physiologie humaine pendant les travaux de recherche expliquent ce choix.

[3] Shu (2010) suggère l'utilisation de ce livre, car il est un livre assez général qui peut être compris par ceux qui n'ont pas de connaissances biologiques approfondies.

Un approfondissement des connaissances sur la physiologie humaine nous a conduits à identifier plusieurs attributs intéressants qui pourraient être explorés plus en profondeur :

- Un « range-extender» bio-inspiré pour véhicules hybrides.

  Les humains ont deux métabolismes énergétiques pour produire de l'énergie (aérobie et anaérobie). Les athlètes utilisent les deux métabolismes pendant l'exercice. Un métabolisme peut par ailleurs être utilisé pour « recharger» l'autre métabolisme.

  Les stratégies de management de l'énergie utilisées dans les véhicules hybrides pourraient bénéficier d'une connaissance plus approfondie du management de l'énergie des humains. Les composantes des véhicules hybrides (sources d'énergie, moteurs, l'architecture de ces véhicules) pourraient aussi s'inspirer de la production d'énergie chez les humains, qui s'adapte à différentes sollicitations.

- Un moteur bio-inspiré qui anticipe les besoins énergétiques.

  Les humains possèdent différents types de fibres musculaires leur permettant de mieux répondre à une sollicitation donnée. La composition des muscles varie selon le type de sport pour lequel l'athlète s'entraîne. Les athlètes peuvent aussi anticiper les besoins énergétiques avec les « cycles futiles ».

  Les moteurs pourraient d'une part être conçus pour mieux répondre à un type de sollicitation donné et la combinaison de moteurs avec des caractéristiques différentes comme chez les humains pourrait contribuer à la réduction de la consommation d'énergie des voitures particulières. Par ailleurs, l'anticipation des besoins énergétiques par la connaissance *a priori* des profils de vitesse pourrait aussi bénéficier aux véhicules de la même manière que les cycles futiles pour les humains.

- Une récupération d'énergie élastique bio-inspirée.

  Le freinage récupératif permet la récupération d'une part de l'énergie cinétique qui n'est pas dissipée sous forme de chaleur au freinage. Les humains utilisent un autre moyen pour récupérer de l'énergie. Ils stockent de l'énergie élastique par l'étirement des muscles et tendons. Cette énergie est ensuite restituée pour diminuer le besoin d'énergie du mouvement suivant.

  Un stockage d'énergie sous forme mécanique dans les voitures pourrait aussi permettre des économies d'énergie, notamment pour un redémarrage après un arrêt.

- Une récupération d'énergie avec les variations de vitesse.

  Les coureurs utilisent des variations de vitesse pour ne pas « épuiser » leurs ressources énergétiques anaérobies, surtout pour les courses supérieures à 1500 m (Billat et al., 2009).

Un véhicule thermique pourrait utiliser des variations de vitesse, alternant accélérations et décélérations pour rechercher de meilleurs points de fonctionnement du moteur à combustion interne et réduire sa consommation d'énergie.

L'identification des concepts bio-inspirés à partir de la physiologie humaine est le résultat d'un travail de collaboration entre les ingénieurs du constructeur automobile et des laboratoires de recherche avec un expert en physiologie humaine.

Chapitre 4 Modélisation et évaluation expérimentale du concept bio-inspiré des variations de vitesse

Un des quatre concepts identifiés dans le chapitre 3 a été choisi pour une modélisation théorique et une évaluation expérimentale de sa faisabilité. Ce concept est celui qui prévoit une récupération d'énergie avec des variations de vitesse comme le font les athlètes.

Une vérification de la littérature dans le domaine de l'automobile nous a permis de constater que cette base de connaissances sur les variations de vitesse n'est pas nouvelle. Elle est appliquée depuis un certain temps pour des systèmes comme des trains et quelques auteurs ont proposé des applications de variations de vitesse aux voitures particulières (Avins, 1978, 1983; Lee et al., 2009). Cependant, cette technique n'est pas utilisée par les constructeurs automobiles. Un modèle théorique et une expérimentation ont été réalisés pour évaluer le bénéfice des variations de vitesse pour des voitures particulières avec un moteur à combustion interne (moteur thermique).

Le modèle théorique a été construit avec une approche backward et est un modèle quasi-statique qui utilise comme base les équations de la dynamique longitudinale des véhicules. Le modèle simplifié s'est inspiré des travaux de Guzzella and Sciarretta (2005) (Figure 3). Différentes conditions de variation de vitesse avec une pente nulle ont été testées avec ce modèle. L'évaluation expérimentale a été réalisée sur une piste de tests du circuit de Satory en France. Le même conducteur a réalisé tous les tests de variation de vitesse avec le même véhicule sur pistes (sans trafic) sur deux conditions de vitesse et différentes conditions de décélération :

- Variations de 50 km/h à 70 km/h en 3e vitesse et en 4e vitesse, décélération avec le frein moteur ou avec la boîte de vitesses au "point mort"

- Variations de 90 km/h à 110 km/h en 4e vitesse et en 5e vitesse, décélération avec le frein moteur ou avec la boîte de vitesses au “point mort”

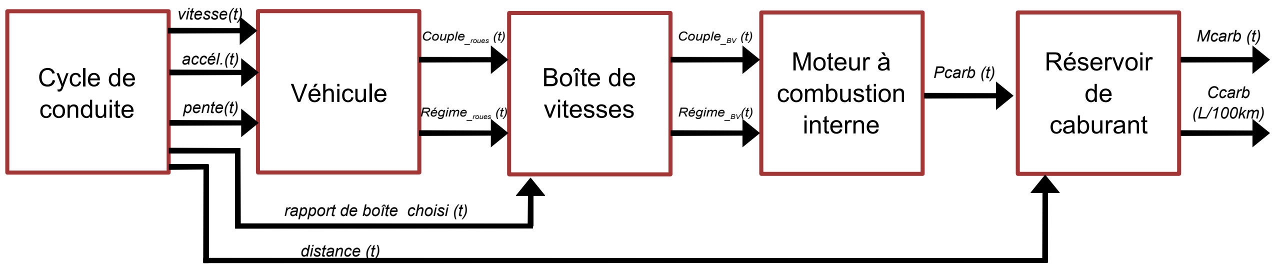


Figure 3: Représentation graphique du modèle backward du fonctionnement d’un véhicule avec moteur à combustion interne, avec les principales entrées et sorties de chacun des blocs qui le composent.

Les résultats théoriques et expérimentaux montrent qu’une réduction de la consommation de carburant est possible avec des variations de vitesse. Cette réduction est vérifiée pour les conditions où la décélération est réalisée au « point mort ». Des économies de carburant supérieures à 20% ont été vérifiés expérimentalement et sur le modèle théorique pour certaines conditions avec la décélération au « point mort ». Pour appliquer les variations de vitesse dans la pratique, une évaluation plus importante du ressenti des conducteurs et de l’impact de ces variations dans une situation réelle de trafic sont nécessaires. Les équipementiers automobiles développent actuellement des systèmes permettant un mode de fonctionnement au « point mort »de manière sûre avec des boîtes de vitesse automatiques (« sailing mode »). Les résultats obtenus avec cette analyse expérimentale valident ceux obtenus par Lee et al. (2009) pour un véhicule thermique testé sur banc à rouleaux. Ils démontrent l’intérêt de mieux explorer les variations de vitesse comme une technique pour réduire la consommation de carburant.

Chapitre 5 Discussion

Trois aspects du travail de recherche présentés dans cette thèse sont discutés dans ce chapitre :

1. Le rôle des connaissances biologiques dans les processus de conception, qui a été l’objet du Chapitre 2.
2. Les aspects pratiques de l’application de la conception bio-inspirée à un champ d’innovation spécifique à une entreprise, traité dans le Chapitre 3.
3. La modélisation et l’évaluation d’un concept bio-inspiré appartenant à ce champ d’innovation

spécifique, développés dans le Chapitre 4.

Le rôle des connaissances biologiques dans le processus de conception est lié à la première question de recherche de ce travail : *Comment la bio-inspiration stimule la génération de concepts en rupture pendant les processus de conception ?* L'analyse avec la théorie C–K de la conception d'exemples de conception bio-inspirée a mis en évidence que la connaissance biologique est bien plus qu'une simple source d'analogies pour le processus de conception :

- La connaissance biologique apporte au processus de conception des « propriétés intéressantes » qui partitionnent les concepts de l'espace des concepts. Ces partitions sont « expansives » car elles stimulent la recherche de connaissances nouvelles ou une révision des connaissances existantes.

- Les deux bases de connaissance, la connaissance biologique et la connaissance non-biologique sont révisées et étendues. Les propriétés observées dans le vivant sont également à l'origine de ces expansions – l'interaction entre biologistes et ingénieurs est ainsi « mutuellement inspiratrice ».

L'application de la bio-inspiration à un champ d'innovation spécifique à une entreprise a été réalisé suivant les étapes prévues par la modélisation de la bio-inspiration avec la théorie C–K et est lié à la deuxième question de recherche de ce travail : *Les concepts bio-inspirés permettent-ils une réduction des émissions de* CO_2 *des voitures particulières ?* Cette organisation a permis à la fois la création d'une base de connaissances existantes dans l'ingénierie automobile sur le champ d'innovation du véhicule décarboné et une mise en relation de cette base avec l'espace des concepts qui avait été construit à l'aide des experts de l'entreprise. Les concepts générés avec la bio-inspiration présentent un potentiel pour réduire les émissions de CO_2 produites par les véhicules particuliers. L'évaluation de ce potentiel a été réalisée pour un des concepts bio-inspirés issus de ce processus. Ce concept est l'application des variations de vitesse pour récupérer de l'énergie.

Même si le concept d'appliquer des variations de vitesse à des véhicules particuliers pour réduire la consommation de carburant n'est pas un concept nouveau, il reste peu utilisé par les constructeurs automobiles. L'évaluation théorique et expérimentale de ce concept montre qu'il représente une opportunité pour réduire la consommation de carburant et les émissions de CO_2. Cette réduction est possible grâce à la combinaison d'un fonctionnement du moteur dans des zones de meilleure efficacité pendant les phases d'accélération et une consommation réduite, voire nulle pendant les phases de décélération. Cependant, dans le cadre des travaux de recherche présentés dans cette thèse, seulement quelques situations ont été testées et une évaluation plus complète serait nécessaire pour comprendre le potentiel de ce concept dans la pratique.

Par ailleurs, le concept bio-inspiré pourrait aussi être appliqué à des véhicules hybrides. Dans ce cas, en plus de la variation de vitesse avec décélération au « point mort », une « variation de couple » du moteur thermique à vitesse constante serait envisageable. Cette variation de couple permettrait au moteur thermique de fonctionner dans des meilleurs points de fonctionnement comme dans les cas de variation de vitesse.

Chapitre 6 Conclusions et perspectives

Le travail de recherche présenté dans ce document avait deux objectifs principaux : mieux comprendre le rôle de la bio-inspiration dans le processus de conception et appliquer la bio-inspiration à un champ d'innovation du constructeur automobile au sein duquel les travaux ont été réalisés.

L'analyse d'exemples de conception bio-inspirée extraits de la littérature scientifique (Flectofin®, technologie Whalepower, surfaces autonettoyantes inspirées de la feuille de lotus et des adhésifs inspirés par le Gecko) avec une théorie de la conception, la théorie C–K a permis l'identification de deux rôles pour la bio-inspiration pendant le processus de conception :

- Un générateur de partitions expansives dans l'espace des concepts.
- Un guide de l'expansion et de la révision des connaissances biologiques et scientifiques (non-biologiques).

Cette analyse des exemples nous a également permis d'élaborer un cadre pour l'application de la conception bio-inspirée à un champ d'innovation. Ce cadre a été utilisé pour explorer le champ d'innovation du « véhicule décarboné ». La bio-inspiration a permis de générer des concepts qui peuvent contribuer à la réduction des émissions de CO_2 produites par les véhicules pendant leur utilisation. L'évaluation d'un concept bio-inspiré spécifique avec de la modélisation théorique et des expérimentations, les variations de vitesse, a montré que ce concept permet une réduction des émissions pour les véhicules particuliers avec un moteur thermique conventionnel. Le rôle de la bio-inspiration dans ce cas a été d'activer des bases de connaissances des ingénieurs qui ne seraient pas spontanément activées, les variations de vitesse étant un concept connu mais pas largement exploré pour la réduction des émissions de CO_2 par les scientifiques et constructeurs automobiles.

Ces travaux de recherche ont apporté des contributions dans deux domaines de recherche mobilisés pendant cette thèse. Pour l'ingénierie de la conception, une explication sur le rôle de la connaissance biologique dans le processus de conception et un cadre pour sa réalisation en pratique. Pour l'ingénierie automobile, une ouverture sur l'utilisation plus systématique du vivant en tant que source d'inspiration pour l'amélioration des technologies et l'exploration d'une technique pour réduire les émissions.

Les perspectives pour des travaux de recherche futurs se situent dans ces deux domaines de recherche et aussi dans la biologie. Pour l'ingénierie de la conception, poursuivre les travaux visant à mieux comprendre les impacts des analogies issues de domaines différents (pas uniquement de la biologie) sur la créativité. Pour l'ingénierie automobile, la recherche sur les véhicules hybrides et leurs systèmes de gestion d'énergie peut bénéficier des connaissances sur la gestion d'énergie chez les humains et autres organismes vivants (avec le stockage d'énergie sous forme élastique). La biologie, plus particulièrement la physiologie humaine pourrait aussi utiliser les connaissances sur la gestion d'énergie chez les véhicules et les modélisations théoriques des systèmes énergétiques pour approfondir l'étude des conditions physiologiques permettant aux athlètes de réaliser les meilleures performances sportives.

Chapter 1

General introduction: Biologically inspired design and research questions

HIGHLIGHTS

- The main **definitions** of the approach known as *biologically inspired design* or *biomimetics*;
- The **research problem** treated in the present thesis and the **research objectives** of this work;
- Overview of the **research methodology** for addressing the research questions;
- The **outline** of this document, with a summary of the **contents and contributions** of each chapter.

Chapter contents

Drawing inspiration from natural systems, forms, materials, organizations, to innovate. This is the purpose of the biologically inspired design approach. Different fields have examples of successful innovations inspired by nature, from material science to artificial intelligence. These examples motivate research on how to systematize this process or how to facilitate the use of natural systems in the design process. The benefits of this approach are linked to the diversity of problems "solved" by nature in a very different way from human technology traditional approaches. For example, most of the natural materials are produced at room temperature and do not require extreme conditions of temperature and pressure. The inspiration from nature is also a way of conceiving products more integrated with their ecosystems, instead of only considering natural resources as raw materials.

The work presented in this thesis proposes an application of the biologically inspired design approach to the field of the reduction of greenhouse gases emissions produced by passenger cars. This field is one of the active research fields of the research department of Renault, the automobile manufacturer at which this research work was realized. This first chapter introduces this research work. It presents the main definitions of biologically inspired design retrieved in literature and the process that defined the research problem addressed by this thesis. It also describes the research methodology, showing namely the mobilization of different research fields and how their contribution to disentangling some specific aspects of our research problem. In conclusion we present an overview of the subsequent chapters, summarizing their specific contributions.

1.1 Biologically inspired design: a "new" approach for stimulating creativity or generating innovations?

As its name indicates, biologically inspired design (BID) refers to the use of biological systems as a source of inspiration for new or improved designs. Literature uses different terms to designate this design approach: bionics, biomimetics, bio-inspiration, biomimesis or biomimicry.

The first aspect that should be worth disentangling is whether drawing inspiration from Nature for new or improved designs is a relatively new practice or not. Indeed, using inspiration from Nature to generate concepts for human inventions can be traced back to many, many, years ago: in the unfortunate wings of Icarus in the Greek Myths, in the Renaissance studies of Leonardo da Vinci, who observed different nature properties, such as the structure of tree branches (Eloy, 2011) or the anatomy of humans and animals:

> *Although human subtlety makes a variety of inventions answering by different means to the same end, it will never devise an invention more beautiful more simple or more direct than does nature, because in her inventions nothing is lacking, and nothing is superfluous.* (MacCurdy (1955), *The notebooks of Leonardo da Vinci*)

The Renaissance work of Galileo Galilei also highlights the importance of natural models when proposing explanations for the accelerated motion:

> *Finally, in the investigation of naturally accelerated motion we were led, by hand as it were, in following the habit and custom of nature herself, in all her various other processes, to employ only those means which are most common, simple and easy. For I think no one believes that swimming or flying can be accomplished in a manner simpler or easier than that instinctively employed by fishes and birds.*(Crew and De Salvio (1914), *Dialogues concerning two new sciences by Galileo Galilei*)

One of the most famous "recent" bioinspired invention is Velcro® fabric fastener. The official version of this invention, available at the company website (Velcro®, 2014) states that Swiss engineer George De Mestral, in 1941, was inspired by the attachment of a burdock burr to his dog fur. The burdock burr has hooks that attach to the dogs fur hoops. The Velcro® fastener conceived by De Mestral has in one side hooks and on the other loops, allowing attachment and detachment without the use of glues.

In the 1960s, some researchers started to put forward the idea that using nature more systematically as a source of inspiration could be a way for improving human designed systems. Jack E. Steele, of the US Air Force, coined the term "bionics" in 1960 to describe "*the science of systems which have some function copied from nature, or which represent characteristics of natural systems or their analogues* (Vincent et al., 2006). This term is also claimed to be a contraction between –*bio* (life) and – *ic* (technics) (Gleich et al., 2009) or to mean –*ic* (like) –*bio* (life) (Shu et al., 2011). Later, in 1969, Otto Schmitt, a biophysics and bioengineering scientist, proposed the term "biomimetics" in the title of a paper (*Some interesting and useful biomimetic transforms*) (Harkness, 2002).

One of the first dictionary definitions of this word appeared in the Webster's dictionary in 1974:

> *The study of the formation, structure or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products*

> *by artificial mechanisms which mimic natural ones.* (Harkness, 2002)

Several definitions of these terms (bionics and biomimetics) were proposed since, and other terms such as "biomimicry", "biognosis","bioinspiration", "biomimetic design", "bioanalogous design" or "biologically inspired design" (Shu et al., 2011; Vincent et al., 2006) have also appeared. While some authors, consider them as synonyms:

> *Biomimetics (which we here mean to be synonymous with 'biomimesis', 'biomimicry', 'bionics', 'biognosis', 'biologically inspired design' and similar words and phrases implying copying or adaptation or derivation from biology) is thus a relatively young study embracing the practical use of mechanisms and functions of biological science in engineering, design, chemistry, electronics, and so on.* (Vincent et al., 2006)

> *Biomimesis, biomimicry, biognosis, bioinspiration, biomimetic design, bioanalogous design, biologically inspired design: synonymous with biomimetics to mean emulating natural models, systems and processes to solve human problems.* (Shu et al., 2011)

Others privileged one word to design their approach for learning from nature. Janine Benyus, author of the 1997 book, *Biomimicry: Innovation inspired by nature* (Benyus, 1997), has associated the term biomimicry with a more sustainable innovation approach:

> *From the Greek bios, life and mimesis imitation. Nature as model: Biomimicry is a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems, e.g., a solar cell inspired by a leaf. Nature as measure: Biomimicry uses an ecological standard to judge the "rightness" of our innovations. After 3.8 billion years of evolution, nature has learned: What works. What is appropriate. What lasts. Nature as mentor: Biomimicry is a new way of viewing and valuing nature. It introduces an era based not on what we can extract from the natural world, but on what we can learn from it.* (Benyus, 1997)

All these definitions share a common concept: *Nature has systems that could be worth studying because they can provide humans with interesting functions, mechanisms or properties that could be incorporated to technical devices or that could help in the ideation of new devices.*

In the last decade, the approach received renewed interest: Considering most of the search keywords and variations used when referring to BID: "biomimetics, bionics, biomimicry, bioinspired and bioinspiration", Lepora et al. (2013) verified an exponential growth in publications related to these search keywords during the last decade, going from less than 100 in the mid-1990 to over 3000 publications in 2011. The number of publications doubled each 2-3 years according to this study. Bonser (2006) verified a similar trend in the growth of biomimetic patents from 1985 until 2005. This "boom" on bioinspired developments, and the great variety of domains where biologically inspired designs can be found, from materials to architecture or aviation (Bar-Cohen, 2006; Bhushan, 2009; Singh et al., 2012; Bar-Cohen, 2012) have instigated research laboratories and companies to apply this approach in a more systematic way. The European Space Agency (ESA) constituted an Advanced Concepts Team working on Biomimetics and applications for space applications (ESA, 2015), and justified the importance of biomimetics to space research as:

> *ESA's Advanced Concepts Team views biomimetics as a means of finding new and realistic technologies for application in future space missions. The research is not concerned with mere imitation of biological systems, but rather focuses on understanding the fundamental processes and mechanisms used in nature, in order to discover promising concepts valuable to space engineering. Benefits are expected in areas as diverse as sensors, actuators, smart materials, locomotion, and autonomous operations.* (Menon et al., 2006)

Research networks on the field were constituted in countries such as Germany ("The Society for Technical Biology and Biomimetics" - GTBB [1] in 1990, Biomimetics Competence Network - BioKoN [2] in 2001) (Gleich et al., 2009), while in other countries, these research networks are currently being formed. In France, there are currently research laboratories and industries working with bioinspired approaches, although not having regional or country-level bioinspired research networks (Durand et al., 2012). The CEEBIOS (European Excellence Centre dedicated to Biomimicry) project, which aims at creating a place to promote and develop biomimicry was launched in 2012, is one of the initiatives to promote this approach in France. Associations to promote Biomimetics have also emerged around the globe, such as Biomimicry 3.8 in the United States, which have inspired other biomimicry associations such as Biomimicry Europa (France, Belgium), Biomimicry NL (Netherlands), Biomimicry UK (United Kingdom), Biomimcry IL (Israel), Biomimicry ARG (Argentina) are only some examples.

To sum up, bioinspiration is not a new approach. However, its use it in a more systematic way to foster innovation and creativity is part of a relatively recent trend. The increase on the number of

[1] GTBB – Gesellschaft für Technische Biologie und Bionik

[2] BioKoN – Bionik-Kompetenz-Netz

publications (patents, research articles) including one of its synonyms and the creation of specific research groups and associations studying and promoting the approach support this trend.

1.2 The research problem: understanding and applying biological inspiration in a company research context

Renault, a French automobile manufacturer, is interested in studying and developing alternative approaches to stimulate creativity and contribute to innovation. The competitiveness of the automotive field and the constant evolution of the standards in terms of quality, safety and sustainability motivate this search for more successful creativity approaches (López Avila, 2014, p.29).

In 2011, the Renault's research and development team identified biomimetics as an emerging field that could be worth exploring by the company: conferences and a four-month exposition about the theme were organized at the Innovation Room in the end of 2011 (Figure 1.1)[3]. This room is an exhibition space located at the Technocentre Renault (the R&D Center of Renault, at Guyancourt, France) dedicated to bringing non-automobile related innovations to the contact of the company employees in order to broaden their knowledge about other innovation trends and ultimately stimulate creativity. This exposition about biomimetics showed interesting applications for material science, sensorics, robotics or fluid dynamics. As automotive research include all these fields, it would be worth deeply understanding the potential of this approach, if possible with at least one concrete application in the end. This is the main motivation behind the work presented in this thesis, a three-year research project conducted by its author at Renault, in collaboration with research institutes in the domain of the vehicle-infrastructure-driver integration (the LIVIC - IFSTTAR laboratory), in the domain of bioinspired robotics (the ISIR laboratory) and in the domain of management and design research (the CGS centre).

Considering the context of this research work, involving the application of bioinspiration in the automotive industry[4], we formulated our research problem as:

[3] Activities developed by Renault Creativity department are described by (Börjesson et al., 2014)

[4] One of the works found in literature that propose a similar question in this domain is (Lenau et al., 2011). The object of this action research project is the study of the following question: "natural inspiration could be a valuable inspiration to mechanical problems as those found in the car industry". The problem chosen by this author was car collision and the authors identified different design principles that could be used to solve this problem.

Figure 1.1: The "Biomimicry" exposition at the Renault Innovation Room - November 2011 (Source: Renault)

Can biologically inspired design be used as an approach for stimulating innovation in the automotive industry?

This research problem has two important aspects, the first one refers to the BID as a design methodology that can stimulate innovation, and the second one refers to the application of the BID for the automotive industry. Considering these two aspects of the research problem, we have established two research objectives for this thesis:

- Improve the understanding of the BID process, providing a framework for its realization that can be used for applying biological inspiration to an innovation field[5].

- Identify and evaluate potential bio-inspired strategies, for a specific innovation field developed by the automotive company.

The first research objective deals with the methodological aspects of BID and its practical use in a company context, mobilizing the management and design research domain. The second one deals with the use of bioinspiration in one innovation field of the company, in order to characterize the potentialities of this approach in terms of creativity and innovation, mobilizing the domains of vehicle technology and biology, as it deals with a concrete case of bioinspiration. The multidisciplinary character of this research work is intrinsic to all biomimetic developments, as they require a dialog between biology and engineering.

[5] An "innovation field" represents the different innovation projects related to a theme in the company (Salomo et al., 2008).

1.3 Research approach

Considering the research problem and its objectives, we defined a research methodology allowing us to study the BID process and to applicate it to a concrete case in the automotive industry. The defined methodology is heterogeneous, as it involved very different domains such as design or mechanics.

We started the study with the understanding of BID. We used case studies analysis on BID to characterize the design activities of this approach. This characterization involved modeling these design activities using the C-K design theory (Hatchuel and Weil, 2003, 2009) framework.

The application of bioinspired design to a concrete case of an innovation field of the automotive industry involved the construction of theoretical models, which replicated the systems for which we wanted to test biologically inspired concepts and field experimentations to validate the simulation results. Among the different automotive innovation fields, we have chosen the low carbon vehicle, i.e. the reduction of carbon dioxide (CO_2) emissions produced by passenger cars. This field is important for the automotive industry from an environmental and energetic point of view, as we will detail in the subsequent chapters.

These two methodological approaches are different in nature, but they are linked: We defined the steps for the application of the BID approach to the innovation field of the low carbon vehicle using the results obtained with the modeling of the BID process.

We can summarize the two main research questions addressed by this methodological approach as:

> ***RQ1***: *How does biological inspiration stimulate the generation of disruptive concepts during the design process?*
>
> ***RQ2***: *Does the concepts generated using biological inspiration allow* CO_2 *emissions reduction for passenger cars?*

The schematic representation of Figure 1.2 summarizes the research methodology employed to answer the two research questions derived from our research problem.

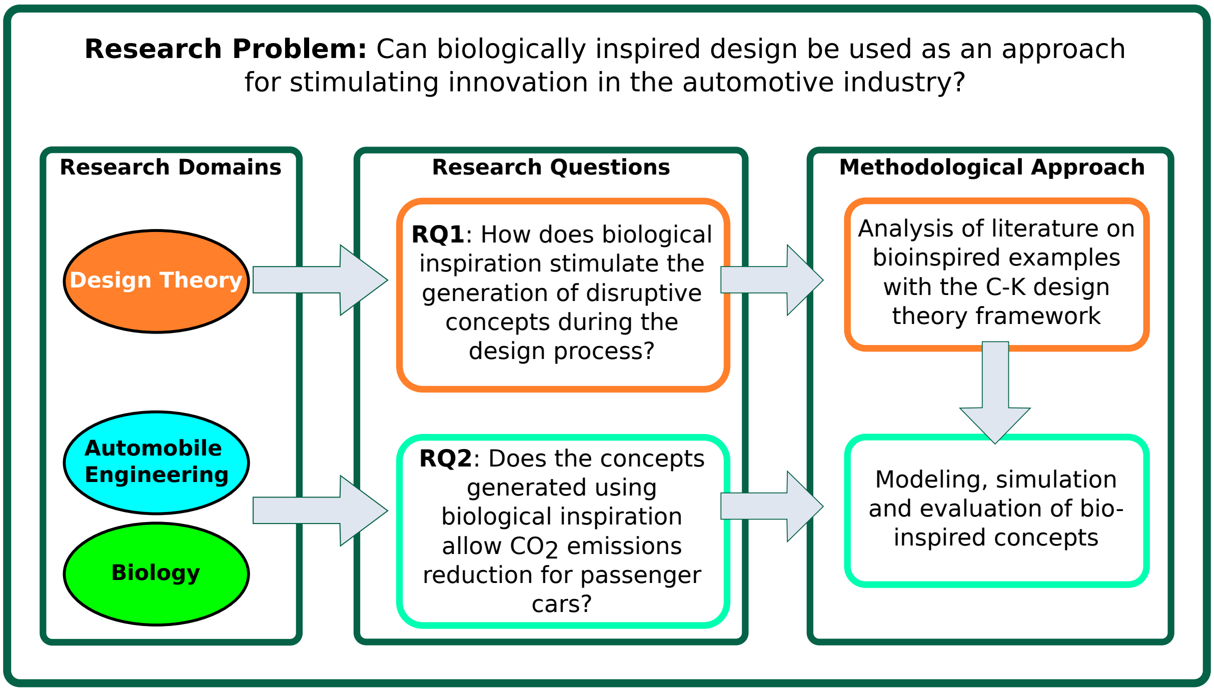


Figure 1.2: Summary of the methodological approach of this research work

1.4 Dissertation outline

The next chapters will sequentially present the steps for treating these two research questions, and the results obtained. In order to ease the identification of the subjects of the different chapters, the beginning of each chapter contains a box with the chapter *highlights*, a table of contents and a brief summary. The chapters are organized in the same order of our research questions, as represented in Figure 1.3:

- Chapter 2 presents the analysis of the biologically inspired design process, justifying the use of the C-K theory as an adapted framework for this analysis. The result is a model, based on the C-K framework, targeting the organization of the biologically inspired design process and the interpretation of its creativity properties.

- Chapter 3 details the application of the biologically inspired design C-K framework to the case of the low carbon vehicle innovation field. It describes the construction of the traditional knowledge bases on low carbon vehicles and the identification of potentially interesting biological bases considering these traditional knowledge bases. Bioinspired concepts are the outcome of this analysis.

- Chapter 4 shows how one of the bioinspired concepts is modeled and evaluated in simulation and experimentally.

- Chapter 5 discusses the results obtained on the previous chapters from the industrial and academic point of view.
- Chapter 6 concludes the thesis, summarizing its main results and presenting perspectives for future research on biological inspiration that this research work allowed identifying.

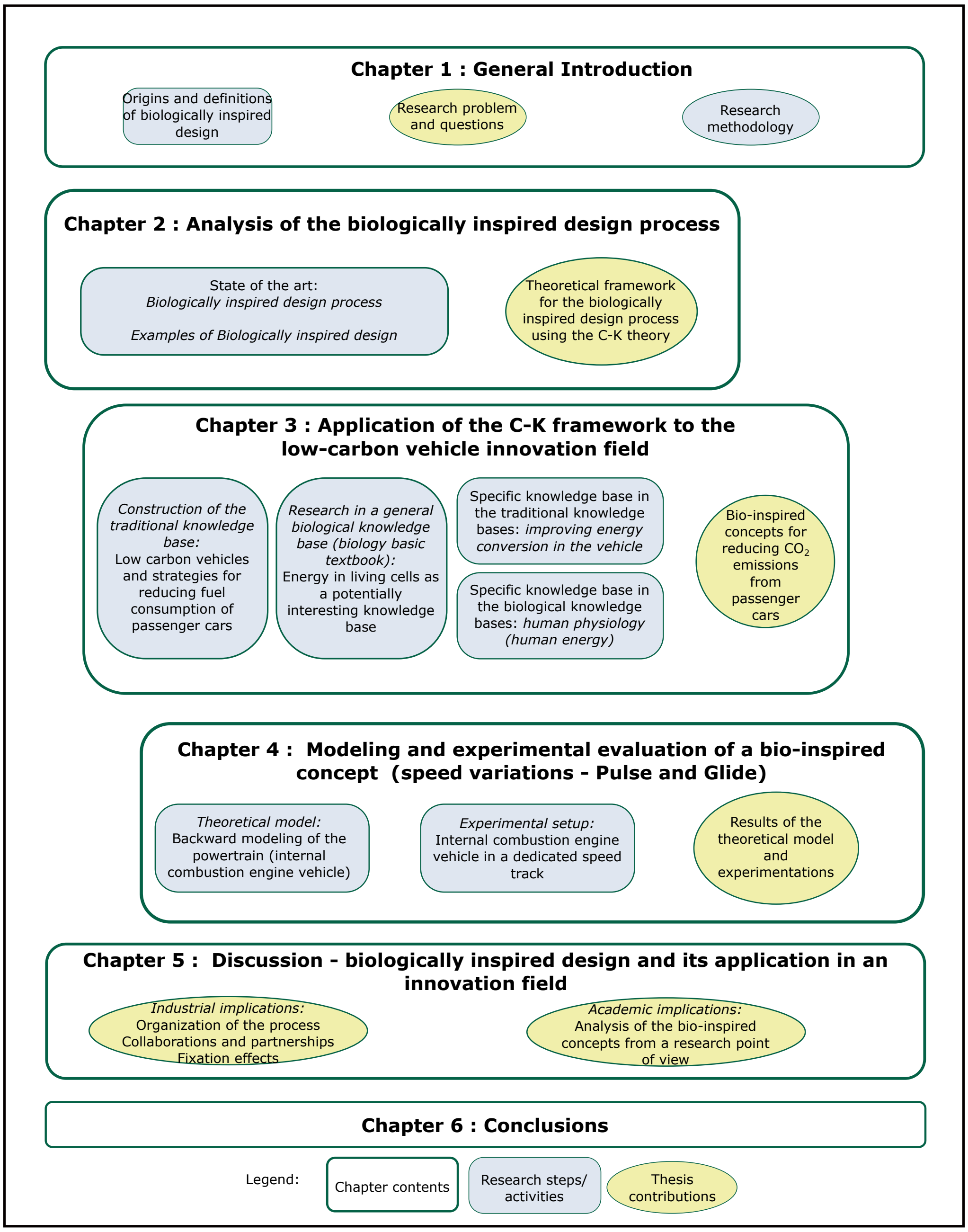


Figure 1.3: Overview of the different chapters: contents, activities and contributions.

Chapter 2

Biologically inspired design: state of the art and modeling with C–K theory

HIGHLIGHTS

- The **state of the art** of the biologically inspired design process;
- Analysis of **examples** of biologically inspired design;
- Hypothesis: biologically inspired design goes **beyond analogies**;
- A **theoretical model** for the biologically inspired design process using the **C–K theory** is proposed.

Chapter contents

This chapter details the research on biologically inspired design methodological approaches. Starting with a presentation of the state of the art in biologically inspired design, we analyse examples of biologically inspired designs retrieved in literature. This analysis uncovers the reasons justifying the use of biological inspiration and their role during the design process.

In order to study this design aspect of the biologically inspired design activity, a design theory, is used. This design theory had to be able to explain the problem-solving aspect of the analogy, its relation with the existing knowledge bases and the generation of alternatives. The chosen theory having these properties is the C–K theory. It allowed us to model some existing examples of biologically inspired design, highlighting the stimulations in the concepts space and in the knowledge space provoked by the activation of biologically inspired design.

2.1 Introduction

The use of biological systems as a source of inspiration for improving or developing new systems is called biologically inspired design (Shu et al., 2011; Helms et al., 2009) or biomimetics (Vincent et al., 2006; Speck and Speck, 2008) or biomimetic design (Shu et al., 2011) or biomimicry (Benyus, 1997).

Different fields have examples of biomimetic designs, including materials (Bhushan, 2009; Singh et al., 2012), artificial intelligence (Steer et al., 2009), construction (Badarnah Kadri, 2012; Scott Turner and Soar, 2008) and transportation (Bar-Cohen, 2012). Some researchers also consider that the outcome of getting inspiration from nature can be more "sustainable" (Benyus, 1997).

These examples of getting inspiration from nature to improve and conceive new products have raised a renewed interest on integrating in a more systematic way the biological knowledge into the traditional design process. This trend is relatively recent[1] and implies understanding the *organization* that should take place to integrate biology efficiently and *disentangling* the reasons and benefits of bringing this extra knowledge base to the design process.

This chapter presents an analysis of the literature about biologically inspired design under two aspects:

- The characterization of the process.

[1] See Section 1.1 for more details and definitions of biologically inspired design.

- The methods for supporting this process.

A design theory is then used to disentangle the creativity and organizational aspects of this design process.

The following sections reviews and complements the following article:

Freitas Salgueiredo, C., Hatchuel, A. Beyond analogy: A model of bio-inspiration for creative design, AIEDAM special edition DCC'14, Vol.30, p.159-170.

2.2 The state of the art on biologically inspired design

As briefly introduced in Chapter 1, the approach consisting in using the inspiration from nature to develop innovations (in human conceived technologies or products) receives different denominations: *biologically inspired design*, *biomimetics*, *biomimicry*, *biognosis*, *bioinspired design*, etc. In this thesis the term "biologically inspired design", abbreviated BID is more frequently used, as this denomination appears in literature articles referring to the analysis of the design process that incorporates biological inspiration (Helms et al., 2009; Shu et al., 2011). This term is however considered as a synonym to the other terms meaning using biological systems as a source of inspiration for "solving problems", as suggested by Vincent et al. (2006) and Shu et al. (2011).

In order to better understand the biologically inspired design process, this section presents the different models proposed in literature for practicing and thinking this activity.

2.2.1 Characterization of the process of biologically inspired design

In the biologically inspired design process, two elements are always present: the biological system and the human-engineered system that is going to be improved using inspiration from the biological system. This human engineered system may or may not exist. For example, a biologist may discover a property that will later be used in a human technology or process, or an engineer may turn to nature to seek an answer to a precise question. This "encounter" between biology and engineering must occur in a biologically inspired design approach.

This encounter is generally characterized as an *analogical transfer process* (Mak and Shu, 2008;

Helms et al., 2009). The description of the BID process, builds on a vast literature about analogies and their use in problem solving (Holyoak, 1985; Gentner, 1983).

Holyoak (1985) defined the role of analogies in problem solving as a means of generating "new rules applicable to a novel target domain by transferring knowledge from a source domain that is better understood", and also proposed the following iterative steps required to perform analogical problem solving:

1. Building mental representations of the source and target domains
2. Choice of the source as a "potentially relevant analog" to the target
3. Map components of both domains
4. Map extension in order to generate a solution to the target

This process involves the analogical mapping between the source and the target domains, with the critical point being exactly knowing what is transferred. This general definition was also used to characterize the analogical transfer that takes place during the biologically inspired design process: Mak and Shu (2008) and Helms et al. (2009) both define biologically inspired design as involving cross-domain analogies:

> *Biological analogies used in engineering are cross-domain analogies, since the domains of biology and engineering are conceptually different.* (Mak and Shu, 2008)

> *Biologically inspired design is inherently interdisciplinary. By definition, it is based on cross-domain analogies requiring expertise across two disparate domains (engineering and biology)* . (Helms et al., 2009)

And describing the mapping activity between engineering and biological domains as necessary during the process:

> *In previous studies, we found that students were able to identify useful strategies from the descriptions of biological phenomena; however, mapping these strategies to the example problem proved to be difficult.*. (Mak and Shu, 2008)

This interpretation of the biologically inspired design as an analogical transfer process, involving cross-domain analogies between engineering and biology leads to the identification of two general directions for the biologically inspired design process. These directions refer to the motivations behind seeking inspiration from nature. There are cases in which the study of biological systems may reveal interesting properties that could be useful for solving human problems. These properties will then be transferred to technical systems that could use it, or be used to conceive another product or technology. In other cases, there is an identified problem in engineering, for which biological systems could inspire solutions. These two directions are referred to in literature as *bottom-up* or *top-down* (See Box 2.1), respectively.

The general steps of these two directions involve four features:

1. The identification of the starting point of the design process: An interesting property of a biological system or a technical problem.

2. The search on biological knowledge: for interesting properties or for a "biological solution".

3. The "abstraction" from the biological model: reframing the biological properties in the technical solutions.

4. The technical application, the development of a bioinspired technology or process.

As an analogy implies finding similarities between the two domains involved, one could inquire which analogies would actually "work"? In the biologically inspired design field, Mak and Shu (2008) identified four similarity types between the source (the biological phenomenon) and the target (the bio-inspired design): *analogy*, defined as the "implementation of the strategies found in the biological phenomenon without transferring biological forms", *literal implementation* of biological forms and behaviors; *biological transfer* that keeps the form, using it with a different purpose; *anomaly*, when there is no apparent similarity between the concept and the source biological phenomena. The analogy is the objective of the biologically inspired design, while the other forms of similarities are considered "errors" (Shu et al., 2011; Helms et al., 2009). However, as observed by Gentner (1983): "*The strength of an analogical match does not seem to depend on the overall degree of featural overlap; not all features are equally relevant to the interpretation*". For example, (Wilson et al., 2010) observed that the novelty of designers' ideas was increased when they were exposed to biological examples and only half of these designs had an attribute transferred from the biological system.

Helms and Goel (2012) proposed a model of analogical problem evolution that takes place during the BID process: a problem definition may evolve (extending or expanding) with the help of an analogy to an already existing solution, which is called *problem-solution co-evolution*. Analogies are then able to expand a problem, by adding other dimensions to the problem.

This brief literature review shows that biologically inspired design has been characterized according to the classic theory of analogy, as an analogical transfer between two domains, biology and engineering. The analogical interpretation may lead designers to search for "the" biological system or property that will solve their problems. An analogical transfer implies that all that is required is to find one or more biological systems and transfer their properties to the designed system. However two aspects deserve a better characterization:

1. Can the "anomaly" described by (Mak and Shu, 2008), in which no apparent similarity is observed between the biological "source" domain and the engineering domain be considered as a biologically inspired design? in which conditions?

2. How does biologically inspiration increase novelty of ideas even without a transfer of attributes as indicated by (Wilson et al., 2010)?

The study of these two aspects requires an understanding of the way in which biological knowledge interferes with the existing knowledge bases available to designers and how this interaction contributes to generate new concepts. Design theories are used to explain the process of design, and they can provide the theoretical basis for studying the two aspects mentioned above.

According to (Ullman, 1991), design theories can have three foci: *(i)*"explaining the designed object itself", how an object evolves to a final manufactured product, *(ii)* "explain how the designer(s) transforms an ill-defined problem into a fully described product" and *(iii)* "explain the process of design". For understanding the biologically inspired design process, theories explaining the process of design would be more useful, although the two other foci can also be found in other design theories.

In the domain of design theories explaining the process of design, and that attempt to formalize the design process are included: the *systematic design* proposed by Gerhard Pahl and Wolfgang Beitz (Pahl and Beitz, 1977, 1988), the general design theory introduced by Yoshikawa (Yoshikawa and Uehara, 1985), the *axiomatic design* by Nam P. Suh in 1988 (Suh, 1990), the *coupled design process* by Braha and Reich (Braha and Reich, 2003), the *infused design* by Shai and Reich (Shai and Reich, 2004), and the *concept-knowledge (C-K) theory* by Hatchuel and Weil (Hatchuel and Weil, 2003). Table 2.1 presents an overview of the main assumptions of some of these design theories[2]: systematic design for being one of the most cited design theories in the biologically inspired design studies, general design theory for being one of the first design theories based on "mathematical foun-

[2]Hatchuel et al. (2011b) provide a more extensive comparison between properties of axiomatic design, general design theory, coupled design process, infused design and C-K theory.

dations"[3] and C-K theory for "abandoning the definition of design as a mapping between functions and attributes"(Hatchuel et al., 2011b).

The research on the biologically inspired process contains clear references to the systematic design of Pahl and Beitz (Pahl and Beitz, 1988):

- Sartori et al. (2010) analyzes different biomimetic procedures described in literature using the systematic design process, and concludes that all these procedures "are intended to support the phase of conceptual design", although pointing out that some biomimetic procedures also include guidelines that support other phases as problem analysis and transition to embodiment design. All these phases are described in Pahl and Beitz systematic design approach.

- The function-based approaches for biologically inspired design, such as those proposed by Nagel et al. (2014), is clearly inspired from a systematic design approach, as the authors state: "a "big picture" approach to a systematic, function-based (drawing from a Pahl and Beitz approach - Pahl and Beitz (1988)) biologically inspired design is presented in this chapter".

- Helms et al. (2009) also consider that the first step of their "problem-driven biologically inspired design process" is "problem definition", that includes the functional definition, one of the four steps of the systematic design process.

- Lenau et al. (2011) concluded in their study about the use of using inspiration from nature to reduce consequences of car collisions that "biomimetics represent a promising way of improving systematic design work".

However, systematic design is based on a set of rules that are previously established, and a rupture, a breakthrough object, requires a new set of rules. The main criticism of these theories, according to Agogué et al. (2014a) is that they cannot describe the activities outside the "dominant design", i.e. the main features that constitute the standard of an industrial product. The two questions about how biologically inspired design generates novelty or increases creativity, and whether anomalies are part of "valid" biologically inspired design solutions, remain unanswered only with systematic design.

[3] See Reich (1995) for more details.

Box 2.1: DIRECTIONS OF BIOLOGICALLY INSPIRED DESIGN

Two directions were identified in literature for the biologically inspired design process. These two directions received different names according to the different authors. These two general directions and their synonyms found in literature are presented in this Box:

- Starting point: **an engineering problem** / *a biological system*
  - **top-down** / *bottom-up* : terms used mainly by the Plants Biomechanics Group Freiburg (Speck and Speck, 2008; Lienhard et al., 2011; Masselter et al., 2012)
  - **problem-driven/** *solution-driven* or *solution-based* : terms used mainly by the Georgia Institute of Technology (School of Interactive Computing and Center for Biologically Inspired Design) (Helms et al., 2009; Vattam et al., 2010; Goel et al., 2014)
  - **Challenge-to-Biology** / *Biology-to-design*: terms used mainly by the Biomimicry 3.8 Institute (Biomimicry3.8, 2015b)

The following representation depicts the main steps of each direction, according to each one of these three references :

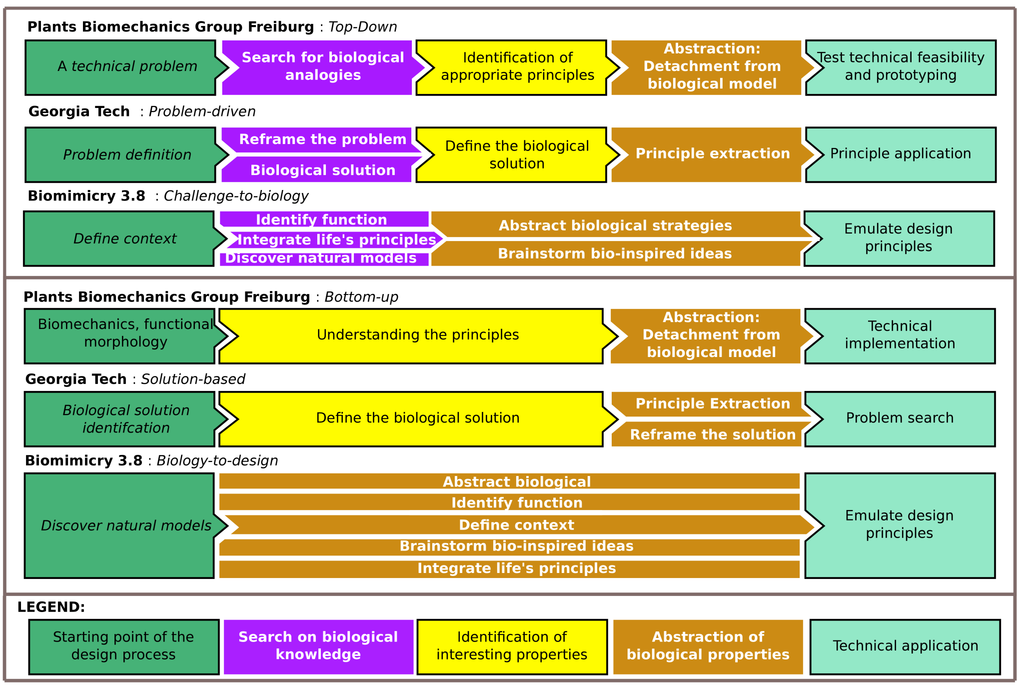


Figure 2.1: The different directions for biologically inspired design, according to three references: (Speck and Speck, 2008; Helms et al., 2009; Biomimicry3.8, 2015b).

In the *Challenge-to-Biology* direction described by Biomimicry3.8 (2015b), there is an evaluation step after the emulation of the bio-inspired design principles. This evaluation is made according to the life principles that "represent these overarching patterns found amongst the species surviving and thriving on Earth. Life integrates and optimizes these strategies to create conditions conducive to life" (Biomimicry3.8, 2015a).

Table 2.1: Main features of selected design theories: Systematic design, General Design Theory and Concept-Knowledge theory.

Design theory	*Main assumptions*	*Steps considered*	*References*
Systematic Design	– Rule-based design – Functional decomposition – The design must meet task-specific and general constraints	*Clarification of the task*: identification of the requirements and constraints to the development of the solution. *Conceptual design*: establishment of function structures, search for solution principles and their combination into concept variants. The concept is also evaluated according to the requirements. *Embodiment design*: using the concept, the designer determine layouts and forms (different variants can be made, and they are evaluated) *Detail design*: materials, form, technical and economic feasibility are defined and checked.	(Pahl and Beitz, 1988)
General Design Theory	– Entity sets (set of real objects that exist and that will exist) – Subsets of entities sets are abstract concepts that are either attributes (properties measured or observed) or functions (behavior of an entity) – "Ideal knowledge (choice of an entity in a catalog) vs. Real knowledge (best fit between group of functions and group of attributes)" – Axioms: recognition, correspondence, operation – Provide guidelines for building CAD systems (Reich, 1995)	Mapping between desired function and artifact description under certain constraints.	(Yoshikawa and Uehara, 1985; Reich, 1995; Hatchuel et al., 2011b)
Concept-Knowledge Design Theory	– 2 spaces: C-space (concepts space) and K-space (knowledge space) – Continuous expansion of these spaces – K-space: all knowledge available – C-space: composed of known properties in K-space, that when combined have no logical status.	Design proceeds by extending both spaces: C and K, until a knowledge becomes knowledge	(Hatchuel and Weil, 2003; Agogué et al., 2014a)

2.2.2 Supporting the biologically inspired design process

Shu et al. (2011) indicates that literature about BID proposes two types of supporting methods to the biologically inspired design process: tools for facilitating the *search and retrieval* of biological analogues used during the design process, and tools for facilitating the *application of these analogies* in design.

Among the different tools for facilitating the *search and retrieval* of the biological analogues used during the design process are databases, consultations with biology experts, search in natural-language written biology texts, ontologies, patents or computational tools such as webcrawling and the functional basis.

In the domain of databases proposed specially for biologically inspired design, the most well-known is Ask -Nature database, from the Biomimicry Institute[4] (Deldin and Schuknecht, 2014). In this database, queries are made based on a functional approach, using the question: *how does nature...?*, examples of groups of functions given in the AskNature database are: (1) break down, (2) get, store or distribute resources, (3) maintain community, (4) maintain physical integrity, (5) make, (6) modify, (7) move or stay put, (8) process information. These groups are composed of subgroups, functions and strategies, that are detailed on the Biomimicry Taxonomy, developed by the Biomimicry Institute[5]. Queries can also be made by products, such as ultra-hard materials, Sharklet^{TM} surface texture. The database has in this way biological strategy pages, in which a biological phenomenon is described and product pages, in which biologically inspired designed products are described. Table 2.2 shows the main features of a biological strategy page and the product page of the bio-inspired product developed using this phenomenon as a source of inspiration.

Vincent (2014) considers that the main problem of the AskNature database is that is has “casual” sources and that are not peer reviewed. According to this author, one of the main difficulties of databases, besides its size and classification limitations is the impossibility to “deduce new relationships”, as they give little indication about the transfer process between biology and engineering.

To overcome this difficulty, this author and colleagues initially proposed an approach based on TRIZ constructs (Vincent et al., 2006). TRIZ is the acronym for the “Theory of Inventive problem solving” conceived and developed by Genrich Altshuller and Rafik Shapiro. According to Vincent et al.

[4]AskNature is an online free-access database, available at: http://www.asknature.org/, accessed on 06.03.2016.

[5]The Biomimicry Taxonomy has 8 groups, 30 subgroups and 162 functions. A complete list of these groups is available at: http://www.asknature.org/aof/browse, accessed on 06.03.2016.

Table 2.2: A summary of a query in AskNature database: self-cleaning (query made on 06.03.2016 at http://www.asknature.org).

Query: How does nature...?	*Strategies*	*Products*
self-cleaning	Result 1/17 (Filter: strategy):	Result 8/11 (Filter: product):
	Surface allows self-cleaning: sacred lotus	*Lotusan® paint*
	Strategy page	*Product page*
	Group: maintain physical integrity	Inspiring strategies
	Sub-group: protect from abiotic factors	Product or process
	Function: dirt/ solids	
	Summary (phenomenon description)	
	About the inspiring organism (The organism / Habitat)	
	Bioinspired products and application ideas	
	Experts	
	References	

(2006), the idea behind this method is to define a problem at a functional level usually using opposing characteristics or contradictions. These contradictions are then compared to contradictions derived from the observations of the principles used to solve problems in more than 3 million patents. 39 contradictions were identified in these 3 million patents. In the study of Vincent et al. (2006) more than 2,500 examples from biology and 5,000 examples from technology were analyzed to make a classification of the solutions to problems according to changes in structure, substances (things), in energy, information (do things), in space and time (somewhere). The results of this analysis show that biology and engineering use different principles to solve problems: at the scales up to 1m, technology manipulates more the energy usage or the material, while biology at these scales use more information and space.

Continuing this previous work, Vincent proposes the use of *ontologies* based on a language for describing structured information (RDF, resource description framework) (Vincent, 2014). The classes and sub-classes defined organize the information and allow establishing relationships between the classes and their members. The process for builiding this ontology for biomimetics is based on the following steps:

1. A chosen abstract of a published, peer-reviewed scientific paper of a biology field. This paper should present the analysis and solution of a biological problem.
2. Define the problem as a contradiction
3. Allocate relevant Inventive Principles (IP) from TRIZ

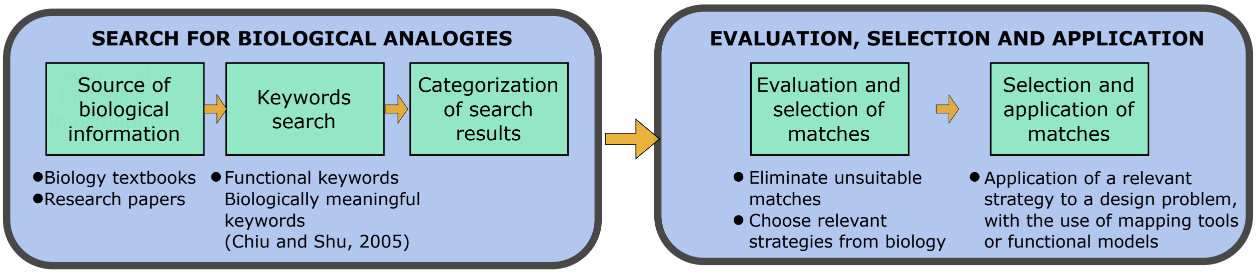


Figure 2.2: The main steps of the natural-language approach according to Shu (2010).

4. Identify functions related to these IPs and compare IPs from biology and TRIZ.

5. Find examples in the ontology that may have a solution to a given problem

Besides databases and the ontology of biomimetics, other approaches involving functional bases were developed. Nagel and Stone (2012) propose a computational tool that instead of using a repository of biological processes, use a biology textbook as the biological knowledge base, an engineering to biology thesaurus (Nagel et al., 2010) and a design repository of engineered systems indexed by engineering function. This tool has also a concept generation software that allows creating different “conceptual design variants”. Computational tools for searching for biological information in the Internet were also developed (Vandevenne et al., 2013).

The group of the Biomimetics for Innovation and Design Laboratory, of the University of Toronto (Chiu and Shu, 2005; Shu, 2010), proposes an approach based on a search in biological knowledge with keywords describing an engineering problem. The biological knowledge corpus is in “natural-language format” (books, papers). This method allows a wider search than a database that is dependent on the data and its organization. Figure 2.2 summarizes the main steps proposed for this approach (Shu, 2010).

Another tool for facilitating the search and retrieval of biological analogies are the consultations with biology experts. In its consulting activities, Biomimicry 3.8 propose an approach called “Biologist at the design table”, in which biologists interact directly with the companies teams wishing to apply biologically inspired design[6].

Among the tools for facilitating the application of the biologically inspired analogies to design figure DANE (Design by Analogy to Nature Engine)(Wiltgen et al., 2011) that provides a knowledge base

[6]More information about Biomimicry 3.8 consulting activities, previously called Biomimicry Guild can be found in the company website: http://biomimicry.net/consulting/ (access on 06.03.2015) and in the review by Peters (2011).

of biological systems, represented using SBF (Structure-Behaviour-Functions) models. Idea-Inspire (Chakrabarti et al., 2005; Chakrabarti, 2014) is a software tool that uses knowledge about biological and technical systems as a stimuli for ideation. This knowledge is presented using the constructs of the SAPPhIRE (State change – Action – Part – Phenomenon – Input – oRgan – Effect), an analogical search algorithm that using information about the problem and SAPPhIRE levels of abstraction retrieves entries that are relevant to the problem description and a graphical user interface (GUI) that helps the designer in specifying the problem and receiving a list of relevant entries. Moreover, Bio-TRIZ (Vincent et al., 2006) is based on TRIZ and was developed for facilitating the transfer process between biology and engineering. It incorporates biological phenomena to TRIZ, using conflicts identified in a database of more than 500 biological phenomena and compares the biological principles to engineering ones and contribute for the final solution developed. Other TRIZ tools such as the law of system completeness and substance-field analysis (Helfman Cohen et al., 2011, 2012, 2014) were also applied to biological systems in order to analyze biological systems and thus the analogical transfer process between biology and engineering.

Lenau et al. (2011) use in their action research project other approaches for supporting theBID process: the transfer checklist approach, the inspiration card approach and the interdisciplinary team approach. The *transfer checklist approach* involves the search of a function that represents the goal of the search for biological solutions and then allocate biological system to the problem using a checklist for biological associations proposed by Lindemann and Gramann (2004). The *Inspiration card approach* formulates a functional problem, generalizes it into keywords, and search for biological analogies using databases, consulting with biologists or in literature[7]. The information about analogies is then put into inspiration cards which represent conceptual ideas and can be used to generate design proposals. The *interdisciplinary team approach* involves an interdisciplinary team (engineer and biologist) that work together: the engineer defines the problem, defining its functionalities, and formulates questions to the biologist. The biologist searches for biological solutions and both discuss "iteratively" on how to adapt the solution from nature to the technical problem.

[7]This approach is described in full detail in Lenau et al. (2010), and the inspiration cards were later renamed "biocards" (Lenau et al., 2015).

2.2.3 Conclusions – the analysis of biologically inspired design process with a formal design theory is required

Two aspects extensively studied in literature about biologically inspired design were described in this section about the state of the art: the characterization of the biologically inspired design process, and the methods used to support this process.

The biologically inspired design process is generally characterized according to the classic theory of analogy: an analogical transfer between the domain of biology and the engineering domain. Besides, the process is described according to the systematic design principles described by Pahl and Beitz (1988) (functional decomposition, clarification of the task, conceptual design, embodiment design, detail design). Two questions remained partially answered by the existing studies about biologically inspired design process:

1. Can the "anomaly" described by (Mak and Shu, 2008), in which no apparent similarity is observed between the biological "source" domain and the engineering domain be considered as a biologically inspired design? in which conditions?

2. How does biologically inspiration increases novelty of ideas even without a transfer of attributes as indicated by (Wilson et al., 2010)?

The characterization of the biologically inspired design building upon systematic design, that is not suited to describe the activities outside the "dominant design" (Agogué et al., 2014a), these questions remained unanswered. As the aim of this research is to provide answers to how the biologically inspired design provides an increase on novelty, on creativity and generate more disruptive concepts, the classic systematic approach does not appear to be sufficient for studying these other aspects of this process.

The methods found in literature for supporting the biologically inspired design (databases, ontologies, functional decomposition, inspiration cards, webcrawling) are based on the characterization of biologically inspired design as an analogical transfer process and a part of the systematic design process, and also do not provide evidence on how BID stimulates creativity or novelty.

Design theories can describe the renewal of an object identity[8], and that in addition, allow an in-

[8] The identity of an object is the "set of stable characteristics of a product" (Agogué et al., 2014a). For example, in the design of Mg-CO2 engines for mars explorations described by Hatchuel and Weil (2009), the identity of engines is

terpretation of the design process in a very general way, taking into account its generativeness[9] and robustness[10] capacities could be useful for studying the biologically inspired design process and its capacity to produce more disruptive designs.

The Concept-Knowledge theory (C–K theory) (Hatchuel and Weil, 2003) has been the object of studies aiming at disentangling its properties of describing the revision of identity of an object (Hatchuel and Weil, 2009) and of generativeness and robustness (Hatchuel et al., 2011b). These studies have shown that this theory is able to show the revision of an object identity, and that its robustness and generativeness capacities are more general, i.e., it models design in a rigorous way, without being dependent on the existing definitions of objects and functions. Moreover, this theory was used to disentangle properties from other design theories or methods, such as the creation of creative solutions using ASIT (advanced systematic inventive thinking) (Reich et al., 2012), the creativity process of Infused Design (Shai and Reich, 2004) or the innovative properties of Parameter Analysis (Kroll et al., 2014), and to explain fixation effects (Hatchuel et al., 2011; Agogué et al., 2014b).

This theory is the basis for the analysis of the biologically inspired process that is described in the following section.

2.3 Interpreting biologically inspired design using a design theory

The methodology used to study the biologically inspired design process with the C–K theory involved the study of examples of biologically inspired design. The design process in these examples was fully described. This study of examples of biologically inspired design involved the identification of the following aspects of the design process:

- The technical issue addressed by the biomimetic development (*first concept* or design path);
- The biological property observed that could bring some insight for this issue (*biological inspiration*);
- The reasons for using inspiration from nature (*biological inspiration use* during the design process).

changed and the types of missions it serves also.

[9] Generativeness: the ability to go beyond the search in a fixed set of solutions.

[10] Robustness: the ability of producing robust designs (designs that have the expected performances).

The examples of biologically inspired designs were retrieved in well known scientific journal databases such as *Scopus*® or specific journals and books about biologically inspired design, such as Bioinspiration and Biomimetics (IOP Publishing)[11], Design and Nature Conference proceedings (WIT Press)[12] and Bar-Cohen (2012). The search used queries such as bioinspir*, biologically inspired, biomim*[13]. The difficulty of this research was to find articles that described the full design process in detail and that were the result of a biologically inspired design process. Some authors used biological inspiration to explain a development. For example, in the initial article about particle swarm optimization (PSO)(Kennedy and Eberhart, 1995) a nature-inspired optimization algorithm, the authors affirm that although the study of social behavior helped in the discovery of the algorithm, the developed algorithm of PSO stands without the social behavior:

> *The method was discovered through simulation of a simplified social model; thus the social metaphor is discussed, though the algorithm stands without metaphorical support.* (Kennedy and Eberhart, 1995)

Although biologically inspired designs could be found in different domains such as architecture, construction, aerodynamics, most were linked to materials properties or forms. Table 2.3 details examples found in literature according to the three aspects previously mentioned. These examples represent those in which the design process was described in sufficient detail in the references mentioned.

Among these examples we have chosen 4 examples for studying using the C–K theory, one belonging to the top-down approach, and three from the bottom-up approach. All these examples were well described in literature, with a considerable amount of information allowing retracing the chronology of the design process and its steps. The choice of three bottom-up examples and only one top-down example is not a problem for the completeness of our study, as the main difference between the two approaches is the starting point and not the design process that takes place, as shown in Box 2.1. Two of these examples are related to materials (Gecko, self-cleaning), one to aerodynamics and forms (Whalepower) and one to architecture and materials (Flectofin®).

- *Flectofin*® (top-down): a hingeless flapping mechanism for buildings facade shading.
- *Whalepower technology* (bottom-up): a technology for improving aerodynamics performance of turbines and fan blades.

[11] Available at: http://iopscience.iop.org/1748-3190/.

[12] Available at: http://www.witpress.com/books/subjects/design-nature.

[13] The keywords reflected the majority of the articles found about the subject. The term biomim* was included because many articles use the terms biomimetics and biomimicry as synonyms to biologically inspired design.

- *Gecko adhesion properties* (bottom-up): surfaces developed for having outstanding dry adhesion properties.

- *Self-cleaning surfaces with Lotus-effect* (bottom-up): surfaces and coatings developed for presenting self-cleaning properties.

2.3.1 Modeling of biologically inspired design with the C-K theory

The study of these four examples of biologically inspired design product developments using C–K theory implied the understanding of these examples according to the constructs and the framework of this design theory. The next paragraph reviews these constructs and framework, which will constitute the basis for the analysis of each example.

2.3.1.1 C-K theory: principles and operators

In the C–K theory (Hatchuel and Weil, 2003) design is defined as an "interplay between two interdependent spaces", the space of concepts (C) and the space of knowledge (K). Each space has its own properties: the space K contains the knowledge that is available to designers, while space C contains concepts. Concepts in C–K theory are propositions that are neither true nor false according to the available knowledge in K. For example, "there exists a smarter way to learn tennis" is a concept (Hatchuel et al., 2012), as one cannot decide if this proposition is true or false only based on its own knowledge base.

The design process is characterized in C–K theory as an expansion of the initial concept into other concepts, which is called *concept partitioning*. Concepts can also expand into new knowledge, until a partitioned concept becomes a true proposition in K. The expansions in the two spaces allow them to have different structures. C space only admits partitioning (adding or subtracting properties), giving it a tree-like structure, while K space contains propositions that are added without following an order or a direct connection, like an "archipelago" (Hatchuel and Weil, 2009).

The *operators* of C–K theory characterize the transformation between and inside spaces K and C (Hatchuel and Weil, 2009; Agogué et al., 2014a):

- *C→K*: searches attributes in K that can be used to partition concepts in C or that contribute to the generation of new proposition in K ("activation of new knowledge bases"). If a new

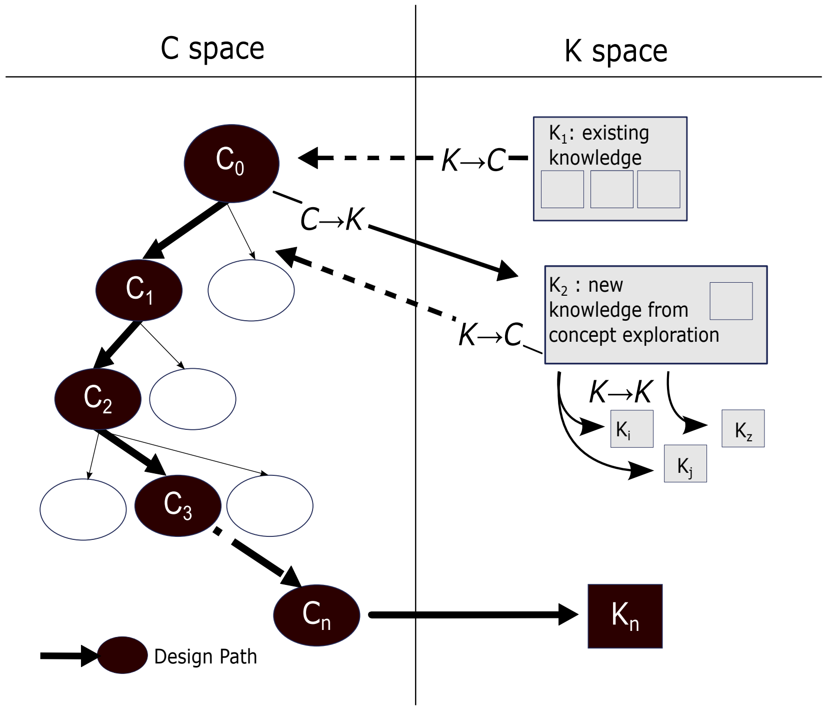


Figure 2.3: C-K theory framework and operators, adapted from (Hatchuel and Weil, 2009; Agogué et al., 2014a).

attribute in K is added, the designer must verify if the concept is still a concept or has become knowledge.

- *K→C*: generates new concepts by assigning new properties to the existing concepts (concept partitioning). The partitions can be *expanding partitions*, that introduces properties to the definition of the object that are not known properties, it stimulates knowledge expansion to define this new object or *restricting partitions* that add known properties having a selective effect, choosing properties in K but not allowing knowledge expansion.
- *C→C*: allows analyzing the design paths (with expansive or restrictive partitions)
- *K→K*: represents the classic types of reasoning (classification, deduction, abduction, inference, etc.).

The *C–K framework* is the representation of these two spaces, C space and K space. If the design path is known, it is represented by the concepts and sub-concepts that become knowledge. Figure 2.3 shows the evolution of the design process from a initial concept C_0 until a final concept that becomes knowledge, with a representation of the operators.

2.3.1.2 Application of the C-K framework to the analysis of biologically inspired design examples

For each example of biologically inspired design analyzed in detail using the C-K framework, it was necessary to identify the aspects of the design process that could be modeled using C–K theory operators and the two spaces of the framework. The aspects that were identified in the previous study of examples (cf. Table 2.3) can be described using C-K operators:

- The technical issue addressed by the biomimetic development (first concept or design path): it can be modeled as a $K \to C$ operator, as it requires the identification of properties in K that can assign new properties to concepts (or create new concepts).
- The biological property observed that could bring some insight for this issue (the biological inspiration): it can be modeled as a $C \to K$ operator, as the concepts searches attributes in K (in the biological knowledge bases) to partition concepts in C.
- The reasons for using inspiration from nature (how the biological inspiration was used during the design process): these reasons are modeled as $K \to K$ operators, that revise the knowledge about biological phenomena and scientific (non-biological) knowledge in order to see how the bio-inspired concept could become a final design path.

Using the descriptions of the design process available in the references about these examples, the design of a C-K framework describing the biologically inspired design process started then by the formulation of concepts linked to a technical issue identified for each case ($K \to C$), followed by the identification of the biological knowledge bases that were activated during the design process ($C \to K$) and the identification of the properties in biological knowledge that provoked concept partitioning ($K \to C$). The last step was observing how the knowledge bases, biological and scientific (non-biological) were revised and expanded ($K \to K$).

2.3.1.3 Study of the Flectofin® example

The study of this example using C–K theory is described in Freitas Salgueiredo and Hatchuel (2014, 2016). This paragraph presents a summary of this study and its main conclusions. Figure 2.5 shows the framework representing this design process.

Knippers and Speck (2012) explain the motivations for the development of bio-inspired building structures in architecture as:

> *The arising question is how one can reduce the complexity of movable building structures. This leads almost automatically to the study of natural role models. Botany in particular provides the most radical answer which stands in total contradiction to the technical solution [...].* (Knippers and Speck, 2012)

Lienhard et al. (2011) cites as the main motivations for the development of Flectofin ® :

> *In architectural constructions such as shading systems like umbrellas or blinds, deployability is currently mainly provided by the use of technical hinges. [...] In contrast, deployability in plants relies in the flexible and elastic properties of their movable organs e.g. leaves, petals).* (Knippers and Speck, 2012)

The BID process is described as a top-down process by Knippers and Speck (2012), although Lienhard et al. (2011) considered the design process of Flectofin® as a bottom-up process, as properties of a specific organism were studied for its development. This is not a contradiction between the articles written by the same research team, but reflects the two steps that were involved in the design process: the first question of the research group, that brought together researchers from engineering, architecture (Institute of Building Structures and Structural Design (ITKE) of the University of Stuttgart, Germany) and from plants biomechanics (Plants Biomechanics Group Freiburg, University of Freiburg, Germany) was how to use the plants movements technically (a more bottom-up approach) (Matini and Knippers, 2008) and then using these specific movements to answer specific architectural questions, such as how to produce hinge-free flapping mechanisms (a more top-down approach) (Knippers and Speck, 2012).

Considering this information gathered in the articles, the bases for the construction of the C-K framework are set: the initial knowledge bases, i.e. the knowledge about deployability in architecture using hinges and rollers, and the elastic materials for deployable structures, and the initial concept, based on the more general article of Knippers and Speck (2012): "design of a deployable system with simpler technical actuators" (step **(1)**, fig. 2.5). The activation of the knowledge about plants movements (step **(2)**, fig. 2.5), allowed the identification of a first partition to this concept: "without using hinges" (step **(3)**, fig. 2.5), as plants have movements that are usually reversible, use little activation energy and work with the absence of local hinges. The other partition to this concept, more in the "dominant design path" would be improving the existing systems using hinges and rollers for requiring less

Figure 2.4: Bird-of-paradise flower perch opening by bending. The force applied by a hand is in nature applied by the weight of a bird that lands on the flower perch.

maintenance.

A screening process of plants movements was made to explore properties of different plants deformations (Lienhard et al., 2009) (step **(4)**, fig. 2.5) . They identified the deformation mechanism of the bird-of-paradise flower (*Strelitzia reginae*) as particularly interesting: according to Knippers and Speck (2012) the two adnate petals that constitute the flower form a perch in which birds can land in the search for the plants nectar. When birds land in the perch, the bending of these two adnate petals expose the flower pollen that gets attached to the birds. When the birds fly away, the bending process stop and the two adnate petals return to the closed position. Figure 2.4 shows the perch bending movement obtained using a real flower.

This knowledge about this specific plant that use elastic deformations to open and close allows the partition of the concept without using hinges in “using elastic deformations” (as in plants) or “without using elastic deformations”. Plants movements activated knowledge belonging to the scientific (non-biological) knowledge domain to explain the reversible elastic operations being observed (step **(5)**, fig. 2.5). The identification of flower movement as a “special form” of a known materials deformation process, the “lateral torsional buckling” (Lienhard et al., 2011) (step **(6)**, fig. 2.5), allows the partitioning of the concept of “without using hinges using elastic deformations” into “using lateral torsional buckling” (step **(7)**, fig. 2.5).

Using the scientific knowledge about this deformation process of lateral torsional buckling (step **(8)**, fig. 2.5), the researchers achieved a first prototype reproducing the phenomena observed in plants, consisting of “attaching a thin shell element to a rib”, that became knowledge when materials allowing to achieve this deformation process were studied and the first prototype of Flectofin®, a façade shading system without hinges was built (step **(9)**, fig. 2.5).

This case shows that the BID process goes beyond a simple search for suitable analogies allowing the solution of a problem. The identification of the bird-of-paradise process as an interesting analogy came after a screening process that required studying other plants deformation processes, and expanding the knowledge about deformation process that were not spontaneously activated. Lienhard et al. (2011) also highlight that the lateral torsional buckling observed in the bird of paradise was interesting as it provoked a revision on the perception of this deformation process by architects, showing how it can be achieved without provoking failure:

> *This special form of lateral-torsional buckling is not unfamiliar to engineers but mainly perceived as undesirable failure mode to be avoided when planning architectural constructions.* (Lienhard et al., 2011)

Therefore, the activation of biological knowledge allowed the creation of at least two expanding partitions, "without using hinges" and "using lateral torsional buckling" that provoked biological and scientific (non-biological) knowledge revision and expansion.

2.3.1.4 Study of the Whalepower technology example

The study of this example using C–K theory is described in Freitas Salgueiredo and Hatchuel (2016). This paragraph presents a summary of this study and its main conclusions. Figure 2.7 shows the framework representing this design process.

The starting point of this example is the observation of an interesting phenomena in biology: humpback whales (*Megaptera novaeangliae*) do not have well-streamlined flippers, they have protuberances, called tubercles, in the leading-edge of the flippers (Figure 2.6), that seemed to be linked to their superior manoeuverability performances when compared to other whales. These flippers have the same shape of foils (airplane wings or fan blades).

> *If the flippers of the humpback are adapted for maneuverability, they should display a morphology for high hydrodynamic performance.* (Fish and Battle, 1995)

Besides, the study conducted by Fish and Battle (1995) aimed at better understanding the correlation between the design of the humpback whale flipper and the hydrodynamic parameters allowing it to be compared to "engineered designs for enhanced maneuverability".

Considering this information gathered in the article of Fish and Battle (1995), the bases for the con-

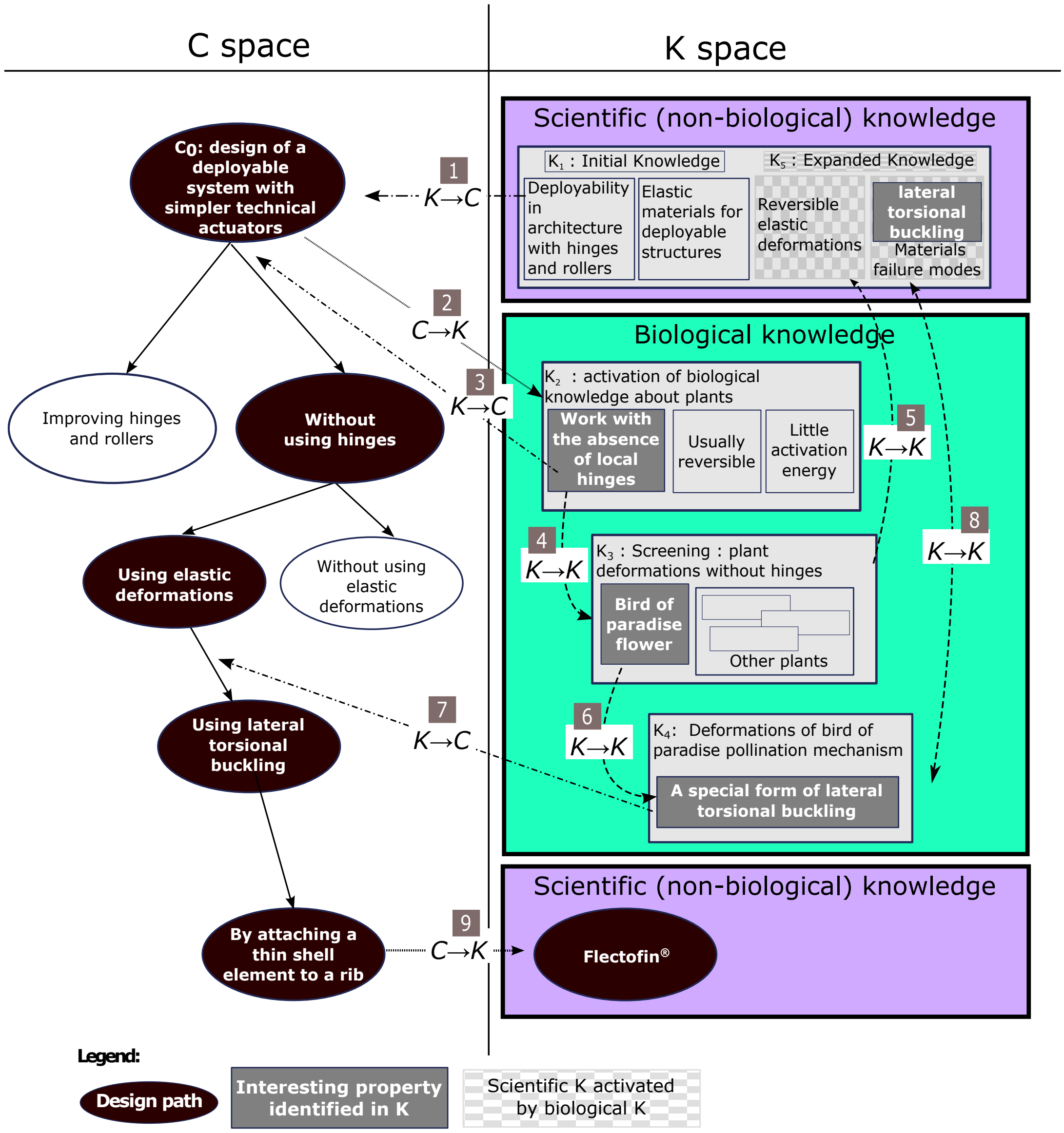


Figure 2.5: C–K modeling for the Flectofin® example. This figure is adapted from previous schemes for this example presented in Freitas Salgueiredo and Hatchuel (2014, 2016).

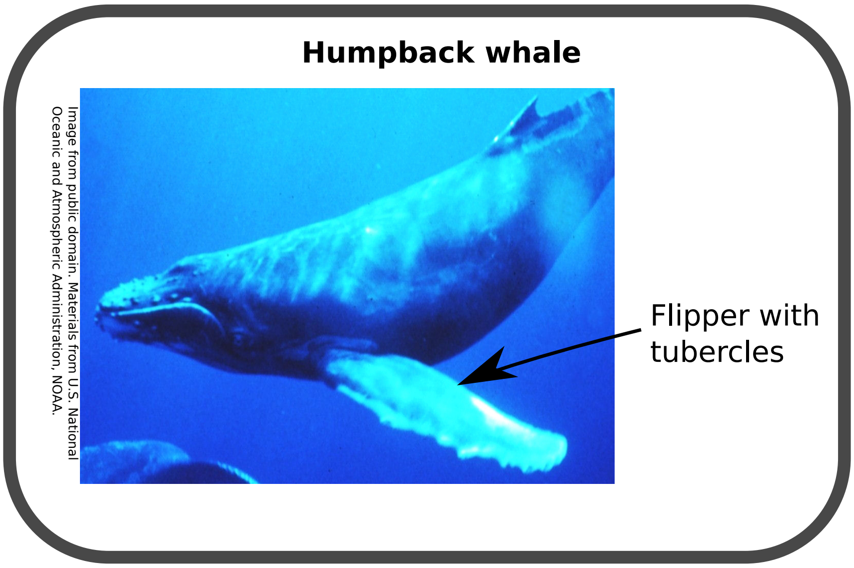


Figure 2.6: A picture of a humpback whale, indicating the tubercles in the flippers of the whale. This figure is adapted from the picture available at: http://www.photolib.noaa.gov/htmls/sanc0602.htm.

struction of the C-K framework are set: the initial knowledge bases, i.e. the knowledge about the humpback whales and their flippers and the initial concept, that could be then formulated as: "design of hydro-/ airfoils with improved aerodynamics" (step **(1)**, fig. 2.7). As the comparison between engineering and nature was established since this first article, we could assume that the initial concept involved the search of properties allowing a better design of wing-like structures.

The conclusion of this study indicated that the tubercles function in an analogous way as the strakes used on aircrafts[14], and that the swimming properties of the whale are considerably improved thanks to tubercles and their hydrodynamic properties, delaying stall and maintaining lift (step **(2)**, fig. 2.7).

This difference between whales flippers with tubercles and usual hydro- and airfoils built by engineers (step **(3)**, fig. 2.7), provokes concept partitioning (step **(4)**, fig. 2.7):

> *Few other passive means of altering fluid flow around a wing-like structure can delay stall and both increase lift and reduce drag at the same time. As a result, the application of leading-edge tubercles for passive control of flow has potential in the design of control surfaces, wings, propellers, fans, and wind turbines.* (Fish et al., 2011)

The partitions created are design of hydro- and air foils with improved hydro- aerodynamics "without using well-streamlined leading edges" and "introducing tubercles to the leading edge" (step **(4)**,

[14] Strakes are vortex generators responsible by changing the stall of a wing, and are fitted on the fuselage of an aircraft (Fish and Battle, 1995).

fig. 2.7). The search of applications that could benefit from this property represent a return to the K-space (step **(5)**, fig. 2.7), and require an expansion of the knowledge about flow control around a wing-like structure (step **(6)**, fig. 2.7).

This design path becomes knowledge with the fan blades that used tubercles in the leading edge, called Whalepower technology (Fish et al., 2011). Examples of designs using this technology include the Altra-air fans, using bumps in the blades leading edge[15]) or even wind turbine blades as proposed by Fish et al. (2011) (step **(7)**, fig. 2.7).

2.3.1.5 Study of the self-cleaning surfaces with Lotus-effect example

The study of this example using C–K theory is described in Freitas Salgueiredo and Hatchuel (2014). This paragraph presents a summary of this study and its main conclusions. Figure 2.9 shows the framework representing this design process.

As in the Whalepower technology example, the starting point of this example is the observation of an interesting phenomenon in biology, related to the possibility for some leaves with rough surfaces to be almost free of contamination, while plants with smooth surfaces were not:

> *During the routine interpretation with respect to systematics of scanning electron microscopy (SEM) micrographs of the leaf surfaces of some 10000 plant species (Barthlott 1990, 1993), we observed a peculiar effect. Independently of the degree of pollution at the collection site, species with smooth leaf surfaces always had to be cleaned before examination, while those with epicuticular wax crystals were almost completely free of contamination.* (Barthlott and Neinhuis, 1997)

In this article, the surfaces of these self-cleaning structures were studied, and the example in which the self-cleaning properties were more accentuated was the lotus (*Nelumbo nucifera*) leaves. The research work revealed that the self-cleaning properties of these leaves came from the combination of “hydrophobic surface components and microscopic roughness” (Figure 2.8). The authors also hypothesized that the same self-cleaning effect could be transferred to artificial surfaces:

> *We assume that this effect can be transferred to artificial surfaces (e.g. cars, facades, foils) and thus find innumerable technical applications.* (Barthlott and Neinhuis, 1997)

[15] Altra-Air Fans, ceiling fans developed by Envira-North System Limited. A description is available at: http://www.enviranorth.com/altra-air.html, accessed on 16.06.2016.

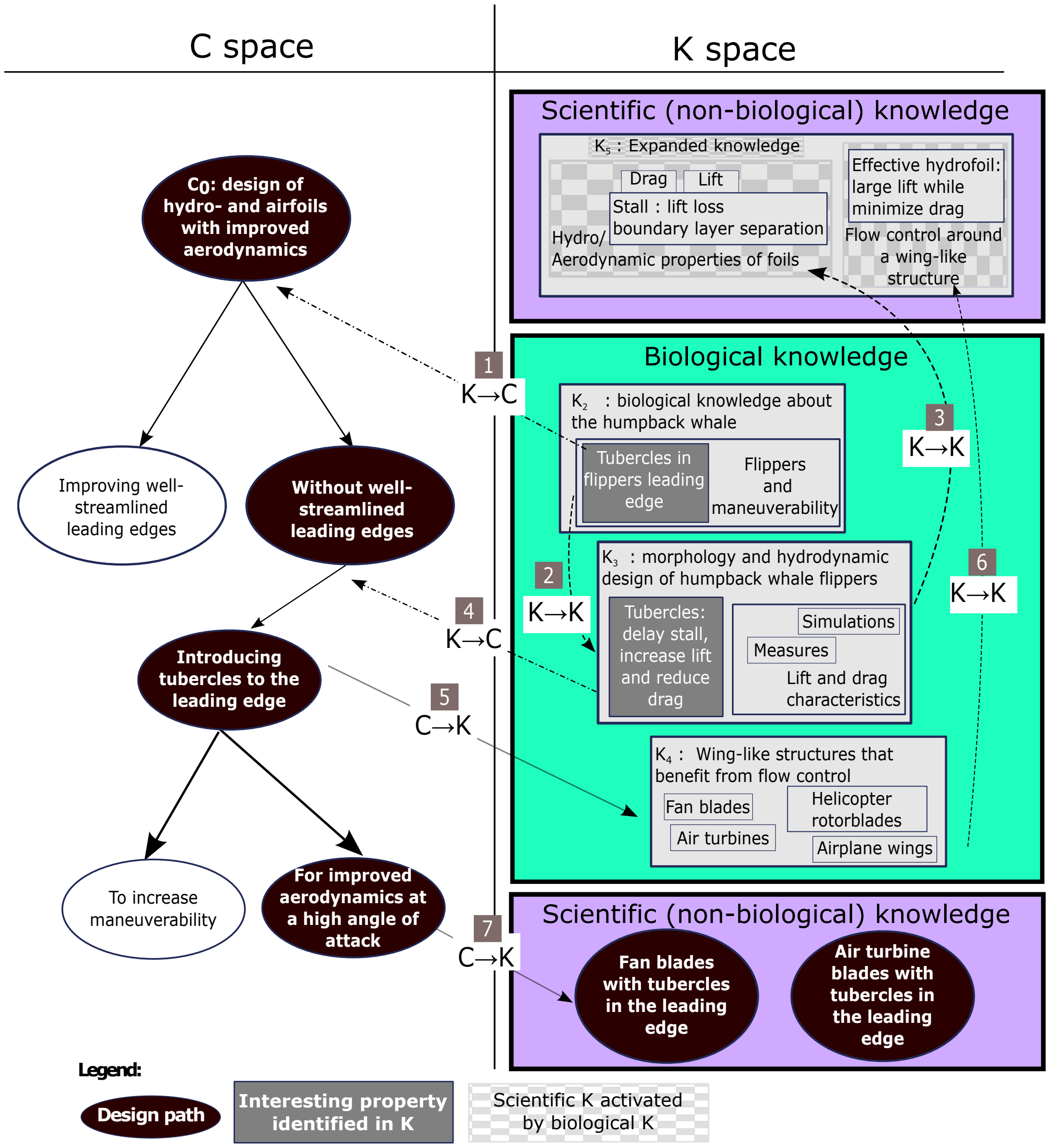


Figure 2.7: C–K modeling for the Whalepower technology example. This figure is adapted from previous schemes for this example presented in Freitas Salgueiredo and Hatchuel (2016).

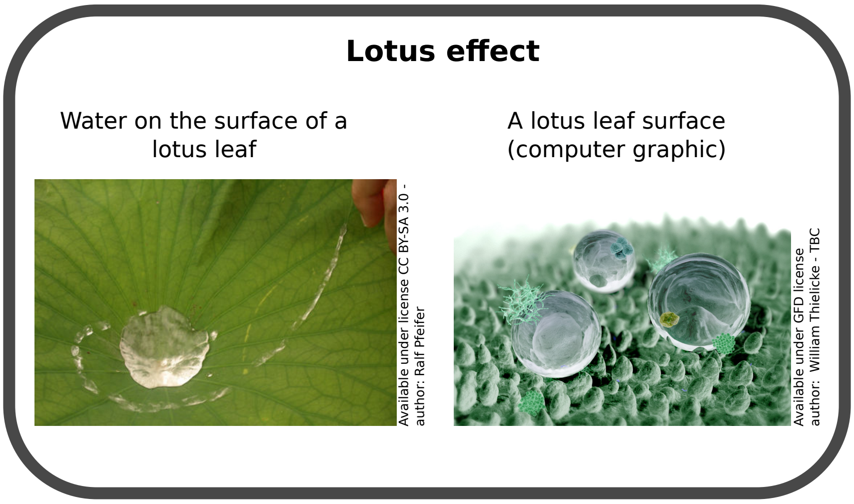


Figure 2.8: The lotus effect: water in the surface of a lotus leaf and its representation in a microscopical scale.

The patents issued by these researchers described the application of the so-called "Lotus-Effect" to artificial surfaces (Barthlott, 1997; Barthlott and Neinhuis, 2000).

Considering this information gathered with the Barthlott and Neinhuis (1997) article and also with the numerous review articles that described this design process afterwards (Bhushan, 2009; Singh et al., 2012), the bases for the modeling of this design process are set: the initial knowledge base activated for this example is biological: the study of the microscopical structure of plants leaves is the first knowledge base, in which an interesting property was identified: there are leaves almost free of contamination with a rough surface. The initial concept can be formulated as: "design of self-cleaning surfaces" and the observation that rough surfaces had this self cleaning properties, partitions this concept into "design of self-cleaning surfaces with rough surfaces", while the other partition, more in the dominant design would be "with smooth surfaces" (step **(1)**, fig. 2.9) .

The further research aiming at better understanding the hydrophobic properties or the leaves and its relationship with surface roughness (step **(2)**, fig. 2.9), and the identification of the Lotus leaves as an interesting example (step **(3)**, fig. 2.9). This better understanding of the reasons for the properties observed required the activation of the knowledge about wettability and the behavior of liquids in rough surfaces, which belong to the scientific (non-biological) knowledge bases (step **(4)**, fig. 2.9). The identification that the combination of microscopic roughness and hydrophobic coating provide self-cleaning partitions the concept "design of self-cleaning surfaces with rough surfaces" into "design of self-cleaning surfaces with rough surfaces with hydrophobic coatings" and "without hydrophobic coatings (step **(5)**, fig. 2.9). The effects of this combination were investigated considering the knowledge activated about surfaces and behavior of liquids applied to surfaces, explaining the observed phenomena (step **(6)**, fig. 2.9).

The patents and commercial developments of coatings using the Lotus-Effect such as Lotusan® (Sto-Corp[16]) constitute the passage from concept to knowledge (step **(7)**, fig. 2.9).

2.3.1.6 Study of the Gecko adhesion properties example

The study of this example using C–K theory is described in Freitas Salgueiredo and Hatchuel (2014). This paragraph presents a summary of this study and its main conclusions. Figure 2.11 shows the framework representing this design process.

As in the Whalepower technology example, the starting point of this example is the observation of an interesting phenomena in biology, related to the outstanding adhesion properties of Geckos, *Gekko gecko*, (Figure 2.10):

> *The ability of gekkonid lizards to climb up vertical glass surfaces and to hang upside-down on ceilings is a problem which has attracted the attention of numerous workers.* (Maderson, 1964)

These adhesion properties were explored by researchers and different hypothesis for these properties observed were made: adhesion by suction, by friction, by electrostatic attraction, by glue, by intermolecular forces (Autumn et al., 2000), which represents a revision and expansion of the scientific knowledge about adhesion properties. Combining microscopical analysis (that revealed that the gecko's foot "has nearly five hundred thousant keratinous hair or setae") and the measurements of a single setal force, Autumn et al. (2000) supported the hypothesis of adhesion using intermolecular forces (van der Waals forces), given the number of setae of the gecko's feet (one billion), that provide a "close contact with the substrate".

These authors also propose that this knowledge could *"provide biological inspiration for future design of a remarkably effective adhesive* (Autumn et al., 2000).

The difference between the gecko adhesion and most of the human-made adhesives (glues, tapes) is that it provide dry adhesion instead of the wet adhesion of glues and tapes human-made (Bhushan, 2009).

[16]Lotusan is a facade paint that guarantees the surface free of contamination, being cleaned with the rain - http://www.sto-sea.com/en/company/innovations/sto-lotusan-/sto-color-lotusan.html - Accessed on 21.03.2016.

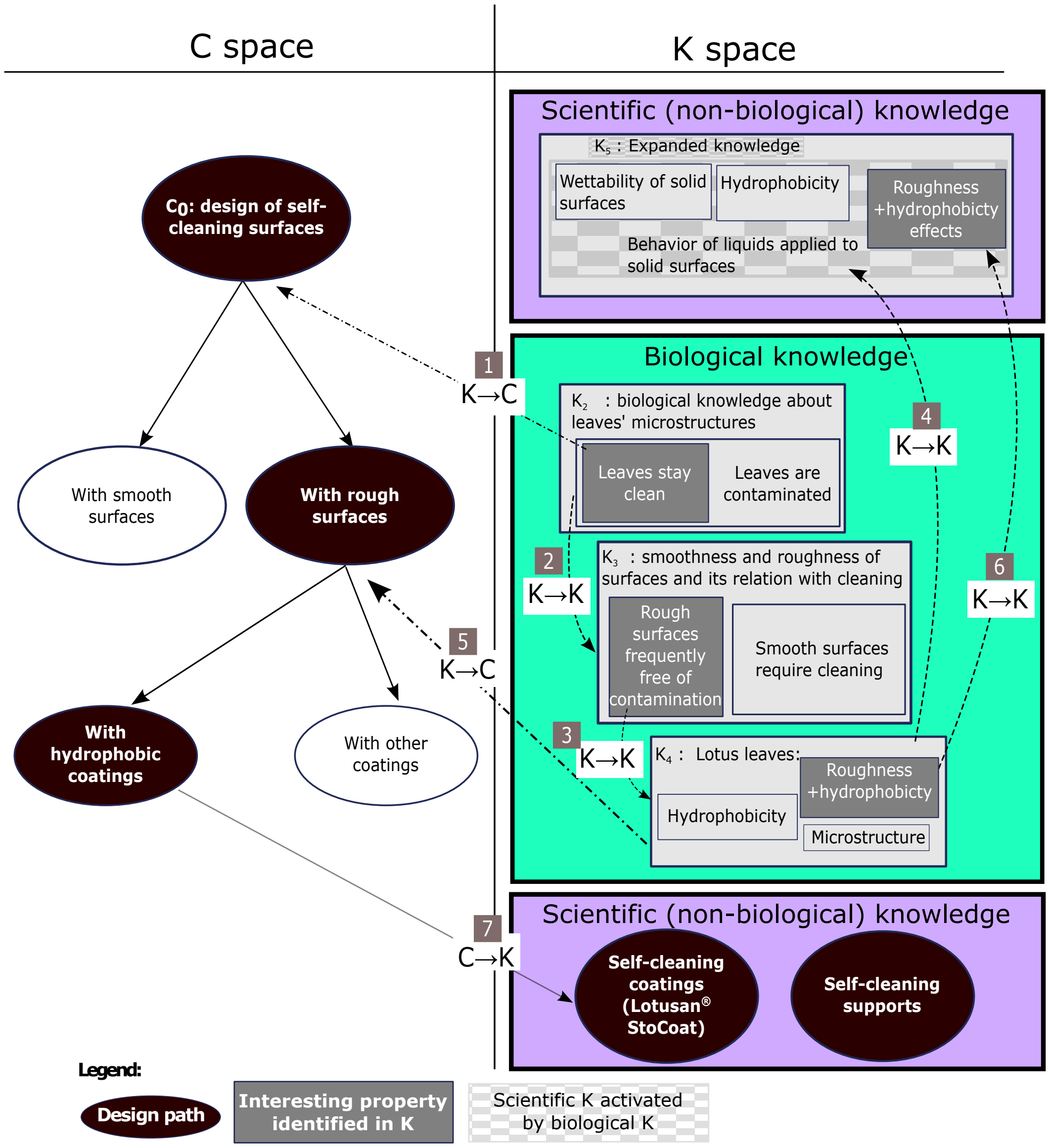


Figure 2.9: C–K modeling for the self-cleaning surfaces with Lotus-effect example. This figure is adapted from the previous scheme for this example presented in Freitas Salgueiredo and Hatchuel (2014).

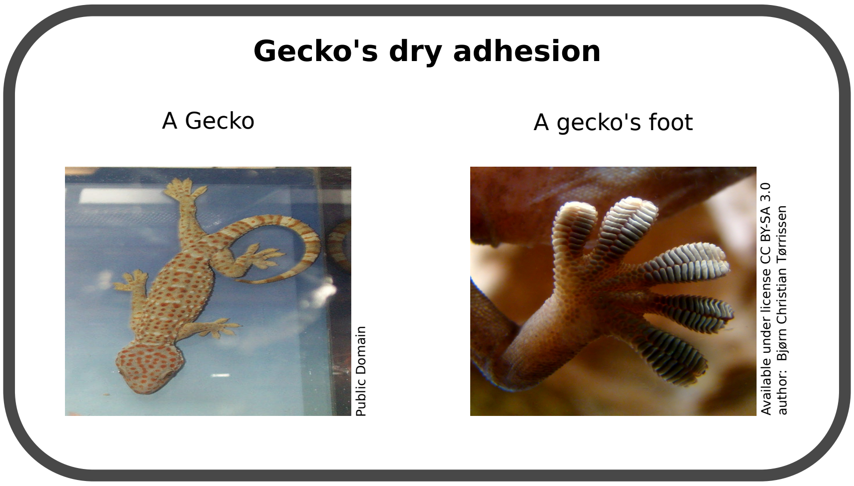


Figure 2.10: A gecko and a zoom of one gecko's foot.

The initial concept can be formulated as: "design of a remarkably effective adhesive" (step **(1)**, fig. 2.11), and the observation that geckos have a surface with a fibrillar structure (the microscopic setae) partitions this concept into "with a fibrillar structure" and "without a fibrillar structure" (step **(2)**, fig. 2.11). The research confirming the van der Waals forces as the main phenomena contributing to adhesion in geckos (step **(3)**, fig. 2.11) allows formulating another partition to the concept "with a fibrillar structure": "using van der Waals forces for adhesion" (step **(4)**, fig. 2.11).

The different studies on the development of human-manufactured surfaces that would use the same dry adhesion phenomena as geckos (van der Walls forces and a fibrillar structure) represent the end of the design process (step **(5)**, fig. 2.11). The first gecko-inspired surfaces used surfaces microfabricated with a replication of the gecko feet microstructure (Geim et al., 2003; Boesel et al., 2010). A more recent study by (Bartlett et al., 2012), using the knowledge about gecko adhesion, developed a scaling theory for adhesives (step **(6)**, fig. 2.11) which allowed creating Geckskin™[17], that is a reversible adhesive structure that does not have fibrillar structures (Bartlett et al., 2012) (step **(7)**, fig. 2.11). This made possible the development of the other possible design path derived of the first concept.

2.3.2 A general model for bio-inspiration using C–K theory

The four examples modeled with the C–K theory operators show some similarities. Firstly, in all examples it is clear that the two knowledge bases, scientific (non-biological) and biological are expanded and revised: the design process activates other knowledge bases belonging to these bases.

[17]More information is available at the website: https://geckskin.umass.edu/, accessed on 27.03.2016.

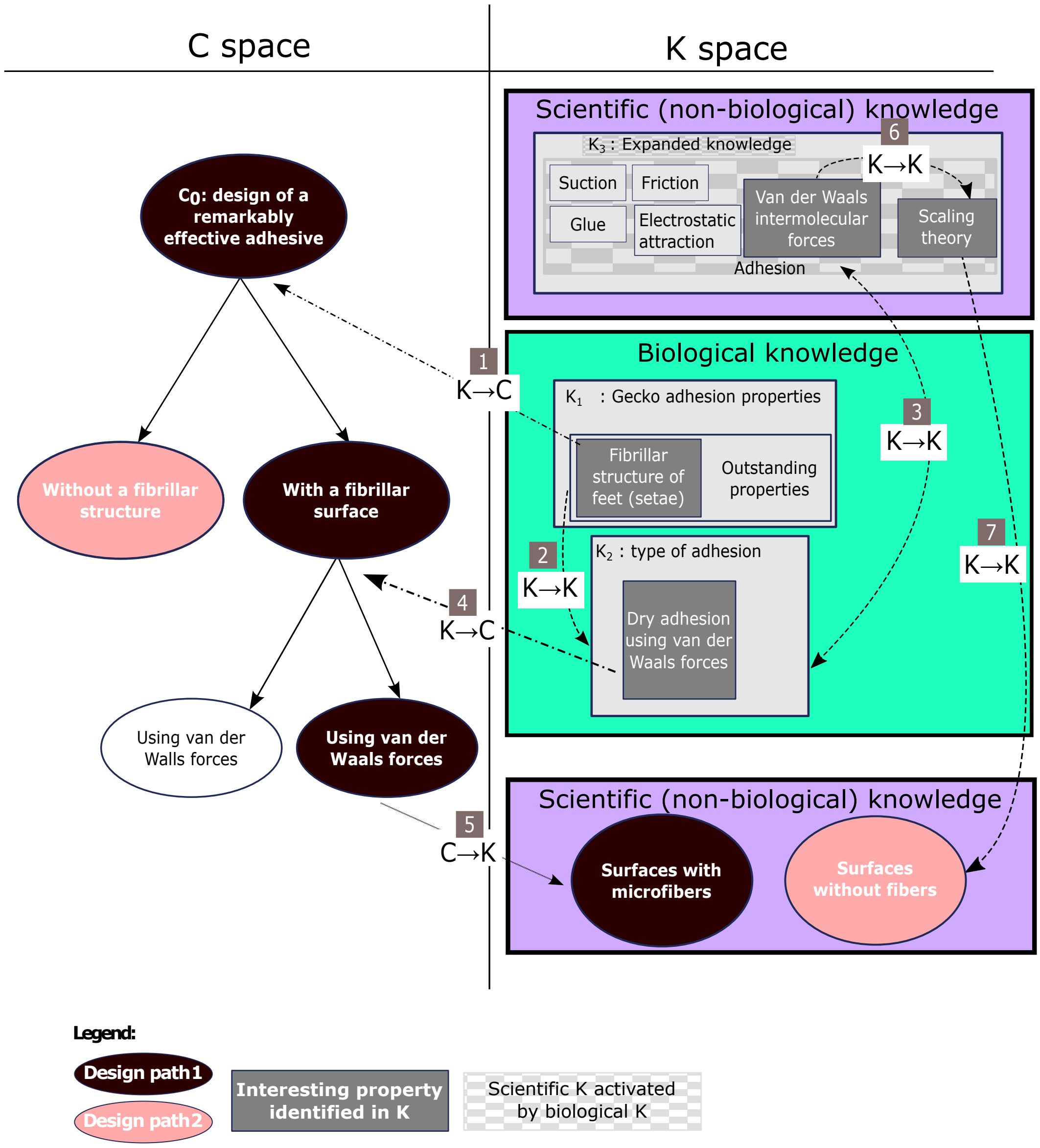


Figure 2.11: C–K modeling for the design of adhesives inspired by Gecko example. This figure is adapted from the previous scheme for this example presented in Freitas Salgueiredo and Hatchuel (2014).

Secondly, the interesting properties observed in biological knowledge, are considered "interesting" because they have a double effect:

- The expansion of the knowledge bases, guided by the interesting property. In the Flectofin® example, the observation of the bird of paradise pollination mechanism activated knowledge on the scientific wnowledge bases about materials deformation and failure.
- They partition concepts, giving them other properties that were not initially sought for. In the Whalepower example, the observation of tubercles allow partitioning the design of airfoils with improved aerodynamics into "without well-streamlined leading edges" and "improving well-streamlined leading edges".

Considering the steps observed in the design process of the four examples described previously, four general steps can be defined for the biologically inspired design, according to the operators and principles of the C–K theory:

1. Identification of design paths for which concept partitioning is required

The design process begins with the identification of design paths that require concept partitioning. This step can become the second step if the design process starts with the observation of an interesting property in biological knowledge, as described in the Lotus, Gecko and Humpback Whale examples.

2. Activation of biological knowledge

The biological knowledge can be activated "naturally" (the researchers are already working in the field and identify an interesting property), or can be activated by the first concept that was defined. In this case, the methods described in literature for retrieving biological phenomena, such as functional decomposition (Nagel et al., 2010; Helfman Cohen et al., 2014), SBF modeling (Wiltgen et al., 2011), the SAPPhIRE model (Sartori et al., 2010) or the natural-language approach (Shu, 2010) can be used for finding biological knowledge bases that could present interesting properties for exploring the initial concept.

3. Expansions in both biological and scientific knowledge bases

With the first concept and interesting properties identified in the biological knowledge, the design process continues with the activation of knowledge bases in both bases: scientific and biological related to the properties investigated. This step also includes the identification of properties allowing

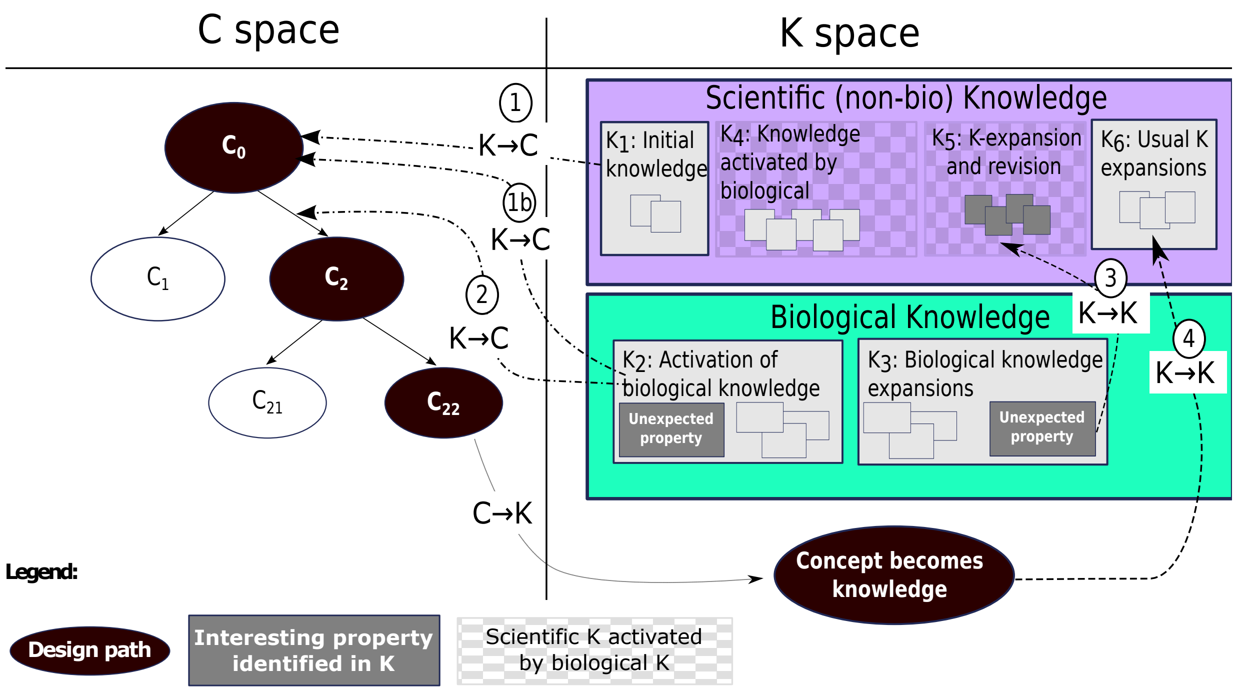


Figure 2.12: C–K general model for biologically inspired design. This figure is adapted from the previous schemes for this model presented in Freitas Salgueiredo and Hatchuel (2014, 2016).

concept partitioning.

4. Return to the scientific knowledge bases

When the design path of the concept space becomes knowledge, it can be developed using traditional knowledge (about materials, techniques, etc.).

These four steps are schematically represented in Figure 2.12.

2.4 Conclusions: Using C-K model as a support for biologically inspired design process for different fields

This chapter presented a state of the art on biologically inspired design. This design process is described and studied in literature using the classical theory of *analogy*: it implies an analogical transfer between biology and engineering. Moreover, the steps of the design process are disentangled according to the steps presented by Pahl and Beitz systematic design process.

The increase of novelty and creativity that is claimed to happen in biologically inspired design and the anomalies of the analogical transfer process that generate interesting concepts are difficult to explain only considering the classical theory of analogical transfer (that considers that anomalies are to be avoided) and the systematic design (that fails to explain the activities outside the "dominant design", which is one of the features of the examples of BID).

In order to understand the role of the anomalies in the BID process and the increase of creativity, the C–K theory was used to analyse case examples retrieved in literature. These case examples had their design process well described and detailed. The steps of the design process were modeled according to the C–K theory spaces and operators. This modeling enable the identification of the role of biological knowledge during the BID process:

- The creation of expanding partitions in the concept space.
  These partitions are related to an increase in creativity as they guide knowledge expansion (the activation of new knowledge bases that would not be spontaneously activated) and revision (the identification of properties of existing knowledge bases that can be interpreted otherwise).
  These expanding concepts can be called *"crazy concepts"* in C–K theory, as they are formed by "partially defining a new object by unexpected attributes" (Hatchuel et al., 2012).

- The expansion of knowledge bases.
  This knowledge expansion is provoked by the expanding partitions created using the interesting properties of biological knowledge. Both knowledge bases expand, as the identification of an interesting property in biology is accompanied by the activation of scientific knowledge bases related to this property and an expansion of biological knowledge, with the identification of an emblematic example using this property, or a deeper understanding of the effects of the property to the organism.
  Crazy concepts also have this role of "forcing" the designer to explore new sources of knowledge, which is exactly the role of the partitions formed using interesting properties of biological knowledge (Hatchuel et al., 2012).

This aspect was not easily visualized with the analogical transfer interpretation of the BID process, as it does not show how the analogous properties found in biological systems interact with the existing knowledge and if this interaction stimulates the search of new knowledge bases or if it leads to remaining in the same knowledge bases. The interpretation of BID as an analogical transfer process does not show this interaction of the properties in the biological system and the existing scientific knowledge or how these properties of biological systems guide the exploration of existing knowledge or allows activating other knowledge bases.

The organization of the BID process in practice can also benefit from this interpretation using C–K theory. The required expansions in biological knowledge bases indicate that engineers that wish to apply BID need a close collaboration with biologists that study organisms or phenomena belonging to these biological knowledge bases. This "close collaboration" differs from a simple knowledge sharing as the engineers must relate the biological knowledge to their own knowledge bases and the biologists also need to revise their knowledge to better understand the interpretations made by engineers, and maybe use the methods used by engineers to better understand the phenomena observed in biology. This process is "mutually inspirational", as both knowledge bases expand with interesting properties found in both bases.

Therefore, the C–K framework for BID represents the design process, with the design paths and knowledge bases activated and can be a valuable representation tool for designers to organize their exploration of the knowledge bases and the concepts explored. One of the limitations to this modelling is that process of identification of suitable knowledge bases in biology related to a concept formulated using scientific knowledge is not described. The methods such as functional decomposition (Nagel et al., 2014; Helfman Cohen et al., 2014), can be used to expand and revise both biological knowledge bases and the natural language approach (Shu, 2010) can help identifying the biological bases that could be explored during the design process. Another limitation of the analysis presented in this chapter is related to the number of case-examples analysed: only four examples were fully analysed using the C–K modeling, and these examples refer mainly to materials properties that were used in the bio-inspired final design. Nevertheless, the steps identified with this model are general and they can be applied to different problems involving biological inspiration.

This framework is used to guide the exploration of the research problem of this thesis, which is not related to material science or forms. This process will be fully described in Chapter 3.

Table 2.3: Examples of biologically inspired design obtained from literature research. The main aspects of the design process and the references are indicated.

Example title	*Technical issue*	*Interesting biological property*	*Reasons for seeking inspiration in nature*	*Top-down / bottom-up process*	*Domain*	*Main References*
Whalepower ®	Improving aerodynamic properties of hydro/airfoils	Humpback whale flippers tubercles and their relation with maneuverability	Tubercles are unique structures in nature.	Bottom-up	Aerodynamics	Fish and Battle (1995) Bhushan (2009) Fish et al. (2011)
Pine-Cone Textiles	Regulation of tissue permeability	Shape change of pine-cone due to changes in humidity conditions	Research about developing tissues that change properties according to hygroscopic conditions	Bottom-up	Materials	Dawson et al. (1997) Singh et al. (2012)
Gecko adhesion properties	Dry adhesion	Origin of gecko dry adhesion properties	Geckos can adhere to different surfaces, with very good performances	Bottom-up	Materials	Autumn et al. (2000) Autumn (2006) Bhushan (2009)
Hydrophobic and self-cleaning materials Lotusan®	Self-cleaning materials	Lotus leaves are almost free of contamination	Render surfaces self-cleaning	Bottom-up	Materials	Barthlott and Neinhuis (1997) Barthlott (1997)Bhushan (2009)
Velcro	Attachment and detachment properties	Cockleburs get attached to clothes or fur and can be ungripped with a light force	Fasteners providing attachment and easy detachment	Bottom-up	Materials	Hesselberg (2007) Bhushan (2009)
Flectofin®	Simplifying technical actuators in architecture (shading mechanisms)	Bird of paradise flower pollination mechanism	Existing shading mechanisms use hinges and rollers that require maintenance. Plants show "hinge-free" movements	Top-down	Architecture Mechanics	Lienhard et al. (2011) Knippers and Speck (2012)
BIOLOCH BIOmimetic structures for LOComotion in the Human body : biomimetic endoscope and multifunctional robot	Develop more powerful and less discomforting devices for endoscopy	Locomotion in ragworms : they can move in slippery substrates and diversity of movements (gaits, body undulations)	The mucous layer of the human intestine is similar to the mud in which one species of ragworm is found.	Top-down (but also investigation of other properties, in a bottom-up approach)	Robotics Biomedical	Hesselberg (2007)
Soft robotic arms inspired by the octopus	Development of advanced soft-bodied artifacts	Octopus have unique "motor skills"	Outstanding properties of octopuses, whose body lacks hard elements although presenting the ability to vary and control their stiffness.	Top-down (although requiring a deep understanding of the biomechanical properties of octopuses)	Soft-Robotics	(Margheri et al., 2012) (Mazzolai et al., 2012) (Rus and Tolley, 2015) (review of different bio-inspired soft-robotics developments)
Eastgate Centre (Zimbabwe)	Build buildings that have a more efficient natural ventilation (adapted to tropical conditions)	The mound of mound-building termites is a "climate-control infrastructure for the termite colony's subterranean nest".	The human-designed solutions for thermal control, including the use of air–condition is not adapted to the conditions of tropical regions.	Top-down	Architecture	Scott Turner and Soar (2008)

Chapter 3

Application of the C–K framework for generating bio-inspired concepts for the low carbon vehicle innovation field

HIGHLIGHTS

- The C–K diagram for the **low carbon vehicle innovation field**
- The **first biological bases explored** in the research of bio-inspired concepts
- The **choice** of a specific biological knowledge base: **“human physiology”**
- The **bio-inspired concepts** generated

Chapter contents

This chapter deals with the application of the bio-inspiration process described on the previous chapter to the low carbon vehicle innovation field. The different steps of this process applied to this specific innovation field are detailed, starting with structuring the knowledge and concepts linked to the low carbon vehicle innovation field. The result of this step is the identification of a design path for applying bio-inspiration: the energy use during the use phase of passenger cars, more specifically focusing on the engine and energy recovery and reuse.

After defining this specific design path, general biological knowledge about energy in nature is activated and leads to a focus on a more specific knowledge base, human physiology. The dialog between these two knowledge bases, automotive engineering and human physiology allowed formulating four bio-inspired concepts. All these concepts have the potential to reduce CO_2 emissions produced by cars during their use phase. One of these concepts suggests that speed variations could be a strategy for reducing fuel consumption and is explored in more detail in the next chapter.

3.1 Introduction

Chapter 2 showed that biologically inspired design proceeds by interactions between the scientific knowledge basis, the scientific (non-biological) knowledge and the biological knowledge bases.

The research problem treated in this thesis is understanding whether a biologically inspired design approach can stimulate innovation in the automotive industry[1]. The specific innovation field of this industry chosen for applying this approach was the reduction of CO_2 emissions from passenger cars, also called the *low carbon vehicle* innovation field[2].

According to the C–K model for bio-inspiration described in Chapter 2, the application of the biologically inspired design to an innovation field firstly requires a mapping of the scientific knowledge basis, and the concepts that can be built only based on the knowledge available to engineers working in this innovation field. This builds the traditional C–K space for a given innovation field. No new biological knowledge bases is activated at this stage.

In this research, this first step, which involves the mapping of scientific knowledge and the concepts for the low carbon vehicle innovation field, preceded the work developed by its author. It was realized during an internship made at the same company as this thesis (Renault) by two engineering internship

[1] See Section 1.2.
[2] See Section 1.3.

students[3]. These students designed a C-space for the low carbon vehicle innovation field, based on the inputs from Renault experts (Amsterdamer and Molin, 2011). These inputs were obtained during workshops and interviews with these experts. The knowledge and experience of these company experts was the basis of this C-space and did not constitute an organized knowledge base associated to the concepts (as is expected in the C–K theory). The C-space they designed defined the low carbon vehicle using two main sub-concepts:

- "A low carbon vehicle by acting on the vehicle" which included all the concepts linked to modifications made on the vehicle (engine, shape, materials) aiming at reducing CO_2 emissions. This path represents the traditional design path followed by engineers of an automotive company, and is represented at the left-side of the C-space.

- "A low carbon vehicle without acting on the vehicle" which included all the concepts that did not include mechanical or vehicle components modifications, such as changing driver behavior or vehicle environment (such as the road infrastructure, climate conditions, etc.). This path, although being part of recent research of the automotive engineering, is considered more disruptive than the vehicle modifications, as they involve considering other actors than the vehicle for the reduction of fuel consumption.

This initial C-space, represented in Figure 3.1, the starting point to examine the low carbon vehicle innovation field and to begin the construction of a knowledge base, representing mainly the different strategies that were already considered for reducing the CO_2 emissions produced by passenger cars. The next sections detail the process of building this knowledge base and the effect this process had on the concepts-space initially proposed by Amsterdamer and Molin (2011).

This upgraded C–K framework of the low carbon vehicle innovation field allows the identification of the design paths for which bio-inspiration should be applied. Bio-inspiration is applicable to any of these design paths belonging to the C-space, but in order to better explore the possibilities for bio-inspiration a specific design path is chosen. This option is coherent with the first step identified in the C–K model for bio-inspiration: "identification of design paths for which concept partitioning is required". In this chapter the application of the bio-inspired approach to the low carbon vehicle innovation field is described, including the first step of construction of the C–K framework for the

[3] The two students were Yohan Amsterdamer and Hugo Molin from Mines ParisTech (2011). Their internship subject was entitled: "the experts-leaders confronted to radical innovation: methods for building and managing the expertise" (original title in French: "Les experts-leaders face à l'innovation radicale: méthodes de construction et de gestion de l'expertise").

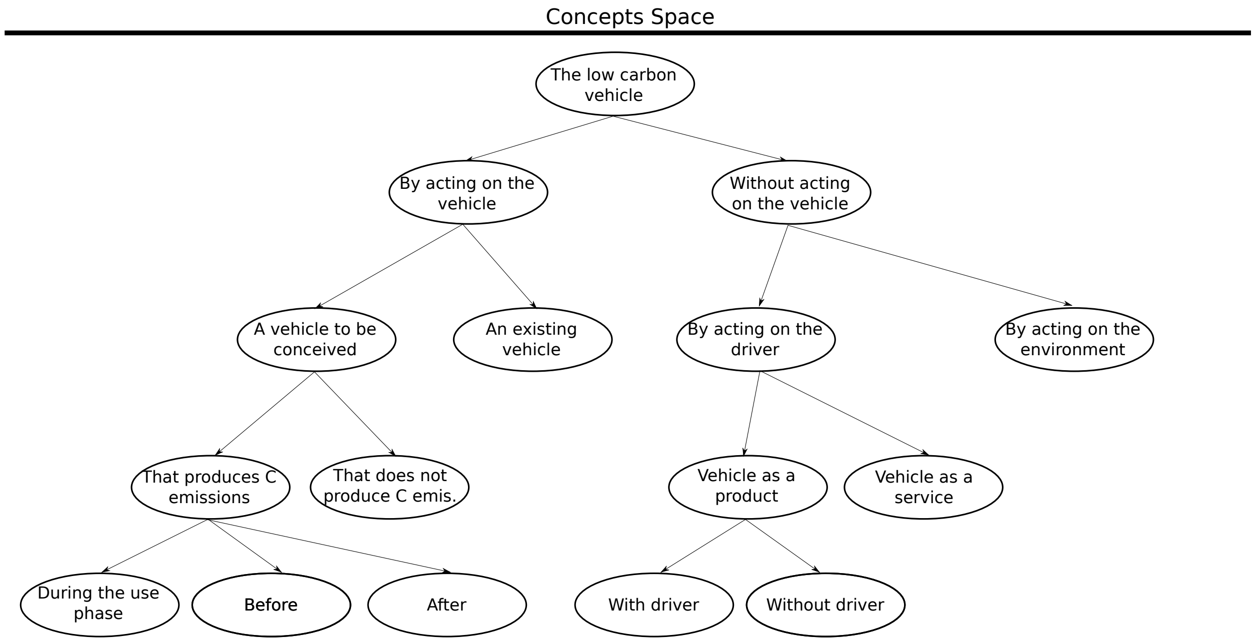


Figure 3.1: The initial C space for the low carbon vehicle, proposed by (Amsterdamer and Molin, 2011). The contents of the original figure were translated from French to English by the author.

low carbon vehicle innovation field (Sections 3.2 and 3.3) and the identification of a design path in this C-space for which bio-inspiration could generate interesting concept partitioning. The next two steps of the C–K model for bio-inspiration follow: the dialog between biological and traditional knowledge bases and the indication of concept partitioning possibilities (Section 3.4).

3.2 The construction of the knowledge base for the low carbon vehicle innovation field

The first concepts of the C-space of Figure 3.1 highlight that the reduction of the CO_2 emissions coming from passenger cars are the outcome of modifications in the vehicle. Moreover, these concepts also show that drivers and vehicle environment contribute to the reduction of emissions produced. In order to structure this knowledge about the different strategies allowing emissions reduction, it was important to review how these emissions are produced and their importance to the automotive sector. This revision helps structuring the knowledge about these strategies and thus complete the initial analysis made by Amsterdamer and Molin (2011), which was essentially based on the company experts knowledge.

The Oxford US English dictionary defines an automobile as: “A road vehicle, typically with four wheels, powered by an internal combustion engine or electric motor and able to carry a small number of people”[4]. The word automobile is synonymous with car or vehicle, vehicle being the more general term to design mobile machines used for transportation such as motorcycles, buses, trucks, etc. An analysis of this very simple definition of automobile shows that it encompasses at least *five* notions:

1. the **“movement enabler”** (the four wheels);
2. the **infrastructure** in which the vehicle realizes the transport (the road);
3. the **type of propulsion device** used by the vehicle (an internal combustion engine or an electric motor);
4. the **type of transport** (individual: carry a small number of people);
5. the **function** of the car (carry people[5]).

The propulsion device is the feature that differentiates automobiles from its predecessors such as carriages, which are also four-wheel road passenger vehicles, powered by horses (Oxford US English dictionary). The first automobiles had steam engines (Cugnot - *fardier* - 1769[6]), years later, electric motors started to be used in carriages (Anderson / Stratingh and Becker - Electric carriages - 1830), which opened the way for the electric cars (the city of New York had electric cars as taxis in the late 1890s (Kirsch, 1997)). Internal combustion engines appeared only in 1876 (Otto - first spark-ignition engine - 1876, Diesel - first compression-ignition engine - 1892) and the first cars with these engines started to be manufactured in 1885 (Karl Benz - first gasoline-fuelled motor car - 1885) (Heywood, 1988; Mitchell, 2010).

Internal combustion engines, in which the combustion of the mixture air-fuel takes place inside the engine, were the last to be developed but became the dominant automobile motorization during the last century. Different fuels can be used in these engines, the most common being gasoline[7] and

[4]From Oxford US English dictionary, available on-line: http://www.oxforddictionaries.com/definition/american_english/automobile, Access on 07.11.2014

[5]It is important here to clarify that in English the verb carry is defined as: “Support and move someone or something from one place to another”

[6]Conceived in 1769 by Joseph de Cugnot, the *fardier de Cugnot* is considered as one of the first self-propelled mechanical vehicles. It used a steam piston to produce motion (Ickx, 1971; Bellu, 1998)

[7]Gasoline is the word used in North American English. British English uses the term *petrol* for naming the “light fuel oil that is obtained by distilling petroleum and used in internal combustion engines” (Oxford British and World English Dictionnary, available on-line: http://www.oxforddictionaries.com/definition/english/petrol, accessed on 19.06.2016).

diesel. The almost complete disappearance of the other powertrains, such as the electric motors, from the automotive sector occurred in part because of limitations identified in those alternative systems: electric vehicles had their energy stored in batteries, with had limited capacity and required larger amounts of time to recharge. The capacity limitation of batteries diminished the range of the electric vehicles. The refueling infrastructure was also easier to develop for petroleum-based liquid fuels than for electricity distribution, as liquid fuels were easier to be transported to rural areas, which in the beginning of the century did not have a fully developed electricity network (Kirsch, 1997; Mitchell, 2010). It is worth noting that the use of electric motors in the transportation sector did not disappear from other sectors, such as rail transport. These sectors had dedicated lines, directly linked to the electricity grid and not relying on batteries to store energy.

One of the major drawbacks of the internal combustion engines are the tailpipe emissions produced during the combustion process and diffused into the atmosphere by the vehicle exhaust system, represented in Figure 3.2. These emissions have effects upon air quality and on the environment (Mayer, 1999; Colvile et al., 2001): stratospheric ozone depletion, tropospheric ozone production, smog and climate change. Their origin is linked to the fuels used in the internal combustion engine, normally organic compounds such as hydrocarbons[8] obtained from petroleum, and their combustion in the engine. Indeed, in the ideal combustion of hydrocarbons, the reaction of a hydrocarbon with oxygen should only produce carbon dioxide (CO_2) and water vapour (H_2O) as products. The operating conditions of the internal combustion engines, such as combustion with air and not with pure oxygen and other components present in liquid or gaseous fuels, provoke the production of by-products such as carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM) or unburnt hydrocarbons (HC). The vehicle exhaust system releases these pollutants in the atmosphere. The accumulation and diffusion of these molecules in the atmosphere can be harmful to human health (Colvile et al., 2001; Brook et al., 2003).

To reduce these environmental impacts, aggravated by rise on the number of automobiles circulating in most cities, regulations were put in place all around the world. In Europe, for example, the first directive establishing measures against air pollutants emissions from road vehicles was issued in 1970 (directive 70/220/EEC), evolving in 1993 to the so-called Euro standards (Euro 1 (1993), Euro 2 (1996), Euro 3 (2000), Euro 4 (2005), Euro 5 (2009) and Euro 6 (2014)). These standards determine whether a vehicle can or cannot be sold in Europe, as a function of the compliance to the tailpipe emissions limits for the following air pollutants: NO_x, total hydrocarbons (THC), non-methane hy-

[8] A hydrocarbon is an organic compound consisting of the association of only carbon and hydrogen atoms

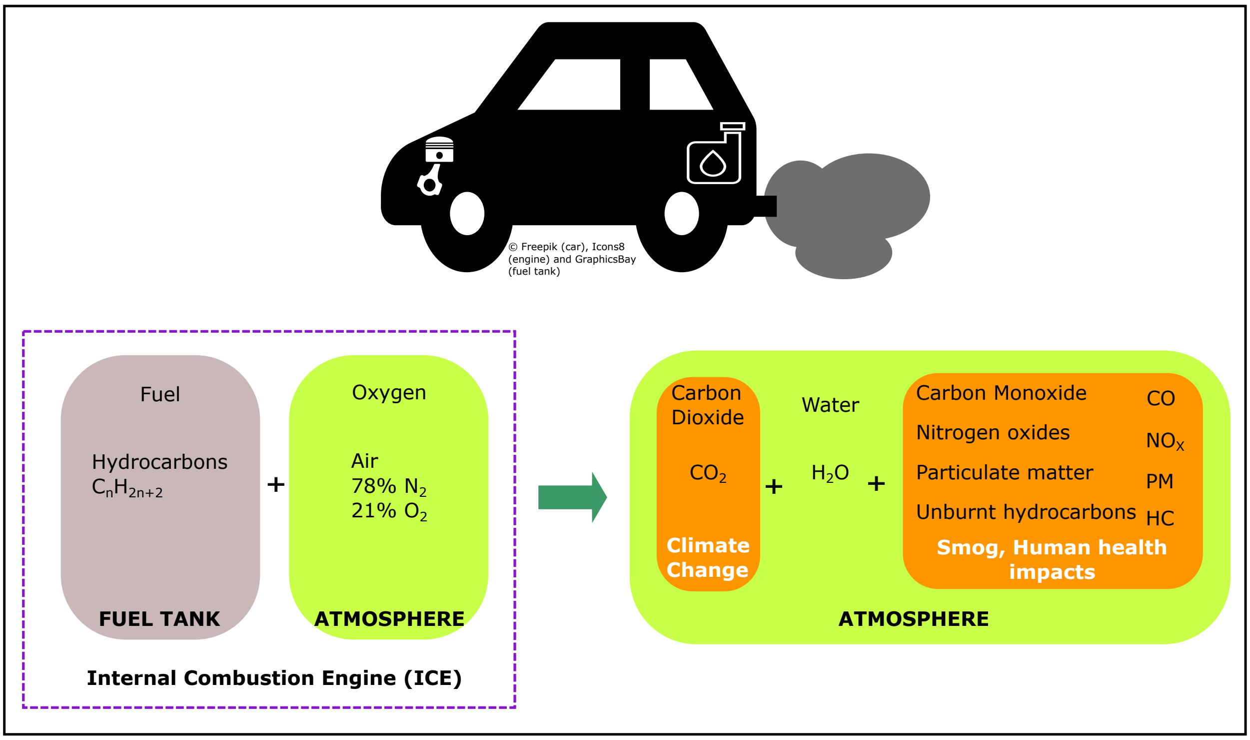


Figure 3.2: The main emissions produced by internal combustion engine during their use.

drocarbon (NMHC), CO and PM. In the United States, the U.S. Clean Air Act was issued in 1970 with the aim of controlling air pollutants emissions from cars. These directives and regulations have stimulated the development of technologies allowing lower air pollutant emissions such as: catalytic converters, three way catalysts, electronic engine control for gasoline vehicles (using spark-ignition engines) and improvements in engine design and fuel injection systems the particle filter for diesel vehicles (using compressed-ignition engines) (Faiz et al., 1996; Gerard and Lave, 2005).

Carbon dioxide, CO_2, is also one of the tailpipe emissions products of a vehicle with an internal combustion engine as previously mentioned. It is a greenhouse gas that contributes to the climate change and to the global warming phenomena (IPCC, 2014). Given the expected raise in the world's automobile fleet, taking place mainly in emerging countries (IEA, 2012b), sticking with the use of fossil fuels in vehicles does not represent a sustainable path for automobile growth. Firstly because petroleum is a finite natural resource, not equally distributed around the world. The two energy crisis of 1973 and 1979 showed the fragility of a petroleum-based economy whose prices are controlled by the countries with the largest reserves. Secondly, the possibility of reaching a Peak Oil, i.e., the limit of maximum oil production in the world, which will be followed by a decline in production, supported by some quite recent studies (Sorrell et al., 2010; Murray and King, 2012)[9] has risen concerns about

[9]The concept of Peak Oil was first introduced in 1956 by King Hubbert, a geologist who indicated that oil production in the US would reach a peak and then decline afterwards. Indeed, this peak occurred in the US production around the

the capacity of the existing reserves of petroleum to cope with the expected world economic growth in the years to come. Reducing the transportation sector dependency on petroleum, opens the way for alternative energies for automobiles, using no or less petroleum, and also allows countries to have a more diversified energy matrix, which has an important strategical value.

Voluntary commitments from the car industry and regulations were established in order to fix objectives and targets for CO_2 emissions reduction of new vehicles. In Europe, the regulation EC No 443/2009, establishes emissions standards for new vehicles produced in Europe, fixing the following limits for the CO_2 emissions: 130 gCO_2/km in 2015 and 95 gCO_2/km in 2020. These emissions refer to the emissions in-use, evaluated using normalized driving cycles, such as the New European Driving Cycle (NEDC).

1970s (Holland, 2008; Priest, 2014). The concept was later extended to the world oil production, indicating a future shortage on oil supply.

Box 3.1: TEST CYCLES

Vehicle exhaust emissions can be measured using a chassis dynamometer (which simulates road load), an exhaust dilution system, a gaseous emissions measurement equipment and a particulate mass and particulate number emissions equipment, as described in regulation UN/ECE No 83. The emissions (in g/km) are measured using a test cycle, which can have different speed profiles (i.e. the form of speed vs. time profile). In Europe, the standard cycle used for vehicle emissions certification is called the New European Driving Cycle (NEDC). This cycle is composed of an *urban cycle*, with speeds not superior to 60 km/h and with idle phases, and an *extra-urban cycle*, without idle phases, and speeds reaching 90-120 km/h. The gear shifting pattern during these phases is determined in the regulation (UN/ECE No. 83). The equivalent distance made in one NEDC test is 11 kilometers, during 1181 seconds.

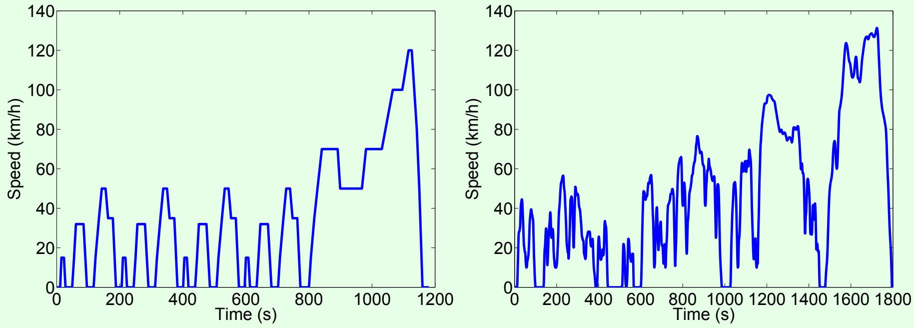


Figure 3.3: Two test cycles: the NEDC cycle (left) and the WLTC cycle (right).

Other countries have established other cycles for measuring emissions. Besides, in the European case, the gaps between the fuel consumption measured using the NEDC test and the real-world fuel consumption are becoming increasingly significant (30% of discrepancy in 2013 according to the ICCT (Mock et al., 2014)). These differences come from the driving style (constant accelerations), and the test conditions (no air conditioning, tires pressure, etc). These differences motivated the development of a harmonized test cycle, called WLTC, which is expected to be officially adopted in Europe in the upcoming years. NEDC test cycle is also the test used for measuring the tailpipe emissions of other pollutants such as NO_x, THC, NMHC, CO and PM, for compliance with the Euro standards. For hybrid electric and electric vehicles the NEDC cycle is used but with some adaptations: it is important to analyze the range in full electric mode and the same state of charge before and after the test. These test conditions are also defined in regulation (UN/ECE No.83).

These CO_2 emissions targets are established by computing the average emissions of the sales of new vehicles by manufacturer, known as the Corporate Average Fuel Economy (CAFE)[10]. Manufacturers not respecting these limits can face penalties established in the country or community-level regulation. The reduction trend on the CAFE values in the last years (Figure 3.4) was mainly obtained with the adoption of vehicle technologies such as the *engine downsizing* or the *stop and start*. The trend of increased powertrain electrification also contributes to the emissions reduction. It is now important to better characterize the different alternatives that can lead to the *low carbon vehicle*. In this thesis we consider a general perspective for defining low carbon vehicles:

> **Low carbon vehicles** are vehicles with as lower CO_2 emissions as possible when compared to conventional internal combustion engine vehicle (ICEV) emissions.

This general definition is coherent with those proposed by the French government in 2008: "[...] the low carbon vehicles, i.e. the vehicles with the lowest CO_2 emissions rates as possible, from fully electric vehicles to plug-in vehicles"[11],while it also includes other solutions than vehicle electrification. Harrison and Shepherd (2014) cite as examples of low carbon vehicles: small ultra-efficient ICEVs, and alternative fuels and powertrains. In the European legislation, cars emitting less than 50 gCO_2/km will receive emissions credits until 2016 and new credits have been set for 2020-2023 for accomplishing the objective of 95 gCO_2/km (Regulation (EU) No 333/2014). These credits are included in the calculation of a vehicle manufacturer mean emissions (the CAFE).

3.2.1 CO_2 emissions are not only produced during the use phase

The previous section described how the regulations in place take into account the emissions produced during passenger cars use phase for establishing CO_2 and other pollutants emissions limits. Electrification is one way of reducing these in-use emissions: when electricity powers the vehicle, there are not exhaust emissions produced. However, emissions occur in other life cycle phases of the vehicle: the materials used in the vehicle required energy for their extraction, transportation to transformation

[10]The term CAFE was first used in the 1975 US regulations aiming at improving cars and trucks fuel economy - http://www.nhtsa.gov/fuel-economy/, Access on 02.12.2014

[11]This definition is taken from the discourse of the French president, Nicolas Sarkozy, in the occasion of the launch of the French governmental plan to stimulate the low carbon vehicles development - "la France va s'engager dès maintenant dans un vaste plan de recherche et de soutien aux véhicules décarbonés, c'est-à-dire des véhicules ayant les plus faibles niveaux d'émission de CO_2 possible, qu'il s'agisse de véhicules entièrement électriques ou de véhicules électriques rechargeables (Nègre, 2011)

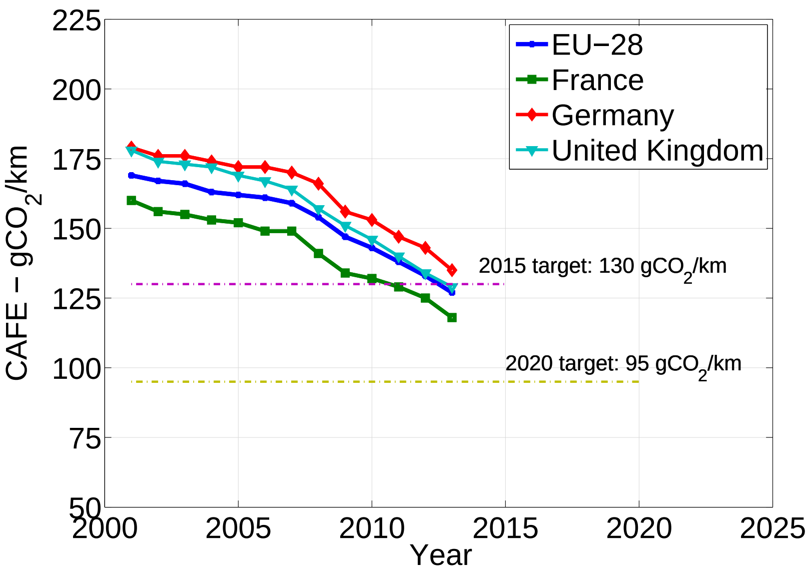


Figure 3.4: Evolution of the CO_2 emissions from passenger cars in Europe, elaborated using data from the ICCT (ICCT, 2014).

units and fabrication of the parts that constitute the vehicle; In vehicle's end-of-life, energy is used for the recycling and disposal processes.

Depending on the local electricity mix, there are lower or higher environmental impacts (including greenhouse gases emissions) associated with all the energy used during the whole vehicle life cycle. In order to characterize the strategies allowing a reduction on passenger cars emissions, an understanding of the implications of the other vehicle life cycle phases in the analysis of the whole greenhouse gases emissions[12] produced by a passenger car is essential.

A life cycle assessment (LCA) is a technique that enables the estimation of the greenhouse gases emissions and other environmental impacts during the all the phases of the life cycle of a vehicle, from the extraction of the raw materials, passing by the use phase, until the vehicle end-of-life[13]. The CO_2 and other greenhouse gases emissions associated with the different steps of the vehicle life cycle are evaluated by an impact called global warming potential (GWP) [14]. The four steps for carrying out a LCA, according to ISO 14040 standards are:

[12]For passenger cars, one of the greenhouse gas produced on the highest amount is CO_2.

[13]The ISO standard 14040 defines an LCA as : a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO standard, 2006)

[14]Global Warming Potential is an indicator that quantifies the non-natural increase of greenhouse gases in the atmosphere, and its unit is kgCO_2eq (kgCO_2equivalent). This indicator was first introduced in 1990 by Shine and Wuebbles, and is currently used in most LCAs to evaluate the impacts associated with climate change (Renault, 2011; Krinke et al., 2005)

i the definition of the goal and scope.

ii the analysis of the inventory. The inventory quantifies each input and output flows.

iii the assessment of impacts. Impacts are evaluated as a function of the flows quantified in the inventory analysis.

iv the interpretation of the results.

Flows calculations in a LCA are made with reference to a *functional unit*. For example, the functional unit of a LCA for the Renault Fluence car (Renault, 2011) was defined as:

Transportation of people in a passenger car vehicle for short trips, for a lifetime of 150 000 kilometers, during 10 years, respecting NEDC driving cycle

Once the scope of the LCA and the functional unit are defined environmental impacts can be evaluated. Figure 3.5 schematically depicts the phases of a car life cycle. It is important to observe that the so-called well-to-wheel (WTW) analysis (JRC, 2014) are a part of the full life cycle assessment of passenger cars. These WTW analysis evaluate greenhouse gases emissions and energy use during the well-to-tank (WTT) and in the tank-to-wheel (TTW) phase, i.e. in the production, transformation and distribution of the energy used in cars (gasoline, diesel, natural gas, biofuels, electricity, etc.) and use of the car (powertrain efficiency and tailpipe greenhouse gases emissions), respectively.

Results for internal combustion engine vehicles using conventional fuels derived from fossil fuels confirm that the use phase is the major contributor to the total GWP impact of a conventional passenger car (Leduc et al., 2010; Renault, 2011; Hawkins et al., 2012). Figure 3.6 illustrate three results obtained from published LCAs. In the first study, Leduc et al. (2010), quantify GWP for average European cars (using gasoline or diesel as fuels). In the second study, the GWP was quantified for the conventional Renault Fluence vehicle (gasoline and diesel), for the full electric Renault Fluence (Renault, 2011). In the third study, CO_2 emissions were quantified for conventional Golf vehicle (gasoline and diesel) and the full electric Volkswagen e-Golf (Volkswagen, 2014). The variations in the contribution of each phase of the vehicle life cycle that can be observed in Figure 3.6 are due to differences in the assumptions adopted by these LCAs (functional unit, steps definition and inventory). For pure electric vehicles, the use phase has considerably lower emissions as the conversion of electricity into mechanical power in the electric motor does not produce tailpipe CO_2 emissions.

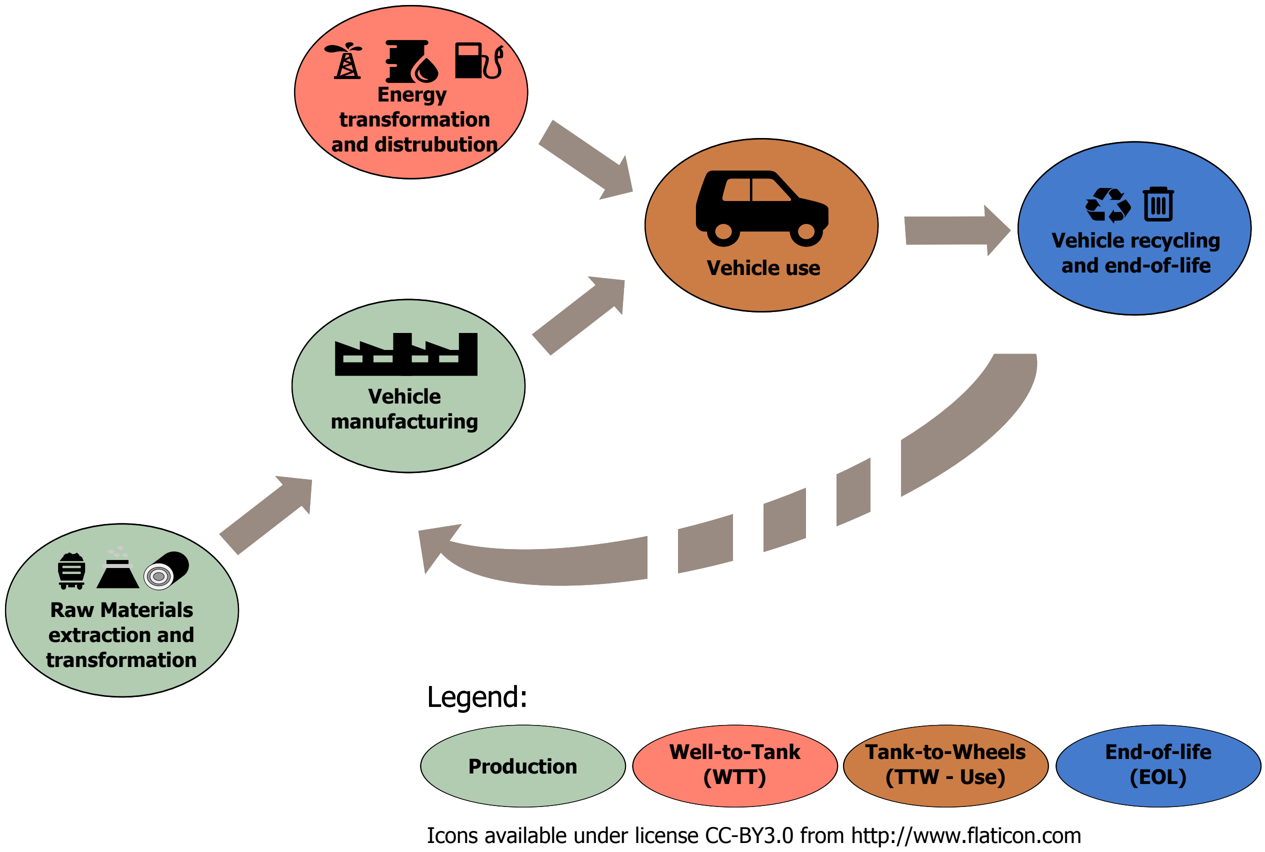


Figure 3.5: The different steps of a car life cycle

However, the emissions in the production phase (of the vehicle and of the electricity) may be responsible for a significant GWP impact, depending on the energy used for producing electricity and on the materials used for vehicle parts such as batteries (Ma et al., 2012; Hawkins et al., 2012). In an extensive comparison of 51 existing studies environmental, energy and material assessments of electric vehicles, Hawkins et al. (2012) indicated that there is a trend on increasing the GWP of vehicle production phase as the electrification level of the vehicle increases (from ICEV until EV), mainly due to battery production, although these authors alert for aspects still to be better accessed in literature studies such as battery "down-cycling, reuse and recycling".

In ICEVs, the emissions reduction during the use phase can allow a significant reduction of the vehicle's life cycle total GWP, while for electric vehicles, it is the energy production phase WTT which can have a higher GWP impact. As a consequence, *most of the measures targeting the* CO_2 *emissions reduction from conventional passenger cars aim at reducing the emissions during the* ***use phase***. During its use phase, the vehicle interacts with its environment: the vehicle is driven in a road by a driver. The fuel consumption of the car may be influenced not only by vehicle technology, but also by the infrastructure used by the car and the driver choices and behavior, which will be referred to as the

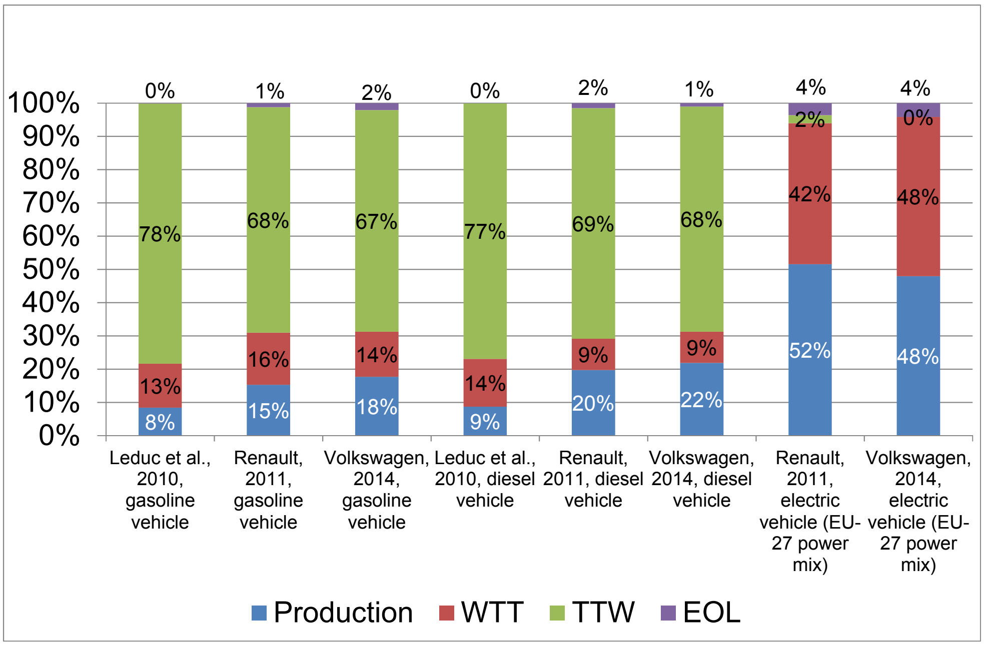


Figure 3.6: Comparison between GWP impact for three vehicle LCAs: Leduc et al. (2010), Renault (2011) and Volkswagen (2014)

Driver-Vehicle-Environment (DVE) system[15] in this thesis (Figure 3.7).

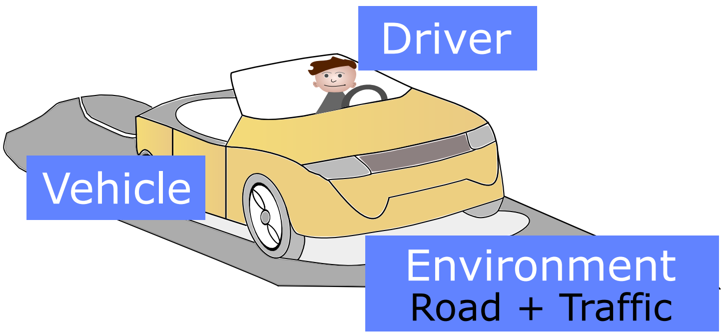


Figure 3.7: Elements of the vehicle-driver-environment system. All these elements can be used in strategies for reducing CO_2 emissions from passenger cars.

We focused our research on the strategies allowing a reduction on CO_2 emissions produced by passenger cars during the use phase of the vehicle. This focus was motivated by two main reasons:

[15]This term comes from road safety research. Enke (1979) uses this term to refer to the control system formed by driver, vehicle and environment in the title of his 1979 article: "Possibilities for improving safety within the driver-vehicle–environment control loop". More recent articles also use this expression: Glaser et al. (2007); Amditis et al. (2010).

1. The importance of the use phase in the total emissions during the life cycle of conventional ICEV (Figure 3.6).
2. The facilitated access to competencies working on aspects linked to the use phase inside the company (experts, engineers) that could be mobilized in the construction of the knowledge base and the generation and evaluation of bio-inspired solutions

Concentrating the construction of the knowledge base on strategies aiming at reducing emissions produced during the use phase does not exclude an evaluation of these strategies taking into account the other steps of the vehicle life cycle. This would allow us to estimate how "low carbon" the solution really is considering the whole life cycle associated impacts.

3.2.2 Literature review of strategies allowing CO_2 emissions during the use phase of passenger cars

A **strategy** can be generally defined as a ''plan of action designed to achieve a long-term or overall aim"[16]. In the context of automobile technology and emissions reduction, the word *strategy* is used to characterize:

1. The choice of the operating mode of each component of the powertrain, for vehicles with more than one powertrain, i.e. hybrid electric vehicles: *energy management strategy* (Musardo et al., 2005; Torres et al., 2014) or more generally, involving *control* of different elements (Manzie et al., 2007; Katrašnik, 2011; Santucci et al., 2014).

2. The sequence or combination of actions that allow achieving a goal: a driving strategy, refer to the pattern used by the driver or an autonomous system to drive a vehicle. If this driving strategy allows an optimal reduction in fuel consumption, it can be characterized as "fuel optimal driving strategy" (Li and Peng, 2012), or if it incorporates eco-driving guidelines, an "eco-driving strategy".

3. Strategies can also involve actions in different domains that contribute to achieving a goal. An example of these strategies are public policy strategies. For example, the European Commission adopted a Strategy on adaptation to climate change in 2013, consisting of a framework and

[16]From Oxford World and British English, available on-line: http://www.oxforddictionaries.com/definition/english/strategy. Access on 02.05.2015

mechanisms for reducing the impacts of future climate change (European Commission, 2013).

This section reviews strategies matching definition # 2: they are linked to the sequence of human or technical actions allowing passenger cars CO_2 emissions reduction. This review is essential for the construction of the knowledge base about the low carbon vehicle innovation field. A discussion about the potential of a strategy combination at regional or country level is out of the scope of this literature review, although a reflexion about the possibilities of CO_2 emissions reduction coming from a combination of individual strategies will be proposed by the end of this section. The next paragraphs review and complement the following article (Freitas Salgueiredo et al., 2014):

> Freitas Salgueiredo, C., Orfila, O., Saint Pierre, G., Coiret, A., Vandanjon, P., Doublet, P., Doncieux, S. and Glaser, S., Overview of strategies for reducing CO_2 emissions during the use phase of passenger cars, Presented at the Transport Research Arena 2014, in Paris.

The literature review was performed by searching in transport and automobile related literature, essentially based on journals available at *Elsevier*[17] and *Springer* [18] databases. *Scopus*, a more general database, also including conference proceedings and other editors journals was also used in this review. Governmental research institutes or world associations reports, such as the United States National Research Council (NRC) or the International Energy Agency (IEA) were also used as references for this review.

This review aimed at identifying strategies related to the three domains of the driver-vehicle-environment system, and whenever possible, identify possible *synergies* between these strategies:

- *Driver*: the emissions reduction comes from driving strategies allowing a reduction in fuel consumption, as in the eco-driving strategies, or from changes in drivers decisions, for example, in choosing to buy less emitting vehicles or in taking less emitting mobility alternatives, such as car sharing or public transportation.

- *Vehicle*: this is the usual domain targeted by vehicle manufacturers, involving vehicle technology modifications, mainly in the vehicle fuel consumption inductors if the classic ICEV are considered or involving partial or full electrification as in hybrid and full-electric vehicles.

- *Environment*: this domain involves adaptations in vehicle infrastructure or environment allowing emissions reductions, going from changes in road attrition to the traffic and urban planning

[17] http://www.sciencedirect.com/
[18] http://link.springer.com/

and management, which influence the fuel consumption reduction.

The quantitative evaluation of the potential of emissions reduction involves measuring the CO_2 emissions during the use phase obtained with the use of the strategy, and comparing these emissions to a reference case that did not use the strategy.

This comparison is more straightforward for vehicle modifications, as CO_2 emissions are directly proportional to the amounts of fuel consumed by the vehicle (Figure 3.2) [19,20]. For example, according to Reif and Dietsche (2014), in the emissions measured using the NEDC cycle in Europe (representing the emissions during the vehicle use phase), a fuel consumption of 1 L/100 km in a ICEV vehicle using a diesel engine is equivalent to 26.5 gCO_2/km, while 1 L/100 km in a ICEV vehicle using a spark-ignition engine powered by gasoline (respecting the Euro 5 standards) is equivalent to 23.4 gCO_2/km.

For driver-related strategies, the impacts may be evaluated using large field operational tests, involving experimentations with a panel of different drivers (as the impacts are not the same depending on the driver behavior and the adoption of the driving tips) or with more general calculations involving the composition of the vehicle fleet by technology and modal shift effects can be evaluated using models such as the International Energy Agency Mobility Model (MoMo) model (Fulton et al., 2009).

Environment strategies may also require simulations or large field experimentations to estimate the emissions reduction potential.

In literature, studies normally estimate the emissions reduction potential according to a specific reference, and these references are different depending on the study. The potential of each strategy is compared qualitatively in the present analysis. This allows a comprehensive overview of the levers used by the strategies to achieve emissions reductions, and avoids comparing values that cannot be compared.

The strategies are reviewed here according to the most relevant domain mobilized: driver, vehicle or environment.

[19]It is important to highlight that this is not true for the other phases of the car life cycle, as vehicle modification may induce higher CO_2 emissions in other phases (manufacturing/ end of life).

[20]The correspondence between the CO_2 emissions and the fuel consumption depends on the chemical composition of the fuel used by the vehicle, the CO_2 being the result of the combustion reaction of the fuel.

3.2.2.1 Driver-related strategies

Driver-related strategies include strategies aiming at changing driver behavior while executing the driving task and also driver, or more generally the vehicle owner decisions (buying decisions, mobility behavior), that can be linked or not to the driving behavior as we will describe in this section.

Literature on driving automation has proposed different approaches aiming at solving the driver problem as shown in a review made by Michon (1985). This author identified three levels of "skills and control" of the driver:

- The strategical level: defining the trip, establishing its goals, route, modal choice and evaluating the costs and risks;
- The tactical level: the maneuvers executed by the driver, such as obstacle avoidance, gap acceptance, turning, taking into account the goals of the strategical level;
- The operational or control level, receiving the inputs from the environment and providing automatic action patterns, in line with the criteria defined in the two other levels.

These levels are indeed very useful when considering the automation of the driving tasks performed by the driver. The first systems developed were essentially focused on driving safety issues or on driver-assistance. One example is the adaptive cruise control (ACC), a system allowing to regulate the distance between a vehicle and the vehicle in front, using information about the vehicle environment, mainly the distance from the vehicle in front and its speed, together with the own vehicle conditions (desired speed set by the driver) to adapt the distance between vehicles to a safe distance (Boer and Hoedemaeker, 1998; Reif and Dietsche, 2014). ACC is a driver assistance system belonging to what is called Advanced Driving Assistance Systems (ADAS). These systems were initially developed with the objective of automatizing driving tasks and enhancing safety, but a recent trend towards incorporating ecological aspects, such as fuel saving, is being observed (Korzenietz, 2013).

A large field operational test realized in Europe and finalized in 2012 showed that passenger cars equipped with ACC and forward collision warning (FCW) could achieve up to 2.77% fuel reduction when compared to vehicles not using these ADAS, while speed regulation systems (speed limiter and cruise control) allowed fuel savings up to 1.55% (Kessler et al., 2012). An acceleration advisor, proposed by Larsson and Ericsson (2009) did not produce a significant fuel consumption reduction in light-duty vehicles (mail delivery vehicles).

Designing new types of devices focused on fuel efficiency, often called Ecological Driving Assistance Systems (EDAS), seems to be a more promising approach as many automakers are developing their own monitoring devices. The two main challenges for effective EDAS are first to help the driver to learn fuel savings driving tips, and then to maintain efficiency over time once training is complete (Degraeuwe and Beusen, 2013).

Barkenbus (2010) defined eco-driving as following several rules: do not drive too fast, do not accelerate too quickly, shift gears sooner to keep engine speed lower, maintain steady speeds, anticipate traffic flow when accelerating and slowing down and keep the vehicle in good maintenance. According to the main recent studies on this topic, eco-driving could allow about 5% to 20% fuel savings (IEA, 2012a; Sivak and Schoettle, 2012). The currently running European project EcoDriver (http://www.ecodriver-project.eu) focus on building both embedded and nomadic systems for teaching the driver to save fuel and helping maintaining his driving efficiency. Results from the large field tests of this project will provide evidence on the effects of these systems.

The driver (or vehicle owner) decisions can also have a determinant influence on the potential fuel consumption savings (and emissions reduction). Sivak and Schoettle (2012) included this aspect in the strategical level, taking into consideration:

- The vehicle class selection (large car, small car)
- The vehicle model selection
- The vehicle configuration (engine size, variants)
- The vehicle maintenance (tuned engine, tire type and pressure)

Besides, we can also point out that drivers can choose using other means of transportation, such as public transportation or carsharing, and that these strategies can indirectly contribute to a reduction in fuel consumption as they reduce the driving distances made with a single car or a car fleet (Barkenbus, 2010; Jacobson and King, 2009). Drivers can also choose to work from home (telecommuting) or to use another personal means of transportation for short distances, such as walking or cycling. Some of these driver decisions can be applied to the whole vehicle fleet, not only to the new vehicles, which can bring large benefits in terms of emissions reduction. In 2011, the European passenger car fleet had more than 200 million cars in use (ANFAC, 2013), while the new cars registrations accounted for 13 million cars (ICCT, 2014), representing only 6,5% of the vehicle fleet.

These driver-related measures identified in this section and their possibilities of extension to the whole vehicle fleet or only to the new vehicles are summarized on Table 3.1.

Table 3.1: Driver-related strategies identified and their extensibility

Strategy domain	*Strategy description*	*Strategy extent*
Driving behavior (during the driving task and route selection)	use of ADAS	new vehicles
	use of EDAS	new vehicles
	eco-driving	whole fleet
Driver decisions (before driving task)	vehicle selection (model, configuration, maintenance)	whole fleet
	modal selection (public/private transport, telecommuting, cycling, walking)	whole fleet

3.2.2.2 Vehicle-related strategies

As previously mentioned, CO_2 emissions during use are proportional to the fuel consumed by the vehicle during its use. Two factors determine fuel consumption:

- The *energy required by the vehicle*, i.e. the energy required by the vehicle to reach the desired speed or to make a distance in a desired time.
- The *efficiency of the engine*, i.e. the capacity of the engine to transform the energy stored in the fuel in movement.

The *energy required by the vehicle* can be evaluated using vehicle dynamics. Vehicle dynamics is described by Newton's law of motion (from Classical mechanics). Forces can act on three axes of a car center of gravity: the longitudinal (or linear), the lateral and the vertical. The longitudinal dynamics of the vehicle refers to the study of the forces acting upon the x axis of the vehicle center of gravity. For a vehicle moving along a straight road, the magnitude of these forces will be the ones quantifying fuel consumption. The forces acting on the lateral axis, responsible for the cornering behavior of the vehicle, can also contribute to the vehicle energy demand.

The magnitude of the contribution of these lateral forces to energy demand for real routes quantified by Burgess and Choi (2003) reached a minimum of 3% and a maximum of 13% of the total energy demand. The normalized driving schedules used for fuel consumption regulation purposes in Europe,

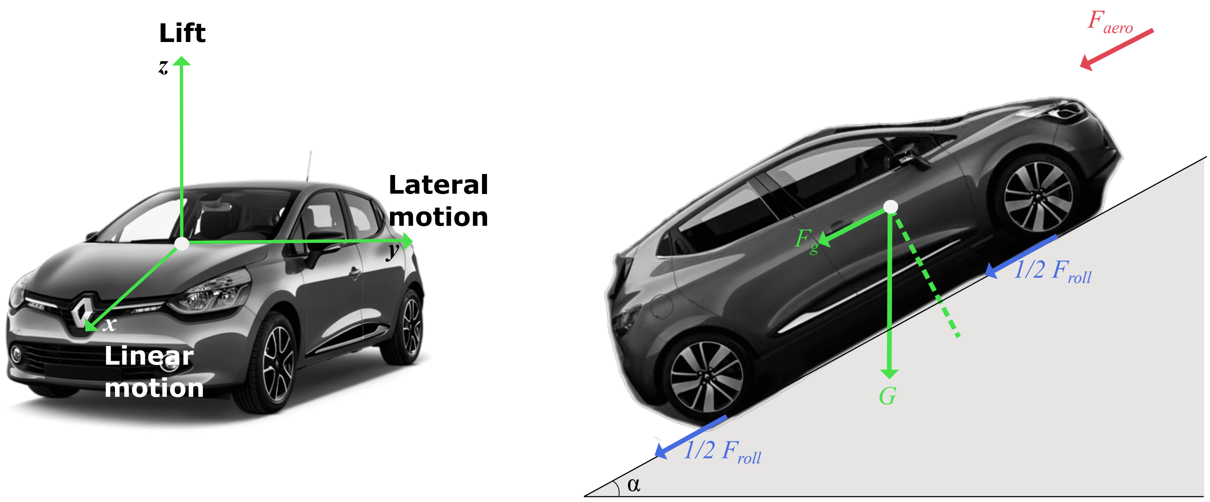


Figure 3.8: A representation of a car three axes of motion and the longitudinal forces acting on a vehicle, based on the Figures [1], page 765 and [1] page 774 from (Reif and Dietsche, 2014)

United States or Japan, do not consider cornering maneuvers. They give only specific targets for speed and time to be achieved by the vehicle. Besides, in the analysis of the fuel (energy) consumption of a vehicle following these driving cycles, only the longitudinal forces are usually considered (Sovran and Blaser, 2006; Guzzella and Sciarretta, 2005).

According to the Newton's second law, the sum of the forces, $\overrightarrow{F}$ acting on the vehicle equals its mass, M times the acceleration, $\overrightarrow{a}$ (Eq. 3.1):

$$M.\overrightarrow{a} = \Sigma\overrightarrow{F} \tag{3.1}$$

The forces acting on the vehicle are the *tractive forces*, F_{TR}, corresponding to the propulsion force generated by the engine (internal combustion engine in conventional vehicles, electric motors in the electric vehicles or both in hybrid electric vehicles) and the *road load force*, F_{RL}, corresponding to the resistance forces, which are opposed to the vehicle movement. This force is the sum of three forces: the *rolling resistance force*, F_{roll}, resulting from rolling tire deformations, the *aerodynamic resistance force*, F_{aero}, resulting from the viscous resistance (air-vehicle surface) and also from the pressure difference (front-rear of the vehicle) and finally the *gravitational force*, F_g, corresponding to the longitudinal component of vehicle weight, G, which depends of the slope (or grade) of the road, α, acting as a resistance force when the vehicle is going uphill or helping traction when the vehicle is going downhill. Figure 3.8 presents the three axes of motion (linear, lateral and lift) and the longitudinal forces acting on a vehicle.

The forces are calculated according to the following equations[21]:

For the rolling resistance force:

$$F_{roll} = C_{RR} m_v g \cos\alpha \tag{3.2}$$

For the aerodynamic resistance force:

$$F_{aero} = \frac{1}{2}\rho_a A_f C_d v^2 \tag{3.3}$$

For the gravitational force:

$$F_g = m_v g \sin\alpha \tag{3.4}$$

Besides accelerating the vehicle, there are also other rotating parts that are accelerated. The inertia of these rotating parts correspond to an additional mass, added to vehicle mass that must be accelerated. Wheels, engine and transmission have inertias that must be accounted for. Considering only the inertia of the wheels, I_w (kg.m^2), and wheel radius r_w for each one of them, the equation 3.1 becomes :

$$\begin{aligned} (m_v + 4[\frac{I_w}{r_w^2}]).\overrightarrow{a} &= \Sigma\overrightarrow{F} \\ (m_v + 4[\frac{I_w}{r_w^2}]).\overrightarrow{a} &= F_{TR} - (F_{roll} + F_{aero} + F_g) \end{aligned} \tag{3.5}$$

The symbols used in these equations, along with their definitions and units are presented in the **List of symbols** on page xxxi.

Each one of these resistance forces (gravitational, rolling, aerodynamics) contribute to the fuel consumption. Reducing the magnitude of these forces can be considered as a strategy to reduce fuel consumption.

Reducing rolling resistance

The rolling resistance is the force corresponding to the rolling tire deformations. The reduction of this force involves the use of low-resistance materials in tires[22], or a good calibration of tire pressure

[21] These are standard vehicle dynamics equations. We can cite Guzzella and Sciarretta (2005) book as reference book where these equations are listed.

[22] The Michelin® low resistance tires, have a C_{RR} inferior to 0.006, while an "usual" tire, 0.01, also reducing the rolling resistance force by the same amount. Source: Actualités Techniques Michelin, available at: http://comm-marques.michelin.fr/download/promotions/ATM-etiquetage.pdf, accessed on 03.05.2015.

(increasing inflation of tires reduces flattening and thus reduces rolling resistance). The range of the achievable fuel economy reduction by the combination of low resistance tires and tire pressure monitoring systems was estimated as 3 to 5% (IEA, 2012a).

Reducing aerodynamic drag

The aerodynamic drag can be reduced by acting upon the frontal area, the aerodynamic drag coefficient (related to vehicle streamlining) or by reducing the vehicle velocity. Considering the two first vehicle-related parameters, Burgess and Choi (2003) estimated that decreasing the frontal area or the aerodynamic drag coefficient by 10% could reduce the vehicle total energy demand by 2%. Fontaras and Samaras (2010) obtained using simulations on the NEDC cycle a reduction in the CO_2 emissions ranging from 1.2 to 2.4% with 10% of combined reduction of frontal area and aerodynamic drag coefficient. The 2014 Renault concept car EOLAB, achieved a 30% reduction in the product $A_f C_d$ when compared to the current manufactured model Clio IV (0.470 vs. 0.670 m^2), thanks to improvements in vehicle design, including modifications in the vehicle underbody, and active systems, such as the "front active spoiler", the controlled suspension, and the active rear flaps (Renault, 2014). This shows that progress is still to be expected from aerodynamics domain, allowing further reduction in fuel consumption, specially at higher speeds (the aerodynamic resistance force is proportional to the square of the vehicle speed).

Reducing the gravitational force

This measure is more related to the road infrastructure, and will be addressed in the corresponding section.

Reducing other vehicle systems energy consumption

Other vehicle loads include energy used for lighting, that can bring up to 0.5% fuel consumption savings with the use of less-energy consuming technology such as light-emitting diode (LED), and improved air-conditioning systems which can also bring up to 3 to 4% fuel consumption savings (IEA, 2012a).

Reducing transmission losses

The reduction on transmission losses is generally achieved using manual-transmission gearboxes. The fuel consumption reduction potential for transmission improvements ranges from 3 to 8% for gasoline engines and from 2 to 5% for diesel engines (NRC, 2011; Smokers et al., 2011), thanks to improvements in bearings, gears, sealing elements and the hydraulic system (for the automatic transmissions) (NRC, 2011).

Reducing vehicle mass

Vehicle weight is the most significant parameter affecting vehicle energy consumption from vehicle loads(Burgess and Choi, 2003), as weight is directly proportional to the inertial forces slowing the vehicle down (equation 3.5). The results obtained by Fontaras and Samaras (2010) for an NEDC cycle, showed that a 10% reduction in vehicle mass could allow CO_2 emissions reduction ranging from 2.7 to 3.6%. These reductions may be achieved by the use of lightweight materials, such as carbon fiber or aluminum, although currently the cost of the substitution may still seem prohibitive: using composite materials such as carbon fiber-reinforced polymers to replace steel could reduce vehicle weight up to 40%, but requiring an additional cost of USD 20 000 per vehicle (IEA, 2012a). The use of other structure optimization methods such as the Soft-Kill Option (SKO) [23] (Baumgartner et al., 1992) could also be responsible for a reduction on the vehicle materials requirement, consequently reducing vehicle weight by 30%, as proposed in the Daimler Bionic Concept Car (Daimler, 2011).

Besides acting on the vehicle energy demand, reducing the resistances to movement, *improving the energy conversion efficiency*, i.e. the effective amount of energy stored in the fuel that is used to run the car, is also a strategy for reducing fuel consumption (and CO_2 emissions).

Improving internal combustion engine energy efficiency

In an ICEV, chemical energy is stored in the chemical bonds of the hydrocarbons of diesel or gasoline. This chemical energy must be transformed into mechanical energy that will allow the vehicle to run. This transformation takes place in the internal combustion engine, where, the chemical energy is transformed in heat energy (combustion of the fuel with air) and the heat energy is used to move the pistons and the drivetrain that will produce mechanical energy at the wheels (and the alternator that produces electrical energy to charge the battery and supply the ignition, lightening, air-conditioning, radio, etc.).

However, the overall efficiency of internal combustion engines is, for diesel engines, maximum 45% and for gasoline engines (spark-ignition engines) maximum 40% with the overall efficiency being defined as the ratio between the available power, P_{eff} and the fuel energy flow, $\dot{Q}$ (Reif and Dietsche,

[23] The Soft-Kill Option is a bio-inspired structure optimization method, inspired by bone mineralization.

2014) (Equation 3.6).

$$\eta_{eff} = \frac{P_{eff}}{\dot{Q}} = \frac{P_{eff}}{\dot{m}_{fuel} H_{fuel-lcv}} \tag{3.6}$$

This overall efficiency inferior to 45% is responsible for a considerable amount of the fuel consumption: from 100% of fuel energy that enters the engine, it is estimated that only 10 to 20% is used for providing the required tractive force in standard testing cycles (Atabani et al., 2011; Lutsey, 2012).

Reaching efficiencies superior to 40 - 45% is not possible for thermodynamic limitations. Nevertheless, it is possible to improve the efficiency of engines by making they work at operating points with better efficiency[24], as internal combustion engine have better operating points, which have higher efficiencies, as shown in Figure 3.9. The engine maps are one way of visualizing these operating points:

- If the instantaneous fuel consumption, also called fuel flow rate, is plotted as a function of the engine operating points (Figure 3.9, *left*), for the same engine speed, the fuel flow rate increases with the engine torque.
- If the specific fuel consumption, calculated as the ratio of the fuel flow rate and the engine power output, is plotted as a function of the engine operating points (Figure 3.9, *right*), the surfaces defined by the iso-specific consumption lines have different surfaces depending on the operating zone of the engine.

As shown in Figure 3.9, for an ICEV the best operating zones (for which the specific fuel consumption has a lower value) are located on the zones with higher loads (higher torque). Another important aspect that this engine map can highlight is that for the same power output (for example, following the line of 40 kW in Figure 3.9, *right*), the specific fuel consumption can be very different depending on the engine speed, which justifies the role of the gearbox as a means of finding the engine best operating points [25].

[24] The operating point here refers to the torque and engine speed values in which the engine is working. There are other possibilities for defining engine operating points, for example, using the brake mean effective pressure (bmep), instead of the engine torque. The brake mean effective pressure is the work produced by the engine during one cycle, and has pressure units (Pa or bar) (Heywood, 1988, p.50).

[25] The vehicle speed and the gear chosen by the driver determine the engine operating point, as the vehicle speed determine the engine load (the torque that must be produced by the engine) and the gear determine the engine speed. A detailed explanation of the relation between the transmission and fuel consumption can be found on (Baron and Pescarou,

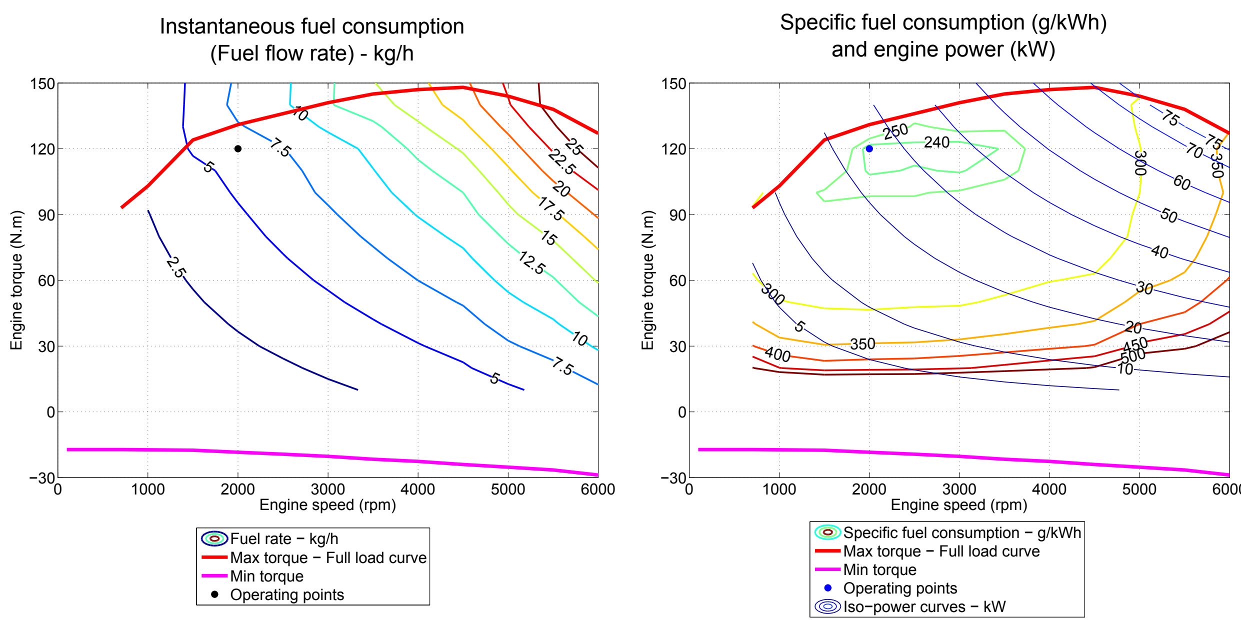


Figure 3.9: An internal combustion engine map, showing the fuel flow rate (left) and the specific fuel consumption (right), which measures the efficiency of the engine - the higher the specific fuel consumption, less efficient is the engine.

Engine downsizing is a strategy belonging to the vehicle-related domain that is related to improving the internal combustion engine efficiency. It consists in reducing engine displacement[26] in combination with technologies increasing engine torque such as turbocharging [27] to keep the same vehicle performance. Downsizing and turbocharging estimated fuel economy benefits ranged from 10% to 17% (IEA, 2012a) with a "strong downsizing" for diesel and gasoline engines, respectively. NRC (2011) considered slightly lower achievable fuel consumption reductions for downsizing: 2 to 6% for gasoline engines with direct injection, and 3 to 5% for diesel engines. Diesel engines are already less fuel consuming than gasoline engines, and the observed differences between the potential of downsizing for diesel fueled and gasoline fueled engines, are due to the superior fuel efficiency of compression ignition engines (Schipper, 2011). Diesel engines for passenger cars are popular in Europe, although their lower fuel consumption is offset by differences in vehicle use, vehicle choice (Schipper, 2011) and also by other pollutants emissions, such as particulate matter.

2013).

[26] The engine displacement (in French: *cylindrée*) is related to the number of cylinders that an engine has and the displacement of one cylinder (given in cm^3).

[27] According to Reif and Dietsche (2014), turbochargers “increase the air-mass flow for a given engine displacement and a given engine speed, thereby increasing the power density”.

Besides modifying the conventional engines, *hybridizations* allow better energy conversion since the electric motor can be used for optimizing the efficiency of the ICE. It allows the adjustment of the ICE torque and speed to their best operating points and the recovery of some energy losses such as braking losses. With the electric motor assistance, internal combustion engines can also be downsized (Reif and Dietsche, 2014, p.724). For the different hybrid types, fuel consumption savings were estimated as: 6% and 1% for gasoline and diesel engines respectively for the stop/start system (NRC, 2011), 20-30% for mild hybrids (Chan, 2007; Smokers et al., 2011), 30-50% for full hybrids (Chan, 2007; Smokers et al., 2011; NRC, 2011) and 50% or more for plug-in hybrids (Atabani et al., 2011). The type of driving conditions can influence these percentages, as hybrids have characteristics that allow greater savings on lower speed conditions (Fonseca et al., 2011). Box 3.2 details the differences between general hybrid electric vehicle (HEV) types.

Box 3.2: Hybrid Vehicles

A hybrid vehicle can be defined as a vehicle that uses another engine in association with the internal combustion engine. For example, HEV are vehicles "using both an internal-combustion engine and at least one electric machine for its means of propulsion" (Reif and Dietsche, 2014, p. 724). It differs from a battery electric vehicle (BEV), that has an electric powertrain (electric motor + drivetrain) instead of a conventional internal combustion engine powertrain (internal combustion engine + drivetrain). According the share of the power produced by the electric motor in the powertrain total power, HEVs can be classified as follows:

Features	*Micro-hybrid*	*Mild-hybrid*	*Full-hybrid*
Capabilities of the electric motor (Chan, 2007; IEA, 2012a)	start and stop the ICE / regenerative braking	power assistance / regenerative braking	propulsion possible at EV-mode only or combined with ICE
Electric motor share of total power (IEA, 2012a)	0–10%	5–30%	>20%
Power range of the electric motor (Chan, 2007)	2.5 kW at 12 V	10–20 kW at 100–200 V	50 kW at 200–300 V

Using alternative energy sources

Alternative energy sources produced using renewable energy sources or with lower fossil fuel content, may represent an alternative for reducing CO_2 emissions reduction. Some of these alternatives do not necessarily imply internal combustion engine modifications: biofuels such as ethanol or biodiesel can be used in conventional engines, and the CO_2 emissions during the use phase of these fuels in cars are considered zero, as they are produced from biomass that absorbed the CO_2 from the air in the photosynthesis process. However, a more important use of biofuels raises questions about the direct and indirect land-use changes and the competition with food agriculture that may occur (Lapola et al., 2010).

Full electric vehicles generate zero CO_2 emissions from the energy use in the vehicle, but the energy-mix used to produce the electricity influences the well-to-tank (WTT) CO_2 emissions (Ma et al., 2012), as previously mentioned in Section 3.2.1. Electricity can be produced using renewable and less CO_2 emitting sources of energy, but there are still factors restraining a widespread adoption of full electric vehicles such as high cost, shorter driving ranges, longer refueling times, infrastructure investments (Romm, 2006; Chan, 2007). Hydrogen is also considered as a zero emissions fuel during the use phase. It can be used in ICEs subject to modifications (Pourkhesalian et al., 2010) or it can be used as an energy vector in fuel cells to generate electricity, in the fuel cell vehicle (FCV). This technology still have high initial costs and depends on the existence of a network of production and distribution of hydrogen (Romm, 2006). Besides, hydrogen can also be produced by fossil fuel consuming technologies, facing the same issues as electricity in the origin composition and the emissions in the vehicle whole life cycle (Alazemi and Andrews, 2015; Dincer and Acar, 2015).

The vehicle-related strategies identified in this section involve vehicle systems modification and thus are considered as being mainly applicable to the new vehicles. They are summarized on Table 3.2 according to the lever used to reduce fuel consumption and CO_2 emissions.

3.2.2.3 Environment-related strategies

The vehicle environment includes the infrastructure in which the vehicle is driven – the road in the case of passenger cars – and the environmental conditions of the use of the vehicle, i.e. the meteorological conditions and the structural organization - the road and urban planning.

Considering these aspects, there is a considerable interest in the road conditions and its impact on

Table 3.2: Vehicle-related strategies identified and the lever used to reduce emissions

Strategy vehicle-related lever	*Strategy description*
Reducing the energy requirement of the vehicle	reducing rolling resistance
	reducing aerodynamic drag
	reducing other vehicle systems energy consumption
	reducing vehicle mass
	reducing engine friction losses
	reducing transmission losses
Improving engine efficiency	engine downsizing with turbocharging
	powertrain hybridization
Using alternative low-carbon energy sources	full electric, fuel cell or biofueled vehicles

the fuel consumption (and CO_2 emissions): Tsang et al. (2011); Coiret et al. (2012) studied the influence of slope and grade on fuel consumption, Burgess and Choi (2003) evaluated the influence of the level of sinuosity on an itinerary on vehicle braking and on the developed lateral forces that has effects on fuel consumption, Tsang et al. (2011); Hu et al. (2012) showed that the road and traffic conditions have effects on fuel consumption. The road and traffic conditions can be the object of local policy measures, aiming specifically at improving urban and economical activities planning. We have decided not to deepen this review with respect to this urban planning and road conditions aspect of fuel consumption, although these aspects are generalizable to all vehicle fleet. They require a very specific knowledge about urban planning and governmental policy that is out of the scope of this thesis.

3.2.3 The combination of strategies - an alternative for emissions reduction

The word "combination" may indicate that some of the strategies can be considered in addition to each other. This is indeed the case for reduction in rolling resistance and improvements in aerodynamics, for example. The interesting aspect of the combination, is not only their additive character, but the effects they provoke on other vehicle systems. A very good example of this synergy is weight reduction: lighter vehicles can use downsized engines that will consume less fuel and will operate with superior efficiencies.

There are currently technologies, such as vehicle-infrastructure communication, that have shown benefits in the fuel consumption: He et al. (2012) showed that vehicle-infrastructure integration technology, with the use of traffic prediction, could bring approximately a 3% emissions reduction for hybrid vehicles, as the traffic prediction can be used in hybrid vehicles energy management strategies.

3.3 The C–K referential for the low carbon vehicle

With the knowledge base structuring detailed in the last Section 3.2, and the concepts tree made with the inputs of the automotive company experts by Amsterdamer and Molin (2011) we were able to propose a C–K diagram for the innovation field of the low carbon vehicle, shown in Figures 3.10 and 3.11. This diagram has also received the inputs of the engineers working with the CO_2 reduction ongoing projects and of the low environmental footprint vehicle expert. During this process of C-space revision using the knowledge from the literature review, other knowledge bases, relevant to the study were also activated. This knowledge activation is a part of the C–K process, in which concepts are also responsible for knowledge activation (the C→K operator, described in Section **??**). The activation of these knowledge bases were provoked mainly by the inputs coming from the projects team and experts.

The color legend used in these figures refers to the color convention adopted in C–K referential by Agogué et al. (2014a, p. 48): the concepts are classified in *known*, when referring to known technical solutions, *attainable*, when a concept must be developed but is attainable and *disruptive*, when they are distant to the dominant design, and require a “dedicated design approach”. The initial concepts were classified as *known* in our case, as examples of these alternatives are already available. The more disruptive were found in the final branches of the concepts tree.

The knowledge is also coded according to the same reference, (Agogué et al., 2014a, p. 46), in three types: *on going learning*: for knowledge that is the object of research programs on the issue, *missing*, for knowledge not present in the company, but that can be activated by expanding the knowledge bases to other research domains and *validated* for knowledge bases belonging to the dominant design or available inside the company. The on-going knowledge and the missing knowledge are the ones that may lead the way for activating biological knowledge bases. Ongoing research is made in practically all domains of the low carbon vehicle. The EOLAB 2014 Renault concept car is one example of this multiple research domains related to the low carbon vehicle. It results from research in almost every domain related to the vehicle part, including hybridization (Renault, 2014).

Other knowledge bases activated during the revision process of the C-space, were the knowledge related to the *on-board carbon dioxide capturing*. This includes two notions, the first one, the transformation of the on-board fossil fuel in a non-emitting fuel, such as hydrogen that can be used in fuel cells to produce electric energy that is used in an electric motor, for example. Automobile manufacturers such as BMW (Lamp et al., 2003), Renault (Rollier et al., 2008) and Volvo (Lindström et al., 2009), have studied the possibility of producing auxiliary power units using fuel cells, in which case the hydrogen could be obtained by gasoline or other hydrocarbons on-board reforming. The advantage of the on-board reforming is that instead of creating a complicated infrastructure to produce hydrogen and use it in the car for having emissions reductions, the hydrogen could be obtained directly in the car from usual liquid fuels. However, there are currently no commercially available passenger car models with this gasoline reforming technology for the auxiliary power unit. Damm and Fedorov (2008) mentions the carbon dioxide sequestration of CO_2 using CaO pellets for its sequestration, producing calcium carbonate proposed by (Kato et al., 2005), and elaborate an alternative method: store the CO_2 produced in a steam reforming reactor and liquefied in a dual fuel tank, that could be emptied later. This technology of CO_2 capturing and sequestration requires further basic research on the catalysts and materials. The second notion behind the carbon dioxide capturing on-board is the capture of the CO_2 produced in the vehicle exhaust system. Some authors have proposed reactants or solutions that theoretically allowed a reduction of CO_2 exhaust emissions, Murray and Murray (2010) proposed a filter that captures CO_2 from the exhaust system in carbonate form that can be removed from the filter when needed [28], and Zielinski et al. (2012) proposed a similar system, commercialized with the name of Strataclear™ technology [29].

The knowledge about the other phases of vehicle life cycle will not be detailed in this thesis, as previously mentioned, because the focus of the thesis is on strategies reducing emissions during the use phase of passenger cars. They are, however, included in the general definition of a low carbon vehicle, and were included in the C–K referential of this innovation field.

[28] Their invention is described in their website, available at: http://carboncapturefilters.com/low-co2-exhaust/ (accessed on 15.05.2015).

[29] Invention described in the company website, available at: http://ryncosmos.com/ (accessed on 15.05.2015).

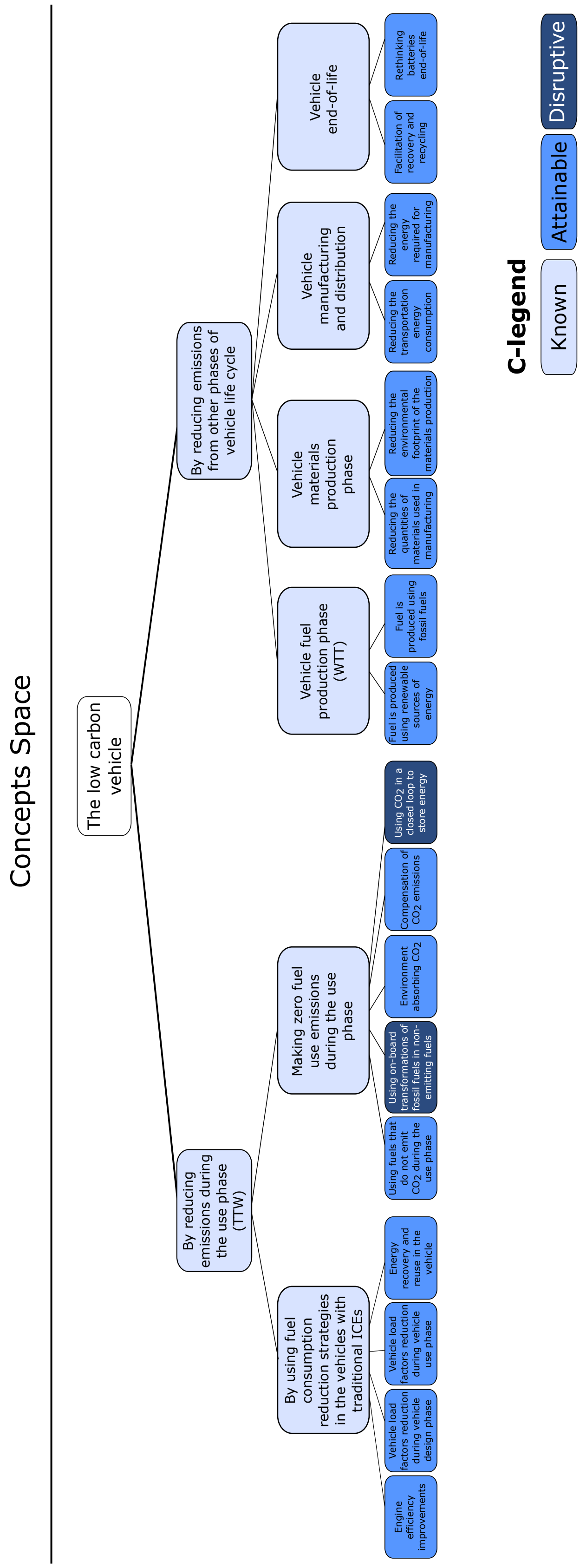


Figure 3.10: The C-space referential for the low carbon vehicle with the first ramifications of the C-space.

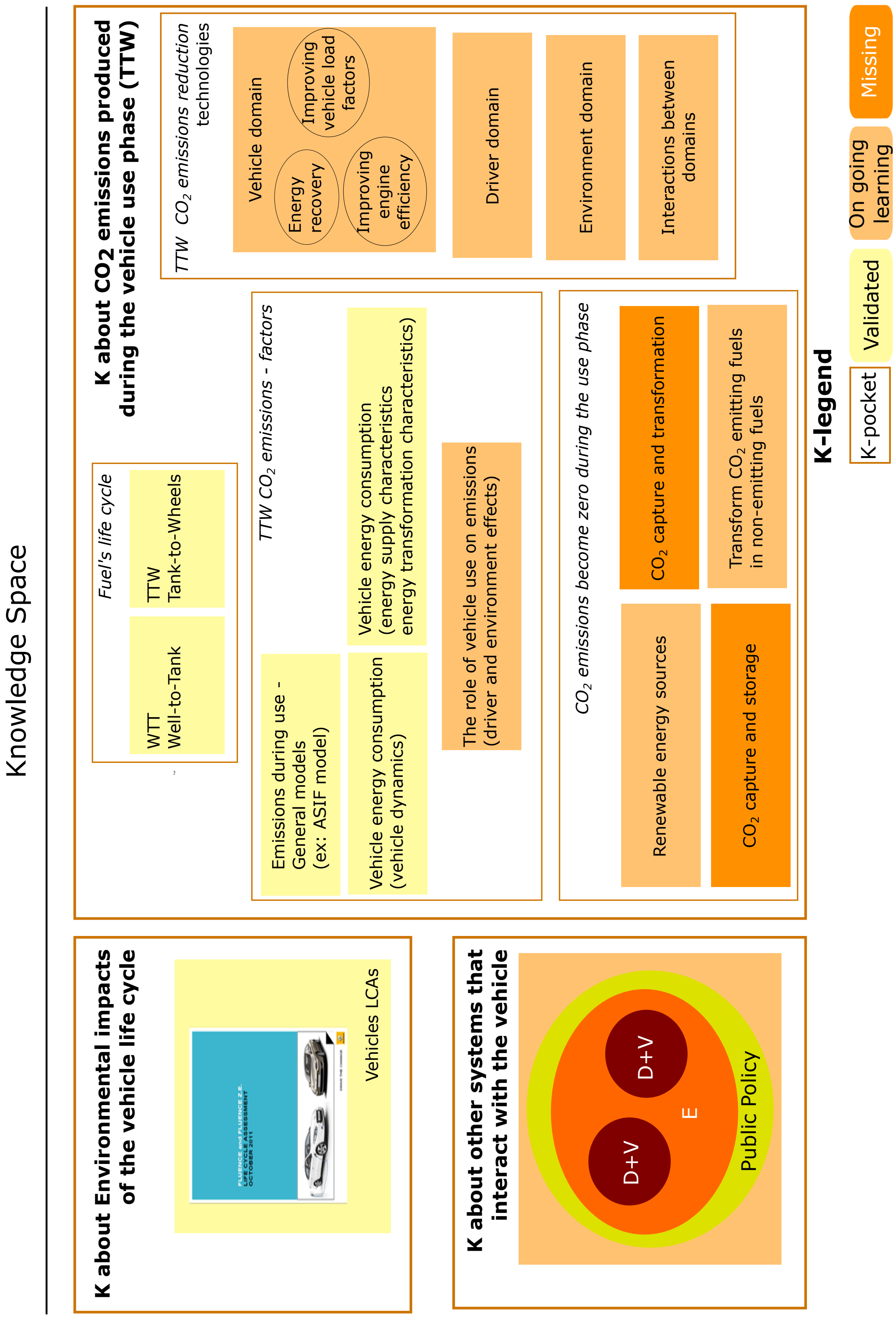


Figure 3.11: The K-space for the low carbon vehicle with the main knowledge bases activated.

3.4 The application of bio-inspiration to the low carbon vehicle

According to the C–K modeling for biologically inspired design shown in the Chapter 2 of this thesis, when applying bio-inspiration it is important to have identified design paths for applying bio-inspiration. These design paths may refer to paths that seem to be "blocked", i.e. for which the current knowledge bases gives no alternatives for its realization or paths for which alternatives are sought for. These "alternatives" correspond to paths that use different ways to achieve the same objective as the one sought for the "blocked" design path.

3.4.1 Identification of design paths for applying bio-inspiration

In the C–K referential of the low carbon vehicle presented in the previous section (Figures 3.10 and 3.11), almost every path could be the object of a search for bio-inspired alternatives, schematically represented in Figure 3.12 such as:

- the sequestration of CO_2, one of the disruptive concepts identified in this referential, could benefit from biological knowledge coming from plants and aquatic organisms, such as algae, that use the carbon dioxide from the atmosphere and transform it into organic compounds by photosynthesis (Ort and Kramer, 2009; Moroney and Ynalvez, 2009)[30], or that mineralized the dissolved carbonates in water as made by corals (Gattuso et al., 1999; Riebesell et al., 2000), that can also have photosynthetic activity.

- the reduction of emissions coming from internal combustion engines during the use phase can benefit from driving assistance systems, which can be used, for example to optimize traffic flow, reducing traffic jams and thus saving fuel and reducing emissions. The swarm behaviors present in nature, such as those from the school of fish, can be a source of inspiration for sensors and algorithms allowing this optimized platooning behavior: Nissan developed the EPORO project in which robots were equipped sensors enabling the simulation of a anti-collision and platooning system inspired by school of fish behavior (Abidin et al., 2015).

- the vehicle aerodynamics (one of the vehicle load factors) can also benefit from inspiration from nature: the boxfish, was used by Mercedes as a model for improving the aerodsynamic

[30] These two texts are reference texts coming from the publication entitled Encyclopedia of Life Sciences, Wiley Publishing, doi: 10.1002/047001590X

coefficient of the Bionic Car concept car (Daimler, 2011).

- the properties of the materials found in nature, that could be useful for lightweighting can also be inspired by the numerous materials with "outstanding properties" found in nature. These materials can also represent an inspiration source for the synthesis of less energy consuming materials as most of them are synthesized in environmental conditions.

- the use of fuel consumption reduction strategies in the vehicles with traditional ICE is linked to the energy use in the vehicle. This energy use is influenced by the engine efficiency and by the possibility of energy recovery and reuse in the vehicle, and could benefit from knowledge about the energy in natural systems and the mechanisms used to save energy.

Answering the second research question of this research implies choosing among these possible design paths. The paths already having biologically inspired designs available or under development, such as the vehicle load factors (aerodynamics, new materials for lightweightening) and the vehicle-to-vehicle interactions were not chosen for this research, as our objective was seeking new domains for biologically inspired design in the low carbon vehicle innovation field.

Two alternatives remained for biologically inspired design exploration: one that would study alternatives to CO_2 capture or sequestration, including energy produced using low carbon fuels or renewable energy and another one that would study the energy use in nature and see whether nature strategies could be useful for the current design paths developed in the automotive industry for optimizing energy consumption.

Selecting one of these two alternatives implied choosing between *different scientific disciplines*, one that would be more related to the chemistry and energy production, and one more related to the knowledge of the automotive sector (cars working principles, energy transformations in cars), respectively. While the automobile knowledge represents the knowledge available inside the car manufacturing company where this research was made, and the knowledge available in the LIVIC laboratory in which the research was realized, the chemistry knowledge required for the development of the first alternative was not available for this research. It would require collaborations with other scientific (non-biological) laboratories, a possibility not feasible during the present research project.

These constraints guided the final choice of the concept path to explore with bio-inspiration towards the energy use in automobiles during the use phase.

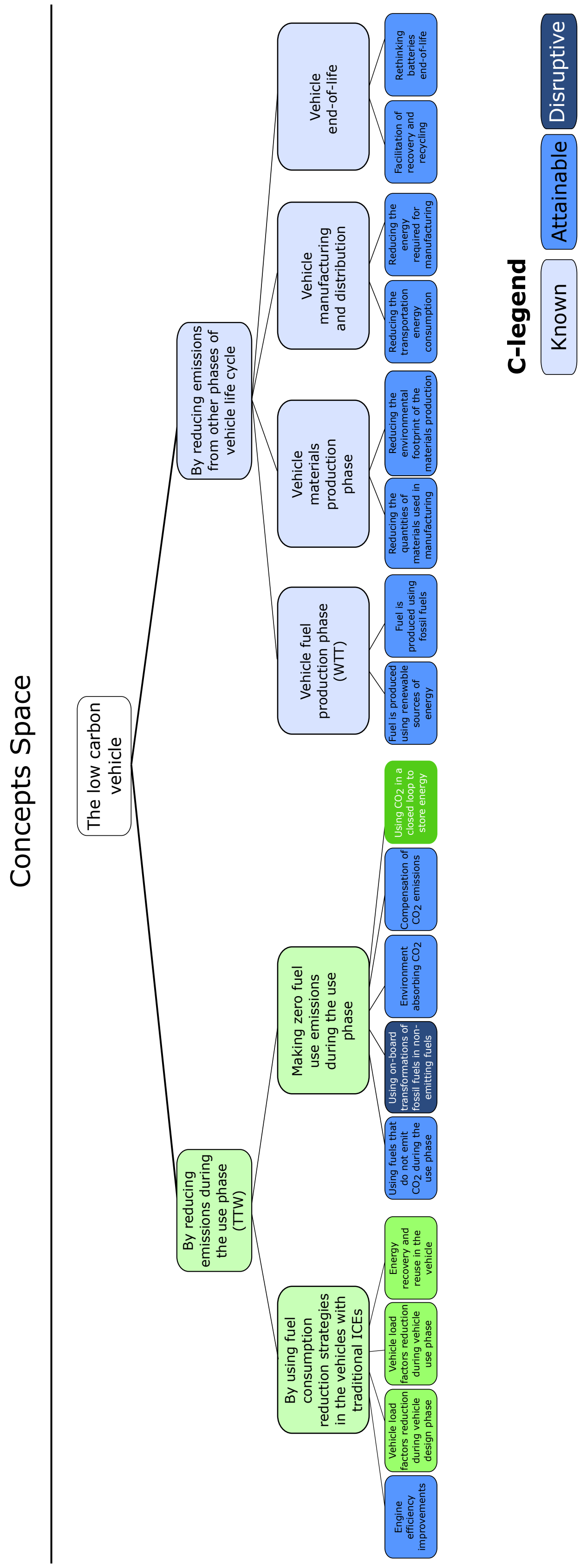


Figure 3.12: The C-space referential for the low carbon vehicle with the indication of possible bio-inspired design paths (indicated in green).

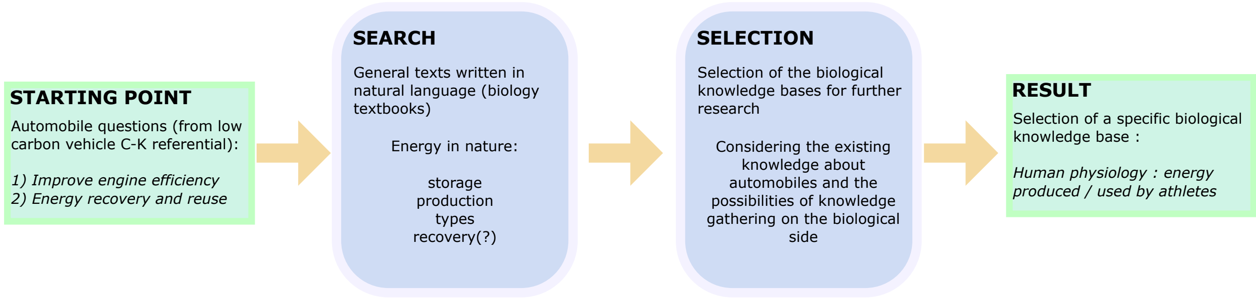


Figure 3.13: Steps of the biological knowledge activation for the energy in vehicles design path

The design path chosen for the application of bio-inspiration: the energy use during the use phase of passenger cars - energy transformations (the engine) and energy recovery and reuse.

3.4.2 Activation of biological knowledge relevant to the energy transformations and use in cars

In order to search the vast literature on biology about energetics, we have decided to apply the principles of the natural-language search proposed by Shu (2010). This search on general biology texts allowed us to identify possible biology research domains that could be worth exploring, and then by consulting with experts from the biological field and the automotive field, we identified a more specific biological domain for research, as shown in the diagram of Figure 3.13. The research domains "worth exploring" were identified by relating them to the automobile knowledge we wanted to explore.

3.4.2.1 Search in general biology texts

According to Shu (2010), a reference textbook for the general search on natural-language texts was the book *Life: The Science of Biology* from Sadava et al. (2011). Shu (2010) used keywords for searching this reference textbook. These keywords are considered *biologically relevant* based on their functionality. In our case, instead of searching using specific keywords, the same textbook was searched using questions about the types of energy and how energy was stored, produced and recovered in nature. Our focus was the energy used by living organisms themselves, although a view of the flows inside an ecosystem could also provide some interesting insights. The main target of this process of search in a biological knowledge base is finding vehicle modifications that could bring emissions reduction. The vehicle ecosystem, including mobility and other environmental aspects was not taken into account in this first part of the study.

Sadava et al. (2011) book has an entire part dedicated to energy, entitled "*cells and energy*", which is divided into three chapters:

- Energy, enzymes and metabolism
- Pathways that harvest chemical energy
- Photosynthesis: energy from sunlight

In an attempt to briefly describe the contents of these three chapter relevant to our analysis the following interesting points can be highlighted:

- Energy transformations are presented as the "hallmark of life": no cell creates energy. The energy always comes from the transformation of one energy form into another: for example, a muscle cell uses the chemical energy stored in its energy stores (fat, carbohydrates) to produce mechanical energy. [p.149]
- The reactions occurring on living organisms (the metabolism) can be catabolic (breaking down of complex molecules into simpler ones) or anabolic (linking molecules). These reactions are linked and while catabolic reactions might release energy stored in the chemical bonds, anabolic reactions may use this energy. [p.150]
- When converting one form of energy into another, 100% efficiency is not achievable: a part of the energy is lost. [p.150]
- adenosine triphosphate (ATP) is a molecule used by cells to "capture and transfer the free energy they need to do chemical work" [p.153]: its hydrolysis releases free energy that can be used for the synthesis of other molecules, active transport and movement. It can also be converted into light (bioluminescence). Its formation implies the capture of energy released by exergonic reactions[31]. Enzymes are important to catalyze these reactions, i.e. to reduce their activation energy.
- Energy can be supplied by glucose and other carbohydrates, fats and proteins. Most of the

[31] An *exergonic* reaction is a reaction that releases free energy (ex. catabolic reactions). An *endergonic* reaction is a reaction that require or consume free energy (Sadava et al., 2011, p.152)

metabolic pathways used to get energy from these molecules are similar, from bacterias to humans [p.169].

- Even if the final products are the same between the combustion of glucose and its metabolism in organisms: $C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + free\ energy$, in the metabolism, there is a "**multistep pathway**", which allows the glucose metabolism to occur at considerably lower temperatures [p.170], This multistep pathway also represent a way of releasing "manageable amounts of energy, one step at a time" [p.178].

- In order to harvest energy from glucose, there are **anaerobic metabolisms**, such as *glycolysis* or *fermentation*, that do not require oxygen. On the contrary, **aerobic metabolisms**, such as *cellular respiration*, use oxygen and allow a complete conversion of glucose into CO_2 and H_2O [32].

- The energy pathways occur in different locations on the cells of eukaryotes and prokaryotes. Eukaryotes can have glycolysis and fermentation outside the mitochondrion, and inside the mitochondrion the respiratory chain (cellular respiration). Prokaryotes have glycolysis, fermentation and the citric acid cycle in the cytoplasm and pyruvate oxidation and the respiratory chain on the plasma membrane [33].[p.172]

- The total ATP yield of glycolysis and fermentation is 2 ATP, while glycolysis followed by cellular respiration produces 32 ATP.

- Carbohydrates, lipids and proteins can provide energy: carbohydrates are converted into glucose, lipids broken into fatty acids and glycerol. Glycerol is then converted into an intermediate of glycolysis and fatty acids are converted into acetyl-CoA which can be used in cellular respiration in the mithocondrion. Proteins are converted into aminoacids, that can be intermediates to glycolysis or cellular respirations [p.184]

- There is **reversibility** in some of these catabolic pathways: the intermediates of glycolysis and cellular respiration can be used to form glucose (*gluconeogenesis*) and acetyl CoA can be converted into fatty acids or other cell metabolites [p.185].

[32] *Glycolysis* is the beginning of the metabolism of glucose of all cells. It converts glucose into 2 pyruvate molecules (with three carbon each). *Fermentation* is the process that converts pyruvate into lactic acid or ethanol. *Cellular respiration* converts pyruvate into carbon dioxide, first oxidizing the pyruvate and then passing by the citric acid cycle with the energy released by breaking the pyruvate covalent bonds being used to form ATP.

[33] The mitochondrion is the organelle that transforms energy in eukaryotic cells.

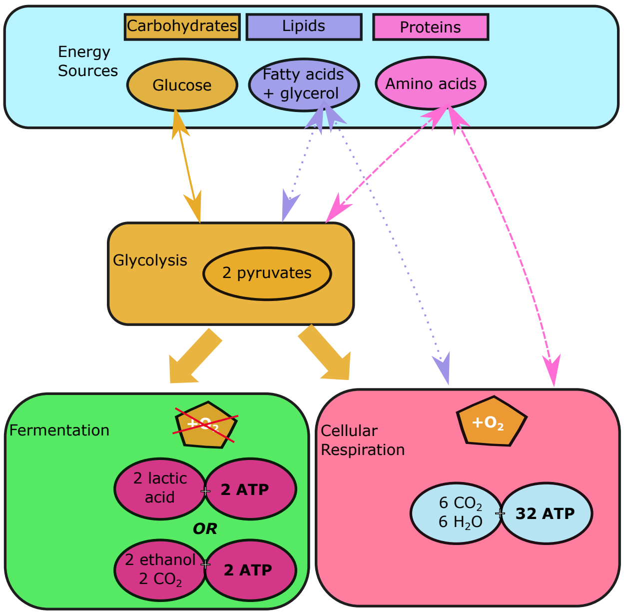


Figure 3.14: The cells metabolic pathways, with the representation of the main energy sources and their use to produce energy.

- These metabolic pathways are regulated systems: if there is no need for producing energy, the energy is stored. The levels of glucose, for example, are remarkably constant in the human body. Enzymes are responsible for this control [p.186].

- *Photosynthesis* is the metabolic process allowing energy of sunlight to be captured and used to convert CO_2 and H_2O into carbohydrates and oxygen. Its equation is the reverse of cellular respiration: $6\,CO_2 + 6\,H_2O \rightarrow C_6H_{12}O_6 + 6\,O_2$ [p.190]. The oxygen formed in this reaction comes from the H_2O molecules. The carbohydrates generated in this process are used to provide energy to the organism.

- "Only 5% of the sunlight that reaches Earth is converted into plant growth" [p.206]

The different metabolic pathways for energy in cells are summarized in Figure 3.14. This search in one general biology book allowed us to understand some basic aspects about energy in nature, summarized in Figure 3.15. Living organisms must obtain their food that is used to produce energy. The energy contained in food molecules is harvested by processes that use oxygen (cellular respiration) and processes that do not use oxygen (fermentation and glycolysis). There are different energy outcomes from these two processes, and some of the reactions used to produce energy can be reversed to produce components able to store energy, which guarantees the regulation of their amounts in the different organisms. Some organisms are able to capture the energy from sunlight and use it to produce their own food (by photosynthesis).

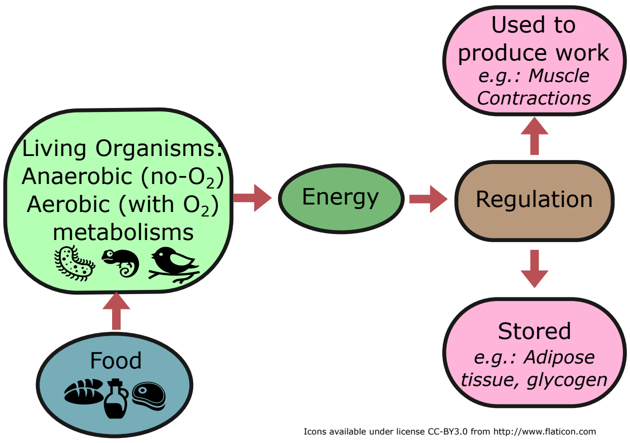


Figure 3.15: Synthetic overview of the main aspects about cells and energy, from the review of Sadava et al. (2011) book

3.4.2.2 Search in a more specific biological knowledge base: human physiology

Using this general knowledge provided by biology books, the next step was to search for more specific examples of energy use in nature. The first biological domain that we explored with a more specific search was **human physiology**. Human physiology is the discipline studying "how the cells and organ systems of the body perform their functions" (Martin, 1995). This choice can be explained by two factors [34]:

1. The proximity of the constraints faced by humans and vehicles (Table 3.3), and also by the facility in finding information about human energy use in scientific and non-scientific knowledge bases. Considering that the researchers in the automobile company and the author of this thesis have a more engineering-oriented background, this choice facilitated the comprehension of the biological phenomena and their relation with the automobile knowledge available.

2. Knowing that human physiology could potentially represent an interesting domain, we have consulted with a biologist, specialized in human physiology and sports performance. This consultation reassured our choice, revealing some interesting analogical and non-analogical systems and functions in human energy systems[35].

[34] An implicit factor that also influenced our choice was the observation that the human body is an example of a "self-optimizing machine", as characterized by Martin (1995) with numerous examples of self regulation and optimization: the adaptation of hemoglobin concentrations in the blood during altitude acclimatization, the changes provoked by training programs such as the increase in muscle mass resulting from strength-training or the increase in the number and size of mithocondria within the muscle cells of distance runners, increasing aerobic outcomes without acidosis.

[35] We collaborated with Professor Véronique Billat from the UBIAE INSERM laboratory (http://billat.net/) from august 2013 until April 2015, during the phase of identification of the biologically inspired concepts and research about the

There are also differences between the human physiology and vehicles energy systems: humans can have their performance restrained by fatigue, while vehicles are not submitted to energetic fatigue (more mechanic-related fatigue of materials, but occurring at relatively larger timescales). These differences will be deeply explored in the sections concerning specific aspects of the cars and human physiology comparison.

Other organisms can also have energy management features that allow them to have outstanding performances. For example, migrating birds are an example of organism have interesting energy management features allowing them to cover very large distances[36].

Table 3.3: An overview of the constraints faced by automobiles and humans, based on general information about human physiology available on scientific and non-scientific knowledge bases.

Domain	*Automobiles*	*Humans*
Energy source / storage	Chemical energy, burned to produce mechanical energy in the engine, stored in the fuel tank and/or Electric energy, stored in an electrochemical battery, and used in the electric motor to produce mechanical energy	Chemical energy, "burned" by aerobic or anaerobic pathways, stored in the muscles or fat tissue, used to produce ATP that can be transformed in mechanical energy in the muscles.
Range of energy stores	Refueling or recharging is required after a certain distance is made with the vehicle	Refueling (eating food) is required after some exercise to keep the vital functions of the human being
Performance	Depends on the engine power, and can be improved by reducing vehicle load factors.	Can be improved with specific training, depending on the desired goal (run a sprint, run a marathon, climb a mountain, do the Ironman). Fatigue can limit performances.

With "human physiology" chosen as the knowledge base for this bio-inspiration process study, the next steps of the research path include the deepening this knowledge and relating it to the automotive domain. This link between these two activities was made with the realization of regular meetings involving the author of this thesis and actors working on the two knowledge bases: the researchers

application of these bio-inspired concepts.

[36]These interesting features of migrating birds are detailed later on this section in the paragraph *Anticipating energy requirements*.

on human physiology (represented by the team of Professor Véronique Billat) and the researchers on the automotive domain (represented by the automobile company experts and the automotive research laboratory (LIVIC) researchers). The different explorations made with this approach and their results are summarized in the next paragraphs.

Two energy pathways: aerobic and anaerobic

Margaria (1972) compare the function of human muscles with the artificial engines (such as the internal combustion engine). Both use fuel combustion to produce its energy, and their performance depends on the fuel and its availability. However, differences are pointed out between these two "engines" (muscles and artificial engines):

> *"In the case of an artificial engine the energy input is easily identified and measured: it is simply the rate of consumption of the supplied fuel. The muscle engine, however, is much more complex. It uses several different fuels, and it regenerates some of them itself"*. (Margaria, 1972).

The energy required for muscle contractions comes from the split of ATP into ADP and phosphoric acid. ATP is available in limited supplies in the cells and must be reformed from ADP and phosphoric acid using other sources of energy, such as phosphocreatine (PCr), glycogen and lipids. The differences between these sources of energy are their rate of ATP production and the amounts of ATP that can be produced. The rate of ATP production is measured in μmol ATP.g^{-1} wet weight.min^{-1}, and the total amounts of ATP in μmol ATP.g^{-1} wet weight. Table 3.4 summarize the main features of each system based on data presented on Hochachka (1985, Table 1), Mc Gilvery (1975, Figure 8) [37] and Williams et al. (2013). This data shows some important aspects of these energetic processes. As previously mentioned, there are processes that do not require oxygen supply (*anaerobic* processes), such as the ATP/PCr and glycogen fermentation, and other processes require oxygen (*aerobic* processes) (cellular respiration, also called oxidative phosphorylation). These processes also differ in their power: anaerobic processes have an ATP turnover (the maximum power) that is sensibly higher than the aerobic processes, although their capacity (i.e. the total energy stored in these systems) is considerably lower.

[37] This author was cited by Hochachka (1985) as its main source for Table 1 presented in his article. We opted to present both sources, as we have taken the data from the tissue supply from Mc Gilvery (1975) Figure 8 data.

Table 3.4: The ATP tissue supply, maximum power and total energy stores in humans, as a function of the energy harvesting processes.

Energy harvesting process	*Tissue Supply* µmol ATP.g^{-1} wet weight (Mc Gilvery, 1975)	*Maximum Power* µmol ATP.g^{-1} wet weight.min^{-1} (Hochachka, 1985)	*Total energy stores in the body* kJ (kcal) (Williams et al., 2013)	Distance covered Running at 100 kcal/mile (262 kJ/km) (Williams et al., 2013)
ATP/ PCr	32	96 to 360	21 (5)	80 m
Glycogen fermentation (with the formation of lactate)	240	60	cf. glycogen stores of oxidation	
Glycogen oxidation in oxidative phosphorylation (*mitochondria*)	3000	30	6 300 (1 500) (liver glycogen) 1 680 (400) (muscles) 88 (20) (serum glucose)	24 km 6 400 m 320 m
Fatty acids oxidation in oxidative phosphorylation (*mitochondria*)	-	20	336 000 (80 000) (adipose tissue triglycerides) 10 500 (2 500) (muscles) 315 (75) (serum triglycerides) 29.2 (7) (serum free fatty acids)	1 280 km 40 km 1200 m 112 m

Human energy combines two types of energy systems: one that has high power and low capacity, and another with low power and high capacity.

A comparison of the energy expenditure of humans and of vehicles could be made at this point. If only the carbohydrate stores were available in the body, they would represent approximately 8 300 kJ of energy stored. Assuming the energy expenditure of 262 kJ/km for the running energy cost [38], or 4 kJ/km/kg for a 70 kg individual, and a total energy store of approximately 8 300 kJ, the total distance that could be made with this energy stores would be 30 kilometers. An automobile equipped with an internal combustion engine using gasoline as a fuel, emitting 130 gCO_2/km [39] has an NEDC fuel consumption of approximately 5.5 L/100km [40], or 1.5 kJ/km/kg for a 1200 kg gasoline automobile. Considering that the fuel tank capacity of a vehicle is of approximately 50 liters, the total distance is approximately of 800 kilometers.

[38] Which corresponds to 100 kcal/mile as suggested by Williams et al. (2013, p.95) for a mean energy expenditure for running.

[39] The average emissions target as specified in the European regulation n443/2009 for the year 2015.

[40] According to Reif and Dietsche (2014), 1 L/100 km in a ICEV using a spark-ignition engine powered by gasoline (respecting the Euro 5 standards) is equivalent to 23.4 gCO2/km.

Humans have essentially two metabolic pathways, or energy systems, one that uses oxygen with high energy stores but lower power, and another one that does not use oxygen and that has high power but relies on energy sources with lower energy stores available. This system is similar to those of hybrid vehicles, which have two energy sources with different properties (the internal combustion engine relies on fossil fuels with high power and high specific energy (energy per volume unit of fuel); while the electric motor relies on the chemical energy stored in the battery (which has lower energy density than fossil fuels).

Hybrid vehicles also have different drive-train architectures. The differences between these architecture come essentially from the propulsion type: both engines can realize it independently (parallel-HEV) or the engines can share the same shaft (series-HEV) or a combination of the two previous architectures (series-parallel-HEV) [41]. Hybrid vehicles also have energy management systems, control systems designed to choose which energy source (or a combination of energy sources) will be used, based on fuel economy or other operational considerations [42]. In the search for knowledge about energy in human systems to improve vehicle systems, now that each energy system is better understood, the energy management strategies are another important part of the construction of a knowledge base that can revise the knowledge about automobiles.

The activation of the different energy pathways during exercise

According to the literature review of Gastin (2001) there are two misconceptions of the interaction and relative contribution of energy systems during maximal exercise. The first one is the idea that energy systems act in a sequential manner during maximal exercise, i.e. one responds when the other stops responding to the energetic demand and the second that the response of the aerobic system is slower when compared to the anaerobic systems (ATP/PCr and nonaerobic breakdown of carbohydrate into lactic acid). In fact, this review of literature studies reveal that all the 3 energy systems (aerobic, anaerobic alactic (ATP/PCr) and anaerobic lactic) respond to exercise intensity increase, and that the sequence exists but with an overlapping between systems:

> *"It now seems evident that all 3 energy systems make a contribution to the energy supply during sprinting, even during efforts as short as 6 seconds"*[p.731] [...] *Together the 3 systems appear well suited to cope with the high, often sustained and usually diverse energy demands placed on them during daily and sporting activities*[p.738] (Gastin,

[41] A review of hybrid vehicles architectures is given in Tie and Tan (2013).

[42] Tie and Tan (2013); Desai and Williamson (2009) are examples of articles proposing a review of hybrid energy management strategies currently used in hybrid vehicles.

2001).

The contribution of each system is quantified in different ways. For the aerobic energy system it is directly related to the **oxygen uptake** ($\dot{V}O_2$), described in Box 3.3. For the anaerobic system, direct measures are more difficult as the detection of ATP and PCr concentration may be measured by muscle biopsy or measures of lactate concentration in the blood.

Box 3.3: Oxygen Uptake ($\dot{V}O_2$) and maximum oxygen uptake ($\dot{V}O_2max$)

The oxygen uptake measures the amount of oxygen consumed by an individual. This measure corresponds to the amount of oxygen that enters the blood circulation (Billat, 2012, p.80). However, muscles cannot increase the oxygen consumption indefinitely. There is a maximum amount, noted $\dot{V}O_2max$, that can be consumed by the muscles (Wagner, 1996). According to (Levine, 2008), this maximum amount is limited by the cardiac output. Although the existence of this maximum oxygen uptake at increasing running speed has been contested, it is a notion that is widely used in human physiology, namely for endurance sports. In this kind of sports, the average speed corresponds to the percentage of the speed at the maximum oxygen uptake ($v\dot{V}O_2max$), for example, a 5000 m is ran at 94% of the speed associated to the maximum oxygen uptake ($v\dot{V}O_2max$) (Billat, 2012, p.150). The oxygen uptake is calculated according to the following equation:

$$\dot{V}O_2 = SV \times HR \times [CaO_2 - CvO_2]$$

where SV is the stroke volume, the volume of blood pumped in one heart beat (L/beat), HR is the heart rate (beats/min) and $[CaO_2 - CvO_2]$ is the difference between the arterial ($[CaO_2]$) and the venous ($[CvO_2]$) oxygen content.
This value is related to the endurance performance of individuals, and there are works aimed at proving that it can be improved by training (Williams et al., 2013, p.135) and also during the exercise (Billat, 2013).

Limits to the use of the different energy systems

When an exercise is made at a constant power output, P, there is an exhaustion time t_{lim}. The relationship between the work performed at exhaustion, W_{lim}, and the exhaustion time is linear (Eq. 3.7), with the slope being a power output that can be sustained during a long time, called the critical power (CP) (related to the rate of the aerobic work that can be made) and the linear intercept, an anaerobic work capacity (AWC), related to the amounts of energy that can be mobilized by the anaerobic system (Vandewalle et al., 1997; Morton, 2006). The link between these parameters and the two energy systems

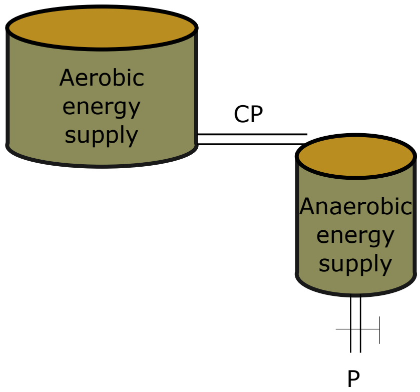


Figure 3.16: The hydraulic model of the critical power model, in its most simple representation. The aerobic energy supply is considered to be infinite and the communication between this energy supply and the anaerobic energy supply limited by the CP (critical power). When the power output required P becomes larger than CP, the level of the anaerobic energy supply drops, and the exercise cannot continue if the anaerobic energy supply is empty (Morton, 2006).

was verified experimentally (Morton, 2006). This model can be conceptualized as a hydraulic model, with a vessel representing each system (aerobic and anaerobic). These two vessels are connected and have different capacities and discharge rates, as represented in Figure 3.16[43].

Morton and Billat (2004) showed that, during intermittent exercise, i.e. exercise that alternates periods of intense work and periods of rest, there is a refiling in the anaerobic capacity by the aerobic capacity.

$$W_{lim} = AWC + CP \times t_{lim} \tag{3.7}$$

The energy systems have different characteristics, and examining the energetic cost of the exercise itself can bring some insight into how humans use the energy produced by these energy systems and convert them into work. This means that it is interesting to analyze the energetic cost of the exercise, i.e., which is best in terms of energy consumption? Walking or running? This is the central question of the 1984 article of Alexander (1984), which tests the hypothesis that “people adjust their gaits as so to keep energy costs as low as possible”, and show that the change from walking to running occurs when a certain speed is reached to ensure the use of the lowest energy consuming gait. For humans, this speed was estimated to be around 2.3 $m.s^{-1}$ (8.28 $km.h^{-1}$). In the same article, Alexander

[43]Figure 3.16 represent the idea of the hydraulic model, however other representations of this model, including other vessels and hypothesis allowing to better represent the energy supply model have been proposed, such as the addition of a third vessel, representing the lactic anaerobic metabolism (Morton, 2006, figs. 4 and 5)

describes the elastic mechanisms involved in running, which are responsible for reducing the running energy costs: "the mechanism is like of a bouncing ball, which converts kinetic energy to elastic-strain energy as it deforms on hitting the ground, and which then makes the reverse conversion as it recoils and leaves the ground again". The tissues linked to these elastic movements are the leg muscles and tendons [44].

The energy cost of locomotion depends on the pattern (walking, running, cycling, etc.). Changes from one mode to another occur in order to "keep the energy costs as low as possible". Elastic movements are used to reduce the energy costs of running.

Methods for improving performance

The characterization of a winner athlete varies according to the sport activity, but all athletes aim at improving their "performances". For a runner, a cyclist or even a swimmer, a performance improvement means being able to finish the race (a given distance) using the less amount of time possible. As described previously in this section, all the energy stores of the body are not unlimited and are used in different proportions according to the effort required. This implies that finishing a race as quickly as possible also requires an energy management system that allows the athlete to complete his activity, and that is sufficiently optimized to use all the energy system that is more appropriate to the effort solicitation. A sprinter may use all its energy sources to complete a 100 m as quickly as possible, but he has to use in a more efficient way its reserves to finish before its competitors.

For the low carbon vehicle, the performance is not only related to the capacity of the vehicle to achieve a certain power requirement (reach a certain speed), but also to the capacity of making the largest distance as possible with the lowest energy consumption. The answer to this question is also an optimized energy management system, that allows using less fuel for each distance unit made with the vehicle. Even if the low carbon vehicle performance and athletes performance are not exactly equal in nature, they are both related to the energy consumption and management.

There are specific training methods developed for each kind of exercise, and our aim was not to review all the possible training methods, but to identify strategies that are interesting in the light of our knowledge about how cars work. Besides interval training, that is proven to be efficient to improve performance and that is interesting because of the refilling systems, there is another aspect identified by Wesfreid et al. (2005) and Billat et al. (2009) that can be particularly relevant, as it implies that an

[44] Tendons can be defined as the connective tissues that "attach the muscles to the bones", while ligaments are connective tissues that hold bones together at the kneel joint, for example (Sadava et al., 2011).

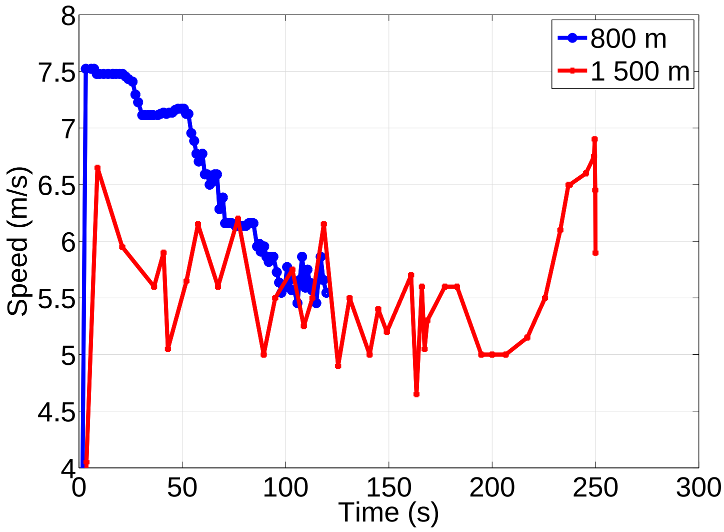


Figure 3.17: A comparison between the speed profiles recorded for 800 m and 1 500 m races, according to data presented for subject 4 on figure 1 of (Billat et al., 2009) article and author own calculations.

energetic optimization during exercise is possible.

In Wesfreid et al. (2005), runners were asked to run a 10 000 m first without any particular protocol, and then, using their running times, the mean running speed of each runner was calculated and they had to run another 10 000 m at the same constant speed. These researchers remarked that some physiological constants, such as heart rate, did increase before 7 000 m, and the runners had difficulties to finish the race (Billat, 2012, p.45).

Billat et al. (2009) showed that the speed variations observed during a race is controlled by the state of the anaerobic reserves. A 800 m is then ran with speed constantly decreasing (a long sprint) with the first 200 m ran with a strong acceleration. A 1 500 m, on the contrary, has a speed variation, with an increase on speed at the final 100m of the run. The speed variation range of a 1 500 m was of 7.5 ± 2.3 m.s^{-1}. Figure 3.17 shows the results obtained for each case.

Energy consumption is related to the improvement of athletes performances. The speed variations could be a means to better manage the anaerobic reserves during courses covering larger distances than 800 m, and allow better running performances.

Adaptations for anticipating energy requirements

Guglielmo (2010) explains in his paper about the use of fatty acids by migrating birds that some species of migrating birds have quite interesting capabilities of endurance, thanks to the use of fats as the main energy storage:

> *Recent satellite telemetry shows that this species can fly for as long as nine days without food or water, traveling as far as 11,000 km [...]. This is a phenomenal feat of endurance, navigation, and sleep deprivation, and we must wonder how they possibly budget all of the fuel (fat and protein) and water for such a journey.* (Guglielmo, 2010).

Weber (2009) points out that these migrating birds have interesting adaptations that take place before the start of the migration period:

> *Animal migrants further decrease the cost of transport by minimizing body mass. They do so by selecting lipids to store energy for muscle work and temporarily atrophy non-essential organs.* (Weber, 2009)

Adaptations for anticipating energy needs were also observed in humans. Newsholme and Leech (2010) describe how a "substrate cycle" (usually called *"futile cycle"*), such as the fructose 6-phosphate is converted to fructose biphosphate in muscle before and during sprinting. When preparing a sprint, passing from rest to the starting blocks and then running, hormones can increase the activity of the enzymes, catalyzing both forward and reverse reactions in a cycle, preparing the body for the required increased ATP production during the sprint.

There are also the adaptations for resisting changes in environmental conditions, such as those of hibernating mammals: metabolism and body temperature are reduced (approximately to 1% of the normal rates and reaching values of -3.0°C, respectively), heart rate and respiration are also reduced. These adaptations allow hibernating mammals to survive up to 8 months only using the energy stores in their bodies (Carey et al., 2003)[45].

Anticipating energy requirements involve changes in the animal's body and energy reserves. The metabolism can also change to face periods of environmental changes, as in hibernating animals.

[45] Wang and Lee (2010) also propose a detailed review about the hibernation phenomena in mammals.

3.4.3 Expansions in both knowledge bases: automobile (traditional) and biological (human physiology)

The activation of the biological knowledge about human physiology allowed us to identify some aspects that could be worth deepening, considering the knowledge about energy in automobiles. In C–K theory, this process of activation of knowledge on the knowledge space are characterized as K $\rightarrow$ K operators. The aspects of human physiology shown in Section 3.4.2.2, pointed out the following directions for knowledge about automobiles expansion and revision:

- Humans can use different types of subtracts to produce energy. This energy is then converted to a unique energy currency, the ATP, which can be used to provide energy to different processes in the body, including muscle contraction. There is the possibility of "regeneration" or "recovery" during or after exercise, using one source to recover the other. In vehicles, the recovery is possible when breaking (with the regenerative braking). There are vehicles able to produce energy using different sources of energy, such as hybrid vehicles or vehicles equipped with "flex engines". Hybrid and pure electric vehicles can recover energy during braking phases.

- Elastic energy is used in the body as a means of storing some amounts of kinetic energy and releasing it in the next movement. This kind of "short" recovery has no analogue in the actual vehicles.

- Speed variations may contribute to a better performance of runners over large distances (above 1500 meters or even a marathon). The use of speed variations in vehicles could also produce fuel consumption savings.

- Anticipation of energy expenditure occurs in different animals, from migrating birds to humans. Anticipation helps these organisms to respond in a better way to the different solicitations, including large distances to cover without refueling or an important energy production. Animals that face a large period without food, such as hibernating animals, also display adaptations. Anticipation of energy requirements could benefit multi-energy vehicles management systems (such as those of hybrid vehicles), making them able to choose the best energy systems for a solicitation.

The next sections explore each of these directions, showing the activation of traditional knowledge bases they provoked and the "unexpected" knowledge bases the biological knowledge activated during this process.

3.4.3.1 Hybrid vehicles and humans - “bio-inspired range-extender”

The two metabolic pathways existing in human cells to produce energy, anaerobic and aerobic, have some similarities with the energy pathways existing in hybrid electric vehicles. These vehicles combine two powertrains, electric (with the electric motor and electrochemical battery) and thermal (with the internal combustion engine and the fuel tank). These two powertrains can be associated in series or in parallel to produce energy (Chan, 2007):

- Series: When combined in series, the electric motor is the final mechanical energy producer, with electric energy coming from the generator moved by the internal combustion engine.
- Parallel: Both powertrains (internal combustion engine + fuel tank and electric motor + battery) can be used to produce mechanical energy to propel the vehicle wheels.
- Series-Parallel: in this configuration, both powertrains can generate power to the wheels (like a parallel hybrid), but there is the possibility of regenerating power to the battery using the internal combustion engine and a generator.
- Complex: in a complex hybrid, the generator can also act as another electrical motor, which can also be used for propulsion.

The final energy currency in hybrid vehicles is the mechanical energy transmitted to the wheels, i.e. both energetic pathways, thermal or electrical, produce mechanical energy that can be transferred to the wheels. The thermal pathway can also be used to produce electrical energy that will be used for producing mechanical energy. This is the case in the series-HEV.

In the human body, the mechanical energy of the muscles comes from the energy stored in ATP molecules, which can come from aerobic or anaerobic pathways that use different fuels. Parallel, series-parallel or complex hybrids seems more similar to the functioning of the cells metabolism, as both metabolisms, anaerobic and aerobic can be used to produce ATP and mechanical energy. The human metabolism and the conventional and hybrid architectures are shown in Figure 3.18.

Moreover, the capacity and power of both systems (electric and thermal) are different: while the thermal source is relatively not limited in capacity (having an energy density of approximately 9500

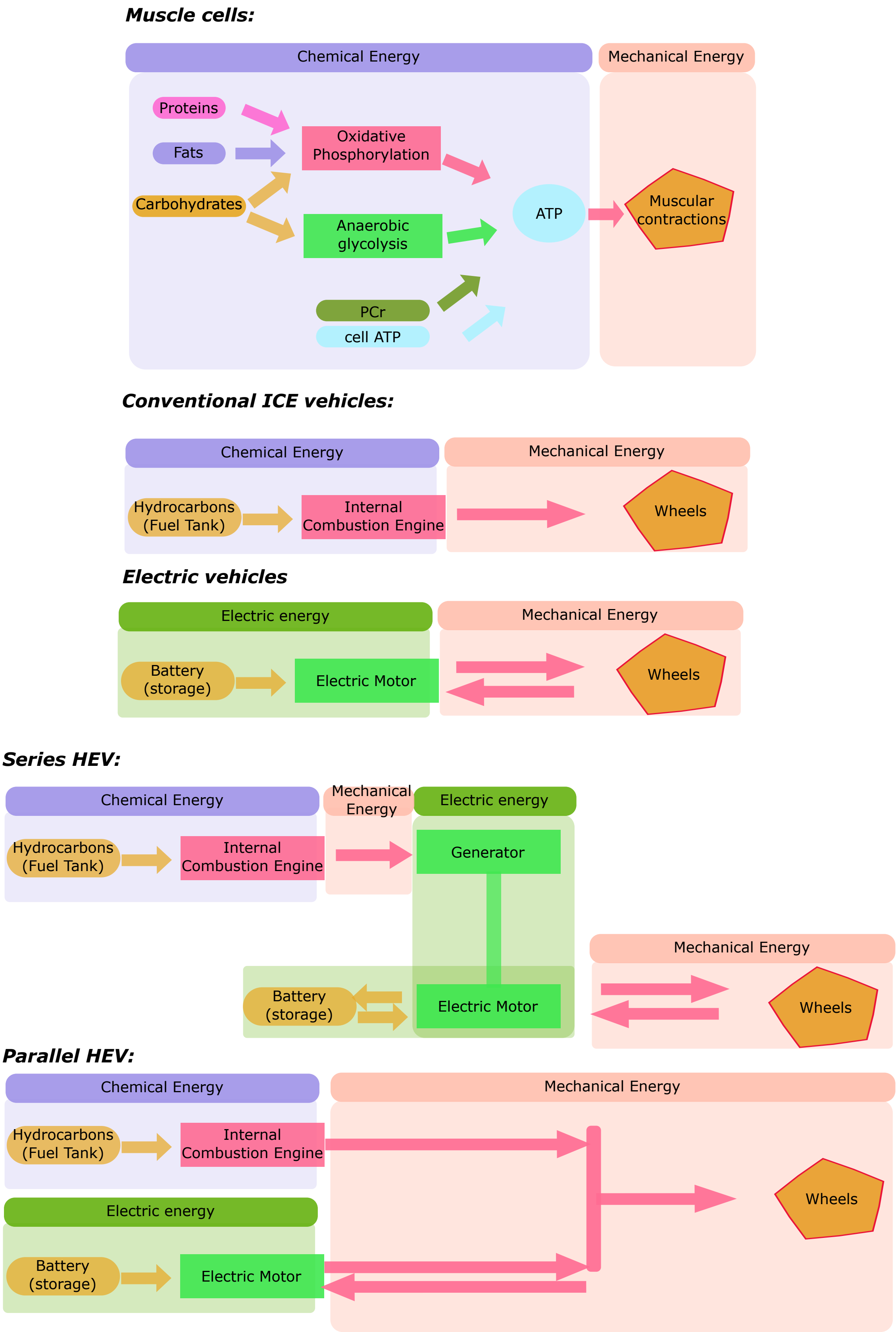


Figure 3.18: Human and vehicle energy systems and the energy types involved - adapted from Williams et al. (2013) and Badin (2013)

$Wh.L^{-1}$ [(46)]), the electrochemical battery (electric motor energy source) has a considerably lower capacity (200-400 $Wh.L^{-1}$ [(47)]). The power of the electric motor is similar to the power of an internal combustion engine, with the difference that the efficiency of the electric motor can be superior to 70% while the internal combustion engine is not superior to 40%.

This limitation in capacity of the sources used for each metabolism is also found in the human metabolism (aerobic metabolisms are limited in power and not in capacity, while anaerobic metabolisms are limited in capacity but not in power).

The critical power model states that there is a critical power that could be sustained using the aerobic system (not limited in capacity) indefinitely, while the anaerobic power is limited by the capacity of the energetic system. When the anaerobic capacity is lower, the part of the energy coming from the aerobic system increases. There is a type of hybrid vehicle that has a quite similar working principle: the primary source of energy is the electricity stored in the battery, however, the battery capacity is generally limited, and the internal combustion engine associated to the electrical powertrain can be used to extend the range of the hybrid vehicle, using a series architecture (with a generator) that can allow the vehicle to make some extra kilometers until a charging point, or to work with full performance by using a larger generator coupled to the internal combustion engine to produce electricity for the electric motor (Badin, 2013, p.340). These hybrid vehicles are called "range-extender hybrid electric vehicles".

This parallel between range extender hybrid vehicles and the two different metabolisms found in human muscular cells could be worth exploring, mainly to improve the energy management strategy applied in hybrid vehicles. These energy management strategies are currently of two types: rule-based (heuristics) or optimization. In the first case, rule-based energy management strategies, include methods classified as deterministic (thermostat - on/off; power follower or state machine control strategies) or as fuzzy (conventional fuzzy strategy or fuzzy adaptive or predictive) (Desai and Williamson, 2009). These strategies are known to be less flexible, because they are based on fixed control operations normally defined for specific operating conditions (Sciarretta, 2013, p.392). In the second case, optimization strategies, an evaluation criteria is defined and global optimization techniques such as linear programming or genetic algorithms are used. Real-time optimization, such as equivalent fuel consumption minimization (ECMS) (Paganelli et al., 2002) or optimal predictive control [48]. There

[46] Values extracted from Table 4 of Tie and Tan (2013)

[47] Values extracted from Table 4 of Tie and Tan (2013)

[48] For a more complete review of hybrid energy management strategies see the articles of Desai and Williamson (2009); Tie and Tan (2013); Sciarretta (2013).

are currently studies developed for improving human running performance that attempt to use similar control concepts to better understand and thus improve the performance of the different energy systems in humans. For example, Bonnans and Aftalion (2013), based on the observations of speed variations made by Billat et al. (2009), used optimal control theory to predict the optimal speed variation pattern considering the anaerobic and aerobic reserves and the possibility of recreating anaerobic energy during deceleration.

This concept could be deepened, with a more complete comparison between the roles of the two energy sources and their interventions during exercise, compared to simulations or experimental results in a hybrid vehicle. These comparisons will have different results depending on the type of hybrid vehicle that is used and the type of energy management strategy they use. Our hypothesis is that the study of the human energy management strategy may lead hybrid energy management strategies to include other terms that are possibly not taken into account in the current systems. For example, the anaerobic system, which has high power and low capacity, has similar properties as those of supercapacitors. These energy storage systems are used for high power operations. They can be used in the so-called hybrid storage systems, supplying power during high power needs, while the battery is used for energy supply in the other operating conditions. Energy management strategies for this kind of hybrid vehicles, combining batteries and supercapacitors are currently being studied (Vinot and Trigui, 2013), and other type of energy storage systems and their energy management systems could be worth studying in the light of what is done in the human body energy storage and production systems. This shows that the study of the human energetic system could also bring some insights into the design of new architecture of the different components (engines, energy storage systems or energy converters).

The two metabolic pathways of the human system and their working principles can be compared to a hybrid vehicle, namely the range extender hybrid vehicles, as the amounts of energy coming from each energy system depends on the state of the reserves and one energy source can be used to regenerate the other. Hybrid vehicles energy management strategies could benefit from the study of the energy management used by athletes during exercise. There are currently studies using optimization and control techniques to explain the energy management system of athletes, using the same mathematical techniques as those of hybrid vehicles energy management systems. The components of humans' energy system and their characteristics could also be used to conceive potentially new and optimized architectures for hybrid vehicles.

3.4.3.2 Anticipating energy requirements - "bio-inspired engine design"

The search on biological knowledge indicated that humans and other animals anticipate energy requirements with the help of *futile cycles* or with changes in the energy stores (using fats instead of carbohydrates to store energy in the case of migrating birds). These two kinds of adaptations led us to examine whether there were other types of adaptations. For example, we know that athletes from different sport modalities have different body constitutions. Figure 3.19, compare the bodies from sprinters and marathoners. While sprinters have larger muscles, marathoners are thinner and have relatively less massive muscles. These differences in body constitution specialize these runners, making them more adapted for a type of exercise. Automobiles also present different constitutions that allow them serving different purposes: economy cars, family cars, sedans, etc.

In literature about human physiology, the efficiency of muscles, i.e. the amount of energy coming from energy stores that is converted into muscle contraction is estimated to be around 30% and the gross efficiency, i.e. the efficiency considering the whole body and the output work effectively produced is even lower (Schenau and Cavanagh, 1990). These values are similar to the values of the efficiency found on internal combustion engines. Humans and automobiles can perform in different situations: humans can make a sprint, a marathon, a cycling competition; automobiles can run on urban, extra-urban and even on speed competitions. One of the factors that can explain these different performances of humans in exercises with different energetic and power requirements is the muscle constitution. Human muscles have three types of fibers:

- The Type I or slow-twitch red fibers, which have higher mitochondria concentrations, are associated with activities requiring the use of the aerobic metabolism.
- The Type IIa or fast-twitch red fibers, have a lower aerobic capacity than the type I fibers, but can also produce energy via the anaerobic lactic energy system.
- The Type IIb also known as twitch white fiber or fast glycolytic fiber, it has high ATP-PCr capacity.

For a person that practice no sports activity, all fibers are encountered at almost the same amount (47-53% of both types, according to (Billat, 2012, p.64, tableau10). However, according to the type of sports activity they practice, the composition of the muscles fibers may vary. Sprinters, requiring large amounts of energy in a very short time, have a greater concentration of Type IIb fibers (55-75%).The long distance runners (> 5000 m) have more type I fibers (60-90%). These differences

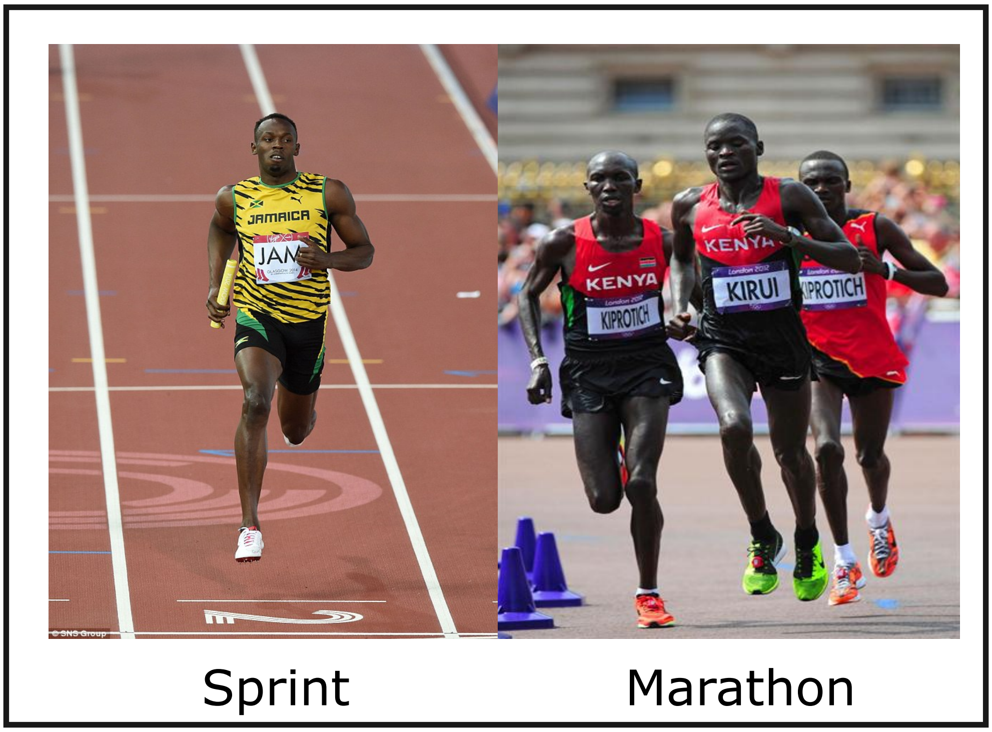


Figure 3.19: Comparison of bodies of sprinters and marathoners: the sprinters have more muscular mass, while marathoners are skinnier.

can be observed when comparing the athletes bodies (Figure 3.19). Training may help changing the muscle typology, as suggested by Powers et al. (1990).

An automobile engine can produce different power outputs depending on the vehicle needs, allowing vehicles to perform in different conditions. However, the observation of the futile cycles on one hand and of the capability of specializing the muscles in one type of activity on the other hand, can bring some insights into vehicles engine specifications design and anticipation of energy requirements for more efficient engine use.

For example, the speed profiles of vehicles can be predicted using traffic simulation models and the vehicle energy management system of a hybrid vehicle can use this data to choose the best energy source, and engine operating points to be used according to the vehicle present and future energy requirements. An example of this approach is shown by He et al. (2012): the combination of the prediction of speed profiles and hybrid vehicles allowed a decrease of 3% in total energy consumption. This is only one example of the interaction between the anticipation of energy requirements and the use of the most adapted energy sources.

Human muscle types are more suited for a determined type of energetic performance (aerobic, anaerobic (PCr), anaerobic (lactate). Depending on the activity (sprinter, marathoner, swimmer, etc) the composition of the muscles fibers is different according to the energy requirement, and futile cycles allow athletes to anticipate energy requirements. Vehicle engines could also benefit from a design more adapted to the real use conditions they actually face, by combining different engines with different characteristics, and anticipation of speed profiles.

3.4.3.3 Elastic energy and vehicles - "bio-inspired elastic energy recovery"

Energy recovery in vehicles is not a new concept. There are different types of energy that are used and produced in vehicles and that can be recovered. Engine exhaust gas heat can be recovered using technologies such as thermoelectric generators (TEG), organic Rankine cycle (ORC), six-stroke internal combustion engine cycle and turbocharger technologies (Saidur et al., 2012). In these cases, heat energy is used to produce electrical or extra mechanical work. Heat energy dissipated at the brakes can be recovered, using an electric motor (used as a generator that produces a negative torque that helps slowing the vehicle and generates electric energy that can be stored and used in the vehicle). The use of electric motors as generators to recover energy during braking phases is called "*regenerative braking*" in literature. The concept of recovering energy with the electric motors appeared in the early 1920s, with one of the first quantitative studies for electric vehicles being made at the 1960s:

- **In railways/trains**: "*Electricity recovering from electric traction lines*" – (Scientific American, 1918) – "resistance braking, when the current generated by the motor is absorbed by resistance on the vehicle, regenerative braking when the current is returned to the supply system and combinations of the two methods". "*Regenerative braking on trains*" – (Nature, 1932) – "in regenerative braking, when the electric tram or train is going downhill, its own momentum drives the motors of the car as dynamos, thus absorbing energy and acting like a mechanical brake. It also converts the gravitational potential energy into electrical energy which is restored to the line, helping the power station".

- **In electric trucks**: "*Electric truck with regenerative braking*"– (Scientific American, 1920),

- **In electric cars - quantitative study**: "*Energy recovery incentive for regenerative braking*" – "does the amount of recovered energy offer sufficient incentive to warrant the increased complexity and cost of regenerative braking?" (Campbell and Hunsberger, 1962).

Current electric and hybrid electric vehicle use regenerative braking technology to recover braking energy and thus to reduce the electric energy consumption. However, braking energy could also be recovered in a "mechanical" form, using springs for storing energy for example. This kind of energy storage and restitution has not yet received great attention because of the energy storage limitations of mechanical storage devices, when compared to electrochemical or chemical energy storage (batteries, liquid hydrocarbons) (Direnzi, 2011).

A comprehensive historical review of the use of mechanical energy was made in the thesis of Direnzi (2011). This review shows that, the first patents of the use of mechanical energy to propel the vehicle were in fact attempts to use only the mechanical energy for propulsion, with the operator compressing and releasing a spring mechanism. In 1938, however, Kromer proposed a concept involving the recovery of braking energy using coil springs and a tank with compressed air to ease the engine, using the stored kinetic energy to propel the shaft during start phases. Years later in 1979, a patent by Stephen Jayner this time involving elastomeric materials to harvest energy, but with the same objective of harvesting kinetic energy during braking phases and using it during engine starting phases. The use of elastomers for recovering energy was more deeply studied by Lionel Hoppie in the period of 1981-1985, although not arriving to a market introduction. Other studies continued with investigations on the use of elastomeric energy storage systems, even concluding that "that fuel consumption could be drastically reduced and warranted further research by automotive manufacturers".

More recently, Tchobansky et al. (2003) proposed a spring coupled to the transmission of a hybrid electric vehicle, achieving gains during stop and go situations. And the system proposed in the research of Direnzi is a converter of "wasted mechanical energy at a vehicle's shock absorbers into stored strain energy".

Besides, the *"Hybrid Air"* technology developed by Peugeot-Citroën company (PSA Peugeot Citroën, 2013) can be considered as a means of storing elastic energy: braking and deceleration phases are used to compress the air, which can be then used to drive the vehicle during acceleration. The vehicle also has an ICE engine which can be used for propelling the vehicle.

This literature review about energy recovery in vehicles shows that many alternatives exist and have already been tested for recovering energy in vehicles, although most of these alternatives have never been truly incorporated into a commercially available automobile. These alternatives include recovering heat from exhaust gases, kinetic energy in braking phases using an electric generator/motor, or mechanical energy using metal or elastomeric springs coupled to the transmissions or shaft, recovering kinetic energy from shock absorbers or from braking phases. In this case, the use of elastic energy made by humans and other animals such as kangaroos (Dawson and Taylor, 1973; Farley et al., 1993), showing that elastic energy is one of the ways used by nature to reduce the energy cost of locomotion opens the way for other studies pointing in the direction of a punctual storage of mechanical energy, that could be easily released to help the next energy requirement of the vehicle, such as the acceleration that occur after braking phases.

Elastic energy storage, as made by human tendons and other animals, could be an alternative to improve existing systems of regenerative braking in cars, using mechanical energy storage instead of electricity or heat energy.

3.4.3.4 Energy recovery during exercise - "bio-inspired energy saving"

Speed variations are spontaneously chosen by athletes in races longer than 1 500 m (Billat et al., 2009). These authors also showed that these speed variations are linked to the state of the anaerobic reserves: these speed variations allow the time to exhaustion to remain constant, allowing the runner to run the first 70% of the race without reaching extreme fatigue levels until the final 30% where a sprint is made. This implies that the athletes can improve their performances not only by training, but also during the race, by using the speed variations.

In conventional internal combustion engine vehicles, the notion of fatigue does not exist, the limitation for vehicle performance is the performance that can be delivered by the engine and the amount of fuel remaining at the fuel tank. In order to achieve lower CO_2 emissions, there is a constraint on the amounts of fuel that can be consumed. The question, based on the observations of the effects of speed variations spontaneously chosen by runners, would be whether a conventional vehicle using speed variations could reduce its fuel consumption. The fact that accelerations may allow reaching greater load zones of the engine that have a better efficiency, may be worth exploring in these speed variations.

This aspect is particularly interesting, the analogy being quite simple: the same principle of runners applied to vehicles can produce fuel consumption savings? Besides, it does not require great modifications on the architecture or vehicle control systems, and can be easily tested with an equipped vehicle in a test track or a real road. Considering these practical aspects and the possibility of easily testing the concept in experimental conditions even for a conventional internal combustion engine vehicle, the speed variations are the concept chosen for a more detailed exploration that will be detailed in Chapter 4. This will allow us to understand whether they could benefit cars as they benefit runners and also to better evaluate real-life conditions that would make possible for speed variations to reduce fuel consumption. The other three previous concepts can be used for further research, but this work did not fully explore them.

Speed variations are chosen by the runner in order to make the time to exhaustion at anaerobic power to remain constant, allowing a performance improvement during the race. Vehicles could benefit from speed variations to reduce fuel consumption during their use phase.

3.5 Conclusions: potential paths for bio-inspired concepts exploration

In this chapter, we have explored two knowledge bases, the automotive knowledge base and the biological knowledge base. This double exploration did not start simultaneously. It was guided by the process described in the previous chapter: first we have identified, in the automotive knowledge base, more specifically on the knowledge about the innovation field of the low carbon vehicle, which would be the paths that we wanted to explore using biological inspiration. The path we have chosen: improving energy use in the vehicle during the use phase, acting on energy transformations (the engine, energy recovery and reuse) was an opportunity to apply bio-inspiration to an unusual field, as most of the attempts of using biological inspiration for automobiles involved materials, vehicle aerodynamics, design optimization of parts and sensors.

The choice of this design path in the innovation field of the low carbon vehicle led us to a first search in general biological textbooks about "energy in nature" (as suggested by the natural-language approach developed by Shu (2010)). This initial search allowed us to identify the human physiology as a potentially interesting knowledge base, as it had many aspects of the energetic problems studied for human health and sports practice. We have also started a collaboration with a human physiologist, which helped us to have an access and establish a more concrete dialog with the biological field. This dialog led us to identify at least 4 concepts, involving the nature of the energy storage and transformations occurring in the human body. These concepts have the potential to be developed using further research, and we have chosen one of these concepts, speed variations to improve performance, in order to evaluate whether a reduction in emissions and fuel consumption is possible. This opens the way for the next chapter that will develop this last question.

This application to the low carbon vehicle innovation field shows the complexity of the bio-inspired design process: the interesting concepts were not “ready-to-use” for cars emissions reduction. They required a certain amount of knowledge acquisition and exploration in both fields, automotive engineering and biology. This knowledge acquisition took place using the usual methods (search in textbooks, scientific articles), but also during the meetings organized between the author of this thesis, the engineers and the physiologist. This chapter is the result of the knowledge acquisition and concepts formulation process. The variety of research approaches and vocabulary used in these two domains could be an obstacle to achieving this goal. The collaboration between engineers and the human physiology researcher enabled by the process described in this chapter was essential to overcome these difficulties and to allow the identification of bio-inspired concepts.

Chapter 4

Modeling and experimental validation of the bioinspired concept of speed variations

HIGHLIGHTS

- A **theoretical model** for fuel consumption of passenger cars using internal combustion engines
- The **results** of experimental tests on a test track

Chapter contents

One of the bio-inspired concepts identified by the biologically inspired design approach used in this thesis is the use of speed variations to save energy when the vehicle is in use. This chapter proposes a theoretical model for evaluating the effects of the speed variations on vehicles fuel consumption. This theoretical model is based on vehicle longitudinal dynamics and vehicle engine maps. The theoretical model allowed a better understanding of the conditions for reducing fuel consumption and CO_2 emissions. These conditions are experimentally evaluated using an internal combustion engine vehicle and a dedicated test track. These tests confirm the possibility indicated by the theoretical model that a reduction in fuel consumption is possible under specific conditions of speed variations.

4.1 Introduction

Billat et al. (2009) observed that for 1,500 m races, runners choose a speed variation pattern (Figure 3.17). This speed variation pattern allowed runners to finish these races without reaching extreme fatigue levels. Bonnans and Aftalion (2013), based on these observations, modeled the human energetic system in order to show that varying speed allowed the runner to “run longer”: considering the possibility of recreating anaerobic energy during decelerations, the optimal speed developed by the runner is a speed variation pattern, that allow a fastest run for a given distance.

This property found in human physiology allows a better performance of the athlete (that runs faster). It optimizes the use of the anaerobic system, which influences the fatigue system. This anaerobic system has large power but also has limited capacity[1]. Reducing emissions produced by vehicles implies finding strategies ensuring a longer lifetime for the energy sources[2]. This extended lifetime could be the result of a lower or a more efficient energy consumption. As the effect provoking this energetic optimization in runners seems to be speed variations, the evaluation of the effects of speed variations on fuel consumption and emissions of passenger cars are an interesting bio-inspired concept to study.

This evaluation encompasses different steps. First, it is important to verify whether the speed variations concept is already applied in the automotive field, which is the object of Section 4.2, and to compare the existing knowledge of automotive engineering to biological knowledge about speed variations, detailed in Section 4.3. Section 4.4.1 defines the research approach used to evaluate the application of speed variations to a conventional car. Section 4.4.2 presents the theoretical modeling

[1]See Section 3.4.2.2 for a detailed explanation about human energetic systems and their characteristics.

[2]In other words, when an energy source is less consumed, it lasts longer.

of the vehicle powertrain. This model aims at better understanding the benefits and defining which strategy of speed variation would be appropriate. Section 4.4.3 details the experimental evaluation of the phenomenon using conventional vehicles, such as internal combustion engine vehicles.

4.2 Literature review of speed variations applied in automobiles

Speed variations during a trip is an idea already explored in some literature and practical examples. Here some of the main applications described in scientific literature of this concept to vehicles are analyzed. There are also some authors that describe constant speed as a strategy to minimize fuel consumption.

The examples analyzed in this section provide the theoretical basis for the discussion about the modeling and experimental results described in this chapter.

Constant speed has been claimed as the best alternative to minimize fuel consumption

The work of Chang and Morlok (Chang and Morlok, 2005), provide a deductive approach for justifying that "constant speed operation of a vehicle tends to minimize fuel consumption". They use the approximation that vehicle fuel consumption is proportional to the propulsive work (defined by an equation in the form of equation 3.5). According to these authors, the classic control theory approaches previously applied to the search of the speed profile that minimizes fuel consumption, corroborated the constant speed as the profile satisfying the minimization of fuel consumption under a certain number of road and grade conditions: in road vehicles for a level road (Schwarzkopf and Leipnik, 1977) and for a constant road grade (Hooker, 1988). Chang and Morlok (2005) do not consider the possibility of " coasting" during braking phases. The importance of this aspect to the fuel consumption savings achieved with speed variations is discussed in the next paragraph.

Speed variations could also produce fuel consumption savings

A vehicle engine map, such as the one shown in Figure 3.9, shows that an engine does not have the same fuel consumption at all operating points: at higher loads the specific fuel consumption is lower, i.e. the amount of fuel required to produce one kWh of work is lower and the engine is more energy efficient.

Avins (1983) described a control system that improved engine efficiency and reduced fuel consumption by making the vehicle "accelerate cyclically for short controlled intervals". These accelerations increased the engine load while the average speed remained relatively constant. This system also included coasting[3] periods after these acceleration periods, which had a very low fuel consumption. The possibility of free wheeling described as an auto transmission in which "the engine drives the wheels but the wheels cannot drive the engine" is presented as another way of producing further fuel consumption savings in this patent.

Table 4.1: Comparison between constant speed and speed variations, as given in Avins (1983) patent for a 1 800 kg (4 000 lb) car

Vehicle Speed	*Power produced by the engine*	*Engine speed*	*Fuel consumption*
Constant speed			
80.5 km/h	11.2 kW	2000 rpm	5.9 kg fuel/h
(50 mph)			(12.9 lb fuel/h ≈ 9.8 $L/100km$)
Speed variations			
Average speed 80.5 km/h	22.4 kW		4.6 kg fuel/h
50% duty cycle pulse in	(coasting at braking phase,		(10.3 lb fuel/h ≈ 7.6 L/100km)
the engine	f.c. 1.5 kg fuel/h)		25 % fuel improvement in mpg
			(**22 %** improvement in L/100km)

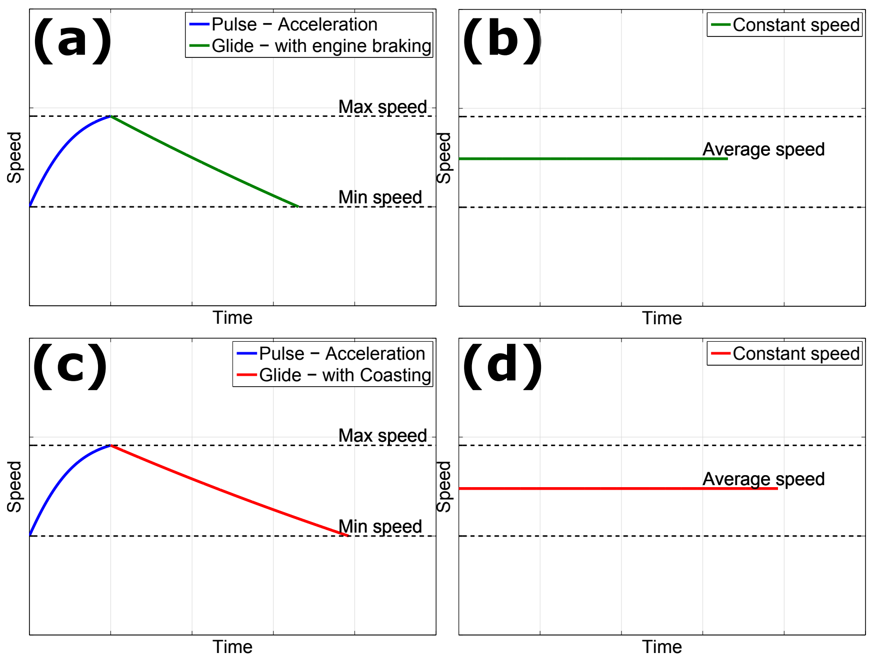
However, this system was not used in the automotive industry, even with the significant fuel savings announced in Avins' 1983 patent[4] (Table 4.1). The idea of speed variations to produce fuel consumption reappears only in a more recent article, published in 2009 by the Society of Automotive Engineers - SAE International (SAE).

This article, written by Jeongwoo Lee and colleagues (Lee et al., 2009) and the first author PhD thesis (Lee, 2009) develop the basis of the "Pulse and Glide" technique. These principles are based on the same assumption of the Avins patent: produce higher engine loads during the acceleration phase, reaching better energy efficiency operating points of the engine, and use the kinetic energy stored during acceleration to decelerate the vehicle. The fuel consumption gain exists if the fuel consumption of speed profiles with speed variation is lower than a constant speed profile that has the same average speed as the speed variation profile. Figure 4.1 illustrates this principle. It is

[3] The definitions of *coasting*, *engine braking* and other vehicle operating modes are shown in Box 4.1

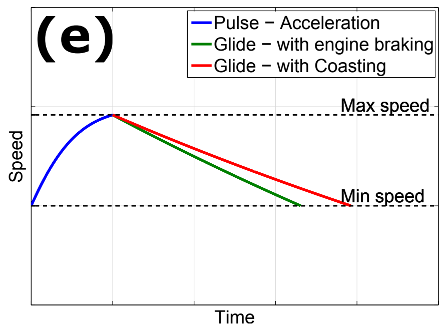
[4] Jack Avins was an US engineer who worked essentially in the radio and telecommunications field, spending most of his career at the US company RCA (1945-1976). His work contributed to improve the performance of radio and television receivers. After his retirement in 1976, he started working on the energy crisis effects. He produced in this period positioning articles and two patents in the automotive field (Goldstein, 1997): one describing the automatic free wheeling as a mechanism to save fuel (Avins, 1978) and the other one describing this automotive control systems for improving fuel consumption involving accelerations and decelerations with coasting or free wheeling (Avins, 1983)

important to notice that these authors do not cite Avins 1983 patent (Avins, 1983). They consider the Supermileage competitions or initiatives[5] the background reference for their "Pulse and Glide" concept. These authors also do not detail the design of a control system if the technique they propose was to be applied in an autonomous manner.



(a) The pulse and glide speed profile, starting from the lower speed (Min speed) and accelerating until reaching the higher speed (Max speed). The deceleration is on engine braking, i.e., the driver only releases the acceleration pedal.
(b) The corresponding constant speed profile - same average speed and time as the speed profile shown in graphic *(a)*.

(c) The pulse and glide speed profile, starting from the lower speed (Min speed) and accelerating until reaching the higher speed (Max speed). The deceleration is on coasting, i.e., the engine and the transmission are decoupled and the engine is off.
(d) The corresponding constant speed profile - same average speed and time as the speed profile shown in graphic *(c)*.



(e) The pulse and glide speed profile, starting from the lower speed (Min speed) and accelerating until reaching the higher speed (Max speed). Both deceleration profiles are shown, with engine braking and with coasting. The deceleration time is *higher* in the coasting case than in the engine braking case.

Figure 4.1: A schematic representation of a theoretical Pulse-and-Glide strategy. These figures were adapted from the description and figures of Lee et al. (2009).

The results obtained by Lee et al. (2009) in a conventional ICEV show important fuel consumption gains: for the 32-48 km/h pulse and glide (deceleration with coasting and engine off), there is a 44% fuel consumption reduction when compared to the constant speed of 40 km/h (2.9 L/100 in Pulse and Glide and 5.1 L/100 in Constant speed). When considering the 48–64 km/h pulse and glide, the benefits are higher when the acceleration phase is shorter: 36% reduction in fuel consumption in 10 s acceleration against 27% reduction in fuel consumption in 20 s acceleration when compared to the 56 km/h constant speed (3.5 and 3.9 L/100 in Pulse and Glide and 5.4 L/100 in Constant

[5] They cite the 2005 Toyota hypermileage marathon, in which teams used the acceleration and decelerations in a Prius hybrid electric vehicle in order to achieve the lowest fuel consumption as possible (Lee et al., 2009).

speed)[6]. These values were obtained by Lee et al. (2009) using a powertrain analysis tool PSAT, version 6.2.

To our knowledge, even with these results and explanations on the principles of this driving technique, the number of publications using this speed variation technique remains not very important: three more publications on the subject were found (Koch-Groeber and Wang (2014), Li and Peng (2012) and Xu et al. (2015)). The article of Li and Peng (2012) applied the pulse and glide strategy in simulated car-following scenarios. These authors continued the study of Pulse and Glide, proposing a near-optimal practical rule for drivers or an automatic control system to apply this strategy in step-gear transmissions (Xu et al., 2015). Koch-Groeber and Wang (2014) proposed that coasting phases could be used in downhill phases of route profiles to reduce fuel consumption, and evaluated fuel consumption benefits using AVL Cruise simulations. The PhD thesis of Saerens (2012) evaluated the benefits obtained with the pulse-and-glide strategy using simulations: 70 km/h was chosen as the constant speed and the pulses were made from 60 to 80 km/h and from 65 to 75 km/h. The results indicate benefits in fuel consumption only in the cases when engine is off during the glide phase with coasting. However, we notice that the techniques allowing the coasting phase with engine disconnected or off have evolved, with vehicle manufacturers and automotive suppliers proposing technologies enabling its safe use in cars[7].

This brief theoretical background about the use of speed variations and constant speed for minimizing fuel consumption shows that both strategies are claimed to be appropriated for minimizing fuel consumption.

[6]The values of the fuel consumption and vehicle speed were in the US units in the original Lee et al. (2009) paper, and were converted to km/h and L/100km by the author. The first pulse is from 20 – 30 mph (32-48 km/h) and the second from 30 – 40 mph (48 – 64 km/h).

[7]See Box 4.1

Box 4.1: Vehicle deceleration modes

The deceleration of a vehicle can be the result of different maneuvers. In conventional internal combustion engine vehicles, deceleration can come from:

- The application of the brake pedal, which dissipates the kinetic energy into heat.
- The release of the acceleration pedal by the driver causes vehicle deceleration: vehicle inertia and engine drag act as forces to slow down the vehicle. This "powertrain braking force" is named "**engine braking**" (Sovran and Blaser, 2006).

Another way of producing deceleration of a vehicle involves decoupling the engine and the transmission, which is named "**coasting**" or "**sailing**". This decoupling allows the deceleration of the vehicle to be the result of only the vehicle inertia and resistance forces (aerodynamic drag, gravitational forces, rolling resistance), and does not include the engine braking resistance. This effect can be obtained in a conventional ICEV with manual transmission by putting the transmission in the neutral gear position or by disengaging it. Driving with the gear in neutral position or with the transmission disengaged is not recommended from a safety point of view, as most of the safety systems such as brakes require a coupling with the engine to work properly. However, there are automobile manufacturers that have developed technological solutions allowing the coasting and transmission disengagement while keeping the safety requirements, namely with mild hybridization techniques that overcome this technical limitation (such as the 48-Volt Eco-Drive system proposed by Continental (Continental, 2014)). Porsche, for example, proposes the "Coasting" mode in the vehicles equipped with the PDK transmissions, in which:

" The engine is decoupled from the transmission to prevent deceleration caused by engine braking". This starts automatically when the driver takes his foot off the accelerator pedal. (Porsche, 2015).

Avins (1978) defined "**free wheeling**" as an "automobile transmission constructed so that the engine drives the wheels, but the wheels cannot drive the engine". This is the same principle of the decoupling between the transmission and the engine proposed in coasting mode.

There is another vehicle deceleration mode, that is possible in vehicles equipped with electric motors (hybrid electric, full electric vehicles), the **regenerative braking**. During braking events, the electric motors are used as generators, producing energy that can be stored in batteries. The energy that would otherwise be dissipated as heat, can be stored, which allows a lower energy consumption (Sovran and Blaser, 2006; Clarke et al., 2010).

4.3 Back to biological knowledge: humans strategy of speed variation and automobile driving strategy

The pulse and glide approach for speed variations appears to be the closest one to the principle of speed variations used by athletes during long-distance races.

Actually, humans vary their speed to avoid completely consuming their anaerobic energy stores, or, in the terms of Billat et al. (2009) article, "*speed variations during the first 70% of the race time serve to maintain constant the time to exhaustion at the instantaneous anaerobic power*". This time to exhaustion is the ratio between the anaerobic stores (ANS) and the instantaneous anaerobic power (PAN). This implies that the running speed depends on the prevailing anaerobic stores. Noticing that the anaerobic stores are limited but also very powerful, if their contents are not completely consumed before the end of the race, the runner has the possibility of accelerating and produce the "final sprint", with no need to "hitting the wall"[8] before the end of the race.

In conventional vehicles, the problem is not quite the same. These vehicles have a powerful source, available in a sufficient amount for covering large distances[9]. However, the constraints on the oil supplies and on the CO_2 emissions[10] put restrictions on the use of this powerful energy source. These restrictions are the main motivation for the research of alternatives allowing lower fuel consumption. Instead of modifying the engine itself (with downsizing, turbo charging, etc) or the vehicle (better aerodynamics, lower rolling resistance or vehicle weight), the regulation of the anaerobic energy stores of athletes can inspire modification on strategies more related to modifications on the *use of the vehicle engine and driving conditions*. The pulse and glide principle that is already studied in the automotive research literature is a modification on the use of the vehicle engine, involving only changes in driver inputs, that could produce fuel consumption savings, while keeping the same average speed. Considering the three domains cited on the review of strategies allowing reducing CO_2 emissions described on Section 3.2.2: Driver, vehicle and environment, the pulse and glide strategy belongs to the *driver* domain.

[8]According to Rapoport (2010), "hitting the wall" is the situation described by endurance athletes in which carbohydrate reserves are exhausted. This limits performance during the race. Cade et al. (1992) described "hitting the wall" as the "sudden onset of extreme fatigue in later stages of a marathon race".

[9]The so-called vehicle range of a conventional ICEV is in general more than 600 km. For example, the fuel tank capacity of a Renault Clio 4 is 45 liters, considering that the fuel consumption is 5.6 L/100 in NEDC cycle (engine D4F 740, petrol) the range of this vehicle could reach 800 km with one full fuel tank (Renault, 2015).

[10]See Section 3.2 for a more detailed explanation of these constraints on oil supplies and CO_2 emissions.

The pulse and glide strategy is not originally bio-inspired[11], but the bio-inspiration (in our case, the observation of the athletes running strategies) led to the identification of this design path as being potentially interesting for the minimization of fuel consumption and emissions. This corresponds to one of the conclusions formulated during the process of modeling bio-inspired design using the C-K theory: the biological knowledge helps identifying and exploring knowledge based that were perhaps not unknown to engineers, but that would not be spontaneously activated otherwise.

The pulse and glide strategy for reducing fuel consumption is identified as one possible path for developing the bio-inspired concept generated with inspiration from the runners strategy of speed variations. In this case, bio-inspiration has indicated a design path that would not be spontaneously activated.

4.4 Evaluating the concept of speed variations in cars

After the identification of the pulse and glide as a suitable strategy for putting into practice the bio-inspired *energy saving* concept for passenger cars using speed variations, a methodology for exploring the conditions in which pulse and glide produces fuel consumption savings needed to be defined. The starting point for defining this methodology were the findings and concepts defined by Lee et al. (2009). These authors evaluated different pulse and glide conditions using vehicle simulations and a hybrid vehicle in a dynamometer. The research approach used in this work also uses simulations and experimentations. However, the simulations are based on a simplified model of an internal combustion engine vehicle powertrain and the experimentations are conducted using a car driven in real-life driving conditions[12].

4.4.1 Research approach

The methodology chosen for evaluating the pulse and glide strategy involved two directions: a practical one, with experimentations conducted using an internal combustion engine vehicle, and a theoretical one, involving simulations made with a simplified model of the vehicle powertrain. This

[11] Avins (1983); Lee et al. (2009) describe the strategy without making references to a biological inspiration.

[12] Lee et al. (2009), used the PSAT simulation model developed by the Argonne National Laboratory. Saerens (2012, p.171) evaluated the conditions of deceleration and acceleration of pulse and glide using simulations with a map-based model.

methodology is summarized in Figure 4.2.

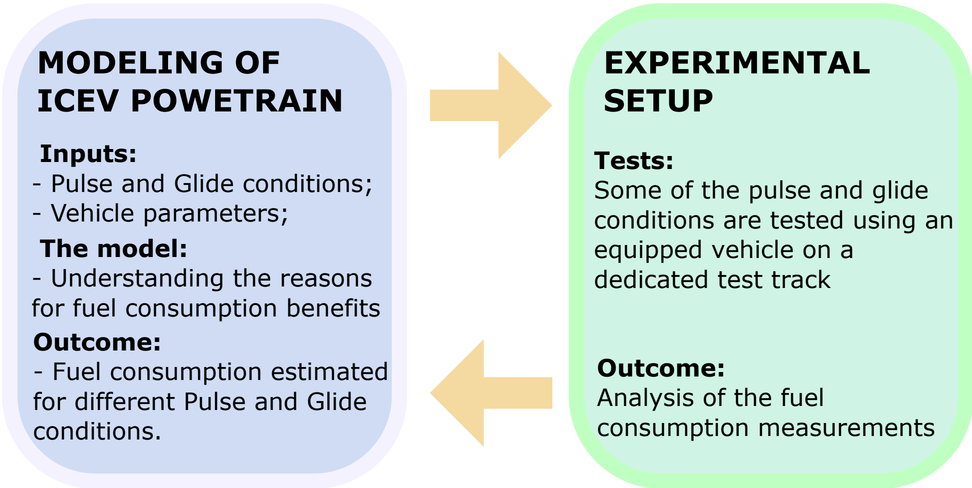


Figure 4.2: The research approach for evaluating the Pulse and Glide strategy. In a first moment, the theoretical modeling of the powertrain allows defining conditions for the experimental setup. The results of the experimental setup may induce changes in the modeling, and thus new conditions for the experimental setup.

The modeling was used to define the conditions that would be tested in the experimental tests. The combination of the theory and practice is key to better evaluate the possibilities and limitations of the pulse and glide strategy for reducing fuel consumption. The outcomes of the experimentations also allowed us to review our modeling assumptions, building a model that is closer to the experimental conditions.

4.4.2 A model for evaluating vehicle fuel consumption

The evaluation of the speed variations and their influence on fuel consumption required a model to estimate vehicle fuel consumption. This model also had to be able to reveal some operating characteristics of the different vehicle subsystems (wheels, transmission, gearbox, engine, fuel tank or batteries). Models fulfilling these requirements exist in different forms: commercial software (AVL Cruise [13], LMS Amesim [14]) and simulation tools (ADVISOR [15], CMEM [16]). These models have

[13] A description of this software functionalities is available at: https://www.avl.com/cruise.

[14] A description of this software functionalities is available at: http://www.plm.automation.siemens.com/en_us/products/lms/imagine-lab/amesim/.

[15] ADVISOR is a MATLAB/Simulink simulation program, developed by the National Renewable Energy Laboratory (in the United States). More information on this software is available at: http://adv-vehicle-sim.sourceforge.net/ and in publications (Markel et al., 2002).

[16] CMEM (Comprehensive Modal Emissions Model) was sponsored by the National Cooperative Highway Research Program and the U.S. Environmental Protection Agency. More information is available on the website: http://www.cert.

variable levels of complexity, and require a certain amount of data to properly simulate vehicle fuel consumption.

Most of the vehicle data available in our case come from vehicle manufacturer and the LIVIC research laboratory previous work. Using the main equations of vehicle dynamics and engine maps, a model was built. The choice of making a simplified model is related to the need of obtaining a greater sensitivity about the role of speed variations on changes on vehicle fuel consumption and to the need of a greater flexibility for testing different operating conditions. The aim of this model was to be precise enough to allow comparisons between the reference vehicles model and the vehicles with the introduced modifications.

In this section, the main constructs of the model are detailed: the approach used for vehicle modeling and the models generated for the conventional ICEV fuel consumption calculations.

Modeling the different vehicle subsystems, their physics and the relationships between these systems to simulate the vehicle performance on different operating conditions is named Full System Simulation (FSS). FSS is largely used in automotive literature to estimate new concepts impacts on vehicle systems NRC (2011). Based on the equations of vehicle dynamics[17], the fuel consumption is calculated for a given driving profile. There are essentially two ways for calculating fuel consumption using these models. These two approaches are defined here according to the definitions provided by Markel et al. (2002). The first way, called *backward* approach, consider that the vehicle meets a given driving profile. It uses the force at the wheels calculated to evaluate the engine speed and torque in order to estimate fuel consumption. In the second way, called *forward* approach, there is a driver model, that uses the required speed of the driving profile, to calculate the throttle and brake commands which are translated into an engine torque and fuel consumption. Then the engine torque is used to calculate the other subsystems torques and forces until arriving at the tractive force at the wheels, which can be used to calculate the acceleration and speed effectively developed by the vehicle. As Markel et al. (2002) also points out, the backward approach is less complex than the forward approach and it does not deal with quantities directly measurable in the vehicle such as throttle and brake commands, which limits its application to detailed control systems.

The core model of conventional internal combustion engine vehicles was built according to a backward approach. However, some elements of a forward approach are also included to account for some specificities of the pulse and glide strategy, as will be detailed in next Section 4.4.2.1.

ucr.edu/cmem/.

[17]These equations of vehicle dynamics are presented in Chapter 3, Section 3.2.2.2, Equations 3.1 to 3.5.

4.4.2.1 The simplified ICEV model

The approach used to build the ICEV model used for simulations is the backward quasi-static simulations, detailed in the book Vehicle Propulsion Systems by Guzzella and Sciarretta. The idea behind this model is to consider as inputs the speed, acceleration and road slope, which can be used to calculate the tractive force at the wheels, F_{TR}, from vehicle parameters, with equation 3.5. The acceleration is supposed constant between a short time step dt. With this tractive force, are calculated the required engine speed and torque, considering the inertia and losses in the elements between the wheels and the engine, such as the gearbox and the transmission.

In order to build the vehicle model, we adopted the same subsystems suggested by Guzzella and Sciarretta (2005): driving cycle, vehicle, gearbox, engine and fuel tank. These subsystems and their inputs and outputs are schematically represented in Figure 4.3[18].

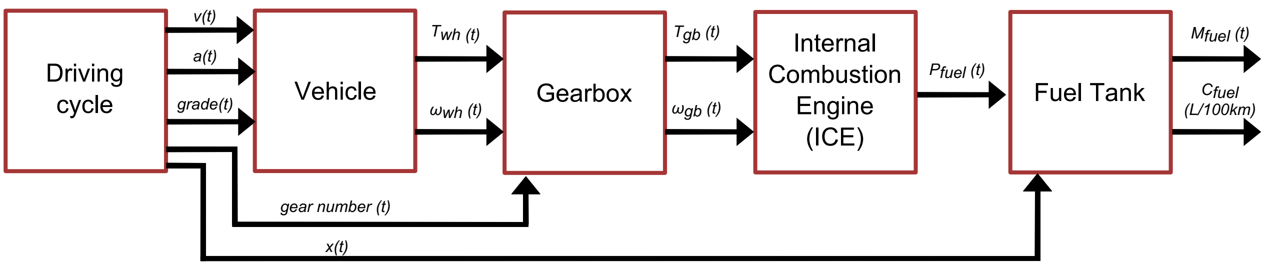


Figure 4.3: ICEV quasi-static backward model subsystems representation, with their main inputs and outputs.

The first input to the model is a driving cycle (also called speed profile or driving schedule in literature), with values of time in seconds and the corresponding speeds. An example of driving cycle is a normalized driving cycle such as NEDC or WLTC (Figure 3.3). The road grade may also be given for each corresponding speed and time values. The gear number is considered as a parameter given in the initial data[19]. If it is not the case, there are experimental models allowing an accurate estimation of the gear engaged by the driver, such as the model derived from empirical data proposed by Orfila et al. (2012). The engine maps (instantaneous fuel consumption as a function of torque and engine speed values) were available for the vehicles modeled[20] and the fuel consumption is calculated by interpolation of the engine speed and torque with the engine map values.

[18]The symbols used on this figure are defined on the List of Symbols on page xxxi.

[19]In the NEDC cycle, the gears are defined within the test cycle.

[20]If engine maps were not available, there are other methods for calculating the fuel consumption from engine torque and speed data, such as the Willans approximation, described by Guzzella and Sciarretta (2005, p.44), which calculates the engine mean effective pressure considering the engine thermodynamic efficiency and the drag mean effective pressure, both depending mainly on the engine speed.

The vehicle used for our calculations is a 2008 Renault Clio 3 Eco2 Estate (Figure 4.4). Vehicle parameters are listed in Table A.1(Appendix A.1), and are essentially the same as those presented by Luu (2010)[21]. The engine map was obtained experimentally[22] and maximum and minimum torque of this engine were estimated using manufacturer data on similar engine models.

Each subsystem of the model (Figure 4.3) has its own calculations and was modeled using MATLAB®. The main equations used in each subsystem are detailed in Appendix A.2.

Figure 4.4: The vehicle modeling parameters were those of the Renault Clio 3 Eco2 Estate of this picture. This vehicle is the one used in the experimental setup. Photo by LIVIC laboratory - used with permission

4.4.2.2 Modeling the "pulse" phase of the pulse-and-glide strategy

The pulse phase of the pulse-and-glide strategy corresponds to the acceleration of the vehicle from an initial speed, v_{min}, until a maximum speed, v_{max}, is reached. Those two speed limits correspond to the "min speed" and "max speed", respectively indicated on Figure 4.1.

This acceleration could be considered as a constant acceleration. However, given that reaching a desired speed is required, the constant acceleration profile would produce a too abrupt acceleration change, that could lead the driver not to accept the speed variations required with pulse and glide. We have then searched for a model that would reproduce the acceleration behavior of cars in a real traffic situation. We opted to use an existing model for car-following situation in freeways and urban-driving with congestion: the Intelligent Driver Model (IDM) (Treiber et al., 2000). The main reason for this choice is the acceleration of this model is based on the acceleration that a vehicle would acquire ($\dot{v}_\alpha$) in order to reach a desired speed v_0 in a free road[23]. This model calculates the vehicle acceleration

[21] This author made experimentations with the same vehicle used in the experimental setup of this thesis.

[22] We used the engine map available at the LIVIC laboratory archives, obtained experimentally.

[23] This is interpolated with the tendency of the vehicle to brake with a deceleration that depends to the "desired gap" (distance) between the vehicle and the vehicle in front.

using the equation 4.1:

$$\dot{v}_\alpha = a\left[1 - \left(\frac{v_\alpha}{v_0}\right)^\delta - \left(\frac{s^*(v_\alpha,\Delta v_\alpha)}{s_\alpha}\right)^2\right] \quad (4.1)$$

In this equation, the second term $\left(\frac{s^*(v_\alpha,\Delta v_\alpha)}{s_\alpha}\right)^2$ refers to the distance between vehicles in traffic flow, s. This term is considered zero in a free-road acceleration ($s \to \infty$). The parameter δ refers to the way the acceleration decreases near the vehicle desired speed (if $\delta \to \infty$ the vehicle approaches the desired speed with constant speed, whereas if $\delta \to 1$ the approach is with an "exponential relaxation"). The δ value recommended by Treiber et al. (2000) is 4. The parameter a refers to the maximum acceleration of the vehicle, which occurs at the beginning of the acceleration phase, and v_α is the vehicle speed. The value estimated by Treiber et al. (2000) for the a parameter is 0.73 m.s^{-2}. The acceleration for the pulse phase is calculated as the free-road acceleration given by equation 4.2:

$$\dot{v}_{\alpha_{free\ road}} = a\left[1 - \left(\frac{v_\alpha}{v_0}\right)^\delta\right] \quad (4.2)$$

This assumption can be made because in the pulse and glide strategy evaluation, we consider that the vehicle is on a highway driving, without interaction with other vehicles. Using this equation for calculating vehicle acceleration during the acceleration phase from v_{min} until v_{max} vehicle speed at a time step is given by equation 4.3:

$$v(t+\Delta t) = v(t) + a\left[1 - \left(\frac{v(t)}{v_0}\right)^\delta\right] \cdot \Delta t \quad (4.3)$$

Figure 4.5 shows the acceleration profile obtained using equation 4.3 for different values of parameters a and δ and the corresponding speed profiles for speed variations from 50–70 km/h, 90–110 km/h and a 0–120 km/h. Note that the initial acceleration differs according to vehicle initial speed, as the IDM model parameter a is the maximum acceleration at $v = 0$ km/h. The effects of increasing a parameter from 0.5 to 2 m/s^2 and of δ parameter changes can be observed: an increased a parameter increases the slope of the speed profile during the acceleration phase, i.e. the maximum speed is reached faster, and very large δ parameters allow reaching the maximum speed in a linear way.

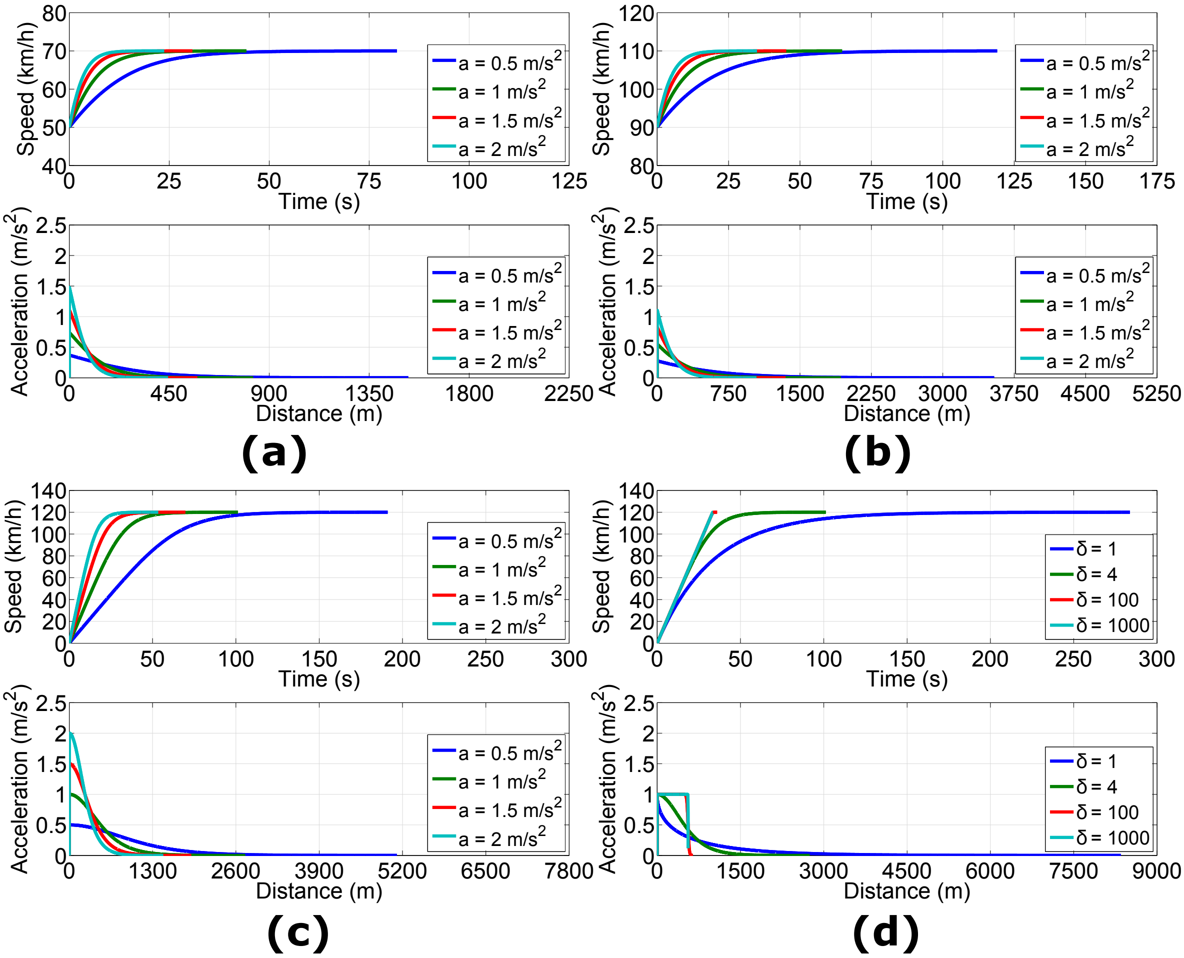


Figure 4.5: The acceleration profiles obtained with different parameters for the IDM free-road acceleration model. In (a),(b) and (c) acceleration profiles are calculated for different parameter a values and δ = 4 , with a speed variation from 50–70 km/h (a), 90–110 km/h (b) and 0–120 km/h (c). In (d) acceleration profiles are obtained using different parameter δ values for a speed variation from 0–120 km/h, and a = 1 m/s^2.

4.4.2.3 Modeling the "glide" phase of the pulse-and-glide strategy

For the "glide" phase, we considered two possibilities. In the first one, when the driver reaches the maximum desired speed v_{max} he lets go the acceleration pedal, and the vehicle decelerates with the same gear engaged or with another gear if the driver chooses to change gears. This situation is called "engine braking", as the engine contributes to slowing the vehicle down. In our model we estimated the minimum torque produced by the engine by using data gathered from similar internal combustion engine, as we did not have the negative torque measured experimentally. These values were estimated as being between -17 and -30 N.m according to data available for other models produced by the same vehicle manufacturer. Vehicle speed during the engine braking phase can be calculated using equation 4.4[24]. The terms used in this equation are defined in the List of Symbols on page xxxi.

$$a(t) = \frac{dv}{dt} = \left(\frac{r_{wh}}{m_v r_{wh}^2 + I_{total}}\right)\left(T_{engine} N_t N_f \eta_{tf} - r_{wh} \cdot (F_{roll} + F_{aero} + F_g + F_{add_{res}})\right)$$
$$v(t + \Delta t) = v(t) + a(t) \cdot \Delta t \qquad (4.4)$$

Where I_{total} is the sum of the inertial effects of the powertrain rotating parts (Equation 4.5[25]).

$$I_{total} = (I_{engine}) \cdot N_{tf}^2 + I_d N_f^2 + I_w \qquad (4.5)$$

The other possibility is for the vehicle to decelerate with the gear in neutral position, which is called "coasting" or "sailing". This situation also uses equation 4.4, but the torque of the engine is considered zero, and the inertias of the transmission and the engine are also zero ($T_{engine} = I_d = I_{engine} = 0$). Figure 4.6 presents the speed profiles obtained for different conditions of the "glide" phase, within the two glide possibilities: engine braking or coasting. In the coasting phase, the model considers that the fuel consumption is the fuel consumption of idle phase[26].

4.4.2.4 Results for the "pulse and glide" strategy using the simplified ICEV model

The simplified ICEV model described on Section 4.4.2.1 is used to calculate the fuel consumption obtained for different pulse and glide conditions. These conditions include:

- the *acceleration phase profiles* defined by IDM parameters, a and δ. The values considered in simulations were $a = 1$; 1.5 and 2 m/s^2 and $\delta = 4$ and 100.
- the *deceleration phase profiles* defined by engine braking and coasting, using the same gear than the one from the acceleration phase or a higher gear. The gear ratio during the acceleration

[24] The deduction of this equation is described by Gillespie (1992) in its chapter 2 (equations 2-5 to 2-11). It is obtained using the equations of the torque delivered through the clutch as input to the transmission, the torque delivered at the output of the transmission and the torque delivered at the axles to accelerate the wheels. This is a forward approach for estimating the tractive forces. This approach is also used by Luu (2010) in its forward model for calculating fuel consumption.

[25] In this equation, I_w refers to the inertia of the four wheels.

[26] This approximation (coasting phase with idle fuel consumption) is closer to the conditions in which the experimentations on the test track were made, i.e. with the gear in neutral position to simulate coasting.

phase was considered to range between 3 and 5, and the engine braking phases were made with the same gear as the acceleration phase or with a superior gear. For example, if the acceleration is in 3rd phase, engine braking was calculated using the same gear (3rd gear) or the superior gear (4th gear).

- the *speed differences* defined by v_{max} and v_{min}. The initial speeds considered for the simulations ranged from 50 until 110 km/h, with speed variations of 5, 10, 15 and 20 km/h.

- the *rolling resistance coefficient and road grade*. All simulations for the speed variations strategy were realized considering a rolling resistance coefficient of 0.018 and no road grade is considered.

- the *fuel consumption during coasting phase* the fuel consumption during coasting phase is considered as the fuel consumption of the idle phase: 0.45 $kg.h^{-1}$ [27].

The fuel consumption results obtained with a speed variation profile are compared to those obtained with a constant speed profile. This constant speed profile had a speed corresponding to the average speed of the speed variation profile. The cases considered for evaluating the speed variations are listed in Table 4.2.

The speed differences were considered to be inferior or equal to **20 km/h**. A higher speed variation[28] would be too uncomfortable for the driver and could not be safe in real life driving conditions. Literature also privileges values of speed variations lower than 20 km/h: Lee et al. (2009) used 16 km/h for the simulations of the pulse and glide strategy, and Koch-Groeber and Wang (2014) also do not use speed differences superior to 20 km/h.

The simulations produced three speed profiles for speed variations, in each profile the acceleration phase was simulated with the same a and δ parameters while the deceleration phase could be done with three different deceleration profiles: *(i)* coasting, *(ii)* engine braking with the same gear ratio as the acceleration phase and *(iii)* engine braking with a superior gear as the acceleration phase gear. The fuel consumption obtained for each case (C_{fuel}) is then compared with the fuel consumption obtained for a constant speed profile ($C_{fuel_{avg-speed}}$), with the same average speed as the speed variation case. This comparison allows the calculation of the fuel consumption variation (FC_{var}), which can be calculated according to equation 4.6, and is given in relative units (percentage). Figure 4.7 shows the speed profiles and Figure 4.10 the average fuel consumption obtained for the 50-70 km/h case.

[27] See appendix A.2.4 for the assumptions leading to this fuel consumption value.

[28] The speed variation is defined as the difference between the initial vehicle speed (v_{min}) and the final speed (v_{max}).

Figures 4.8 and 4.11 illustrate the speed profile and the fuel consumption, respectively for the 70-90 km/h case. Figures 4.9 and 4.12 for the speed profile and fuel consumption respectively for the 90-110 km/h case.

$$FC_{var}(\%) = \frac{1}{100}\frac{C_{fuel_{avg-speed}} - C_{fuel}}{C_{fuel_{avg-speed}}} \tag{4.6}$$

During the acceleration phases, the total fuel consumption is higher than the constant speed profiles. The deceleration phase consumes only the idle fuel consumption (our assumption for coasting phase) or does not have fuel consumption (shutoff of fuel injection during engine braking phases), which allows the reduction of the overall fuel consumption. Besides, the acceleration phases allow reaching areas of the engine map with better engine efficiency, i.e. lower specific fuel consumption. Figure 4.13 shows the specific fuel consumption during the acceleration phase using an engine map (90-110 km/h and acceleration in 4th gear). The engine map representation clearly shows that the acceleration phase allows reaching lower specific fuel consumption zones than the constant speed profile.

Table 4.2 presents the conditions evaluated using the ICEV simplified model for comparing the fuel consumption with speed variations (pulse and glide) and the speed profile with constant speed (with the same mean speed of the speed variations speed profile). The results given in terms of fuel consumption variation (FC_{var}) are schematically represented in Figure 4.14 for the deceleration with coasting phase and in Figures 4.15 and 4.16 for deceleration with engine braking.

Higher fuel consumption variations (reaching 20%[29] – for a = 2.0m.s^2 and δ = 100 in Figures 4.14, 4.15 and 4.16) are achieved in higher acceleration rates, represented by the parameter a of the IDM model and the higher δ parameter, meaning that the desired speed is reached in a more "sharp" manner, instead of a more asymptotic acceleration profile. A δ parameter of 100 produces systematically higher fuel consumption variations than the lower value (a δ parameter of 4). Figure 4.14, the simulations with δ of 100 and a of 1.5 m/s^2 produce higher fuel consumption gains for speed variations with initial speeds between 65 and 80 km/h.

The engine brake conditions, with the same gear or with a higher gear than the acceleration phase produced mostly negative FC_{var} values (speed variations have higher fuel consumption than a speed profile with the same average speed) except for the high end of δ and a parameters (Figures 4.15 and 4.16).

[29]These gains reach higher values if no fuel consumption is considered in simulations during the braking phases.

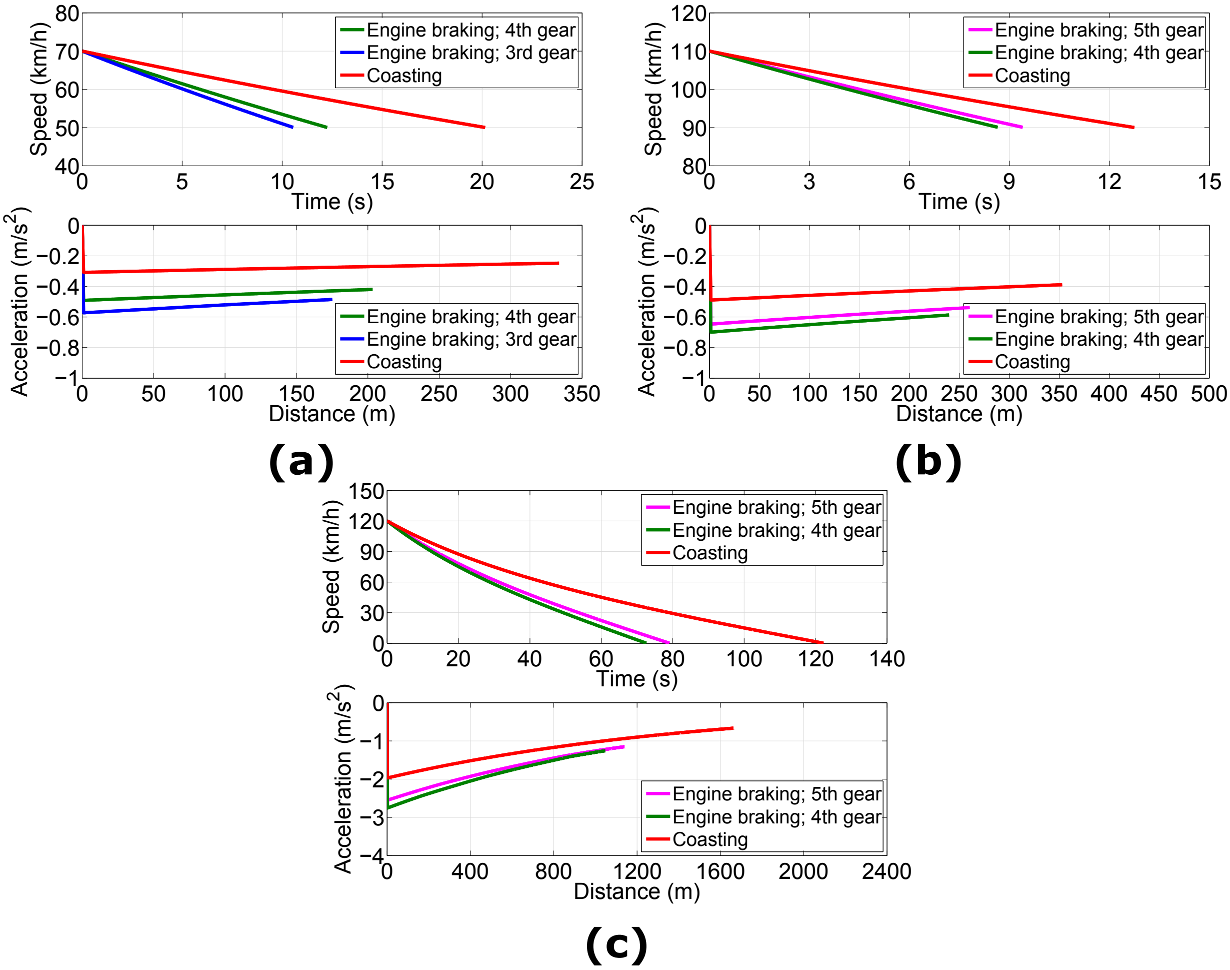


Figure 4.6: The deceleration profiles obtained using the two conditions: engine braking or coasting for the vehicle with parameters listed on Table A.1 and rolling resistance coefficient, C_{RR} *of 0.018. In (a),(b) and (c) deceleration profiles (speed vs. time and acceleration vs. distance) are calculated for different speed variations: from 70–50 km/h (a), from 110–90 km/h (b) and from 120–0 km/h (c). The engine braking phases are modeled with usual values for gear ratio within these speed ranges.*

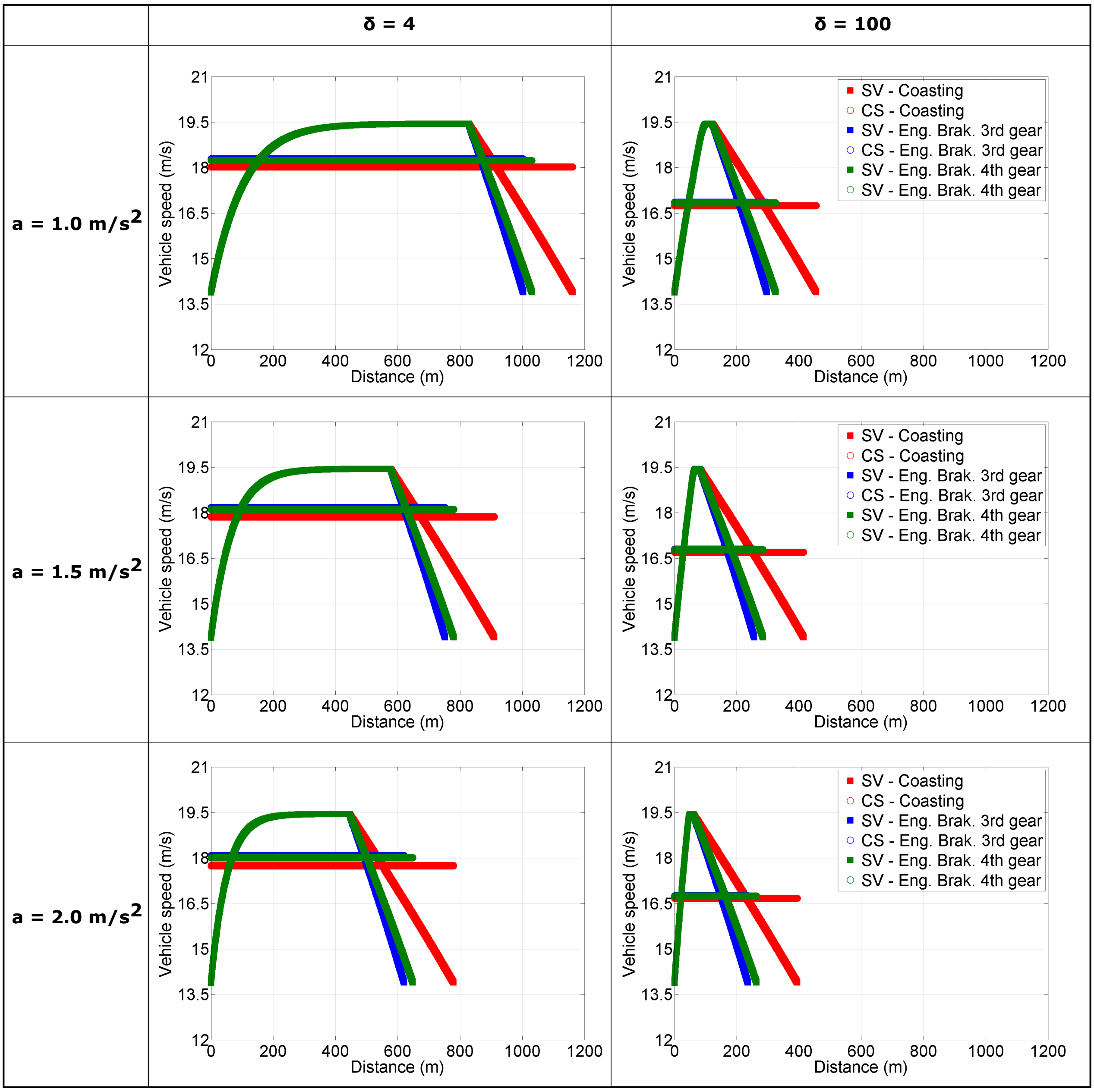


Figure 4.7: Speed variations simulated with the simplified ICEV model for 50-70 km/h, and the vehicle whose parameters are listed on Table A.1. Speed profiles and fuel consumption are given for different acceleration parameters from IDM model (a and δ) and deceleration conditions, with engine braking (SV - Eng.Brak.) or coasting (SV - Coasting), comparing to the constant speed profile with the same average speed of the speed variation speed profile (CS - Coasting or CS - Eng.Brak. respectively). 3rd gear is chosen for acceleration. Deceleration gears are indicated in the graphics legend.

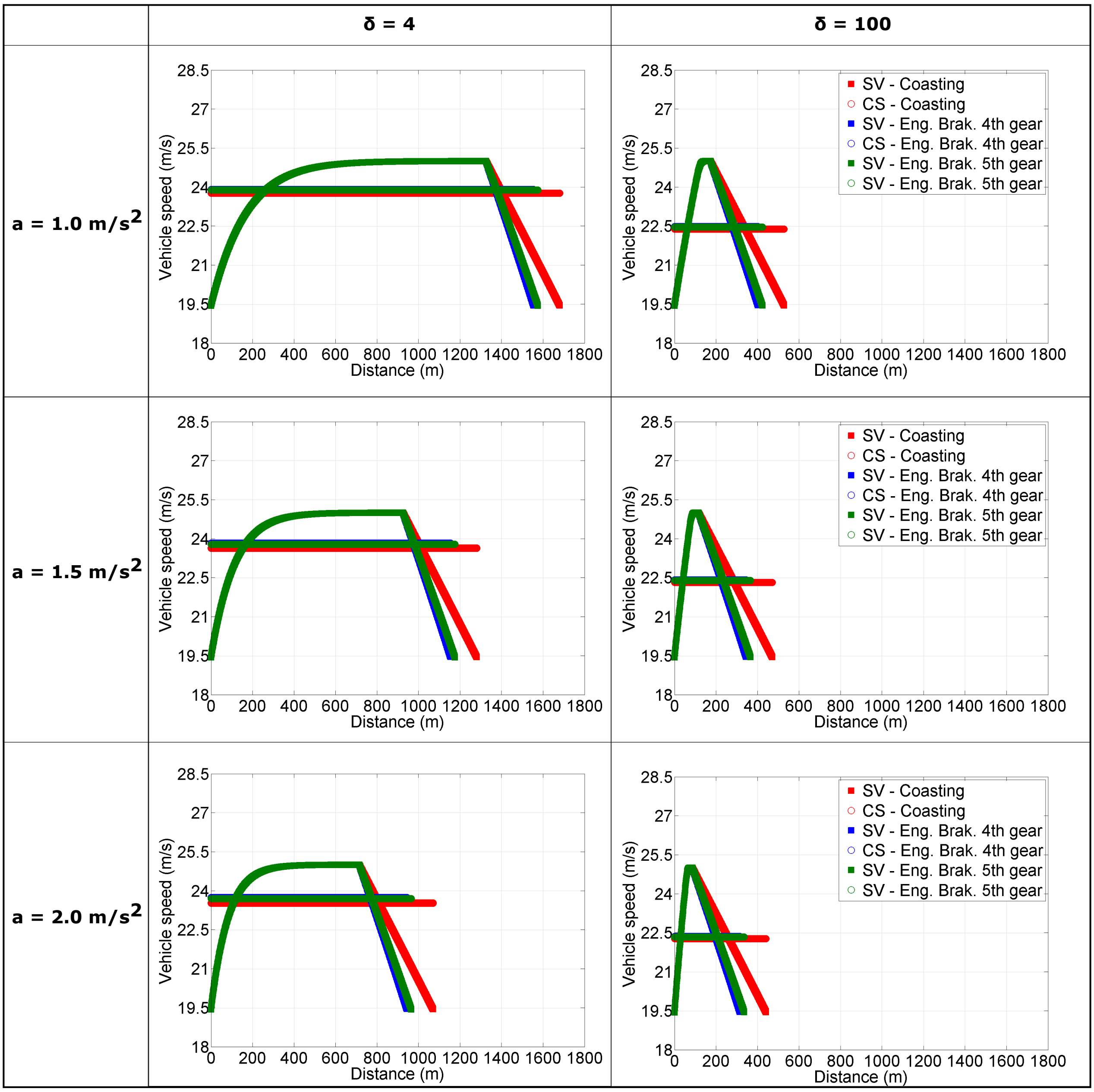


Figure 4.8: Speed variations simulated with the simplified ICEV model for 70-90 km/h, and the vehicle whose parameters are listed on Table A.1. Speed profiles and fuel consumption are given for different acceleration parameters from IDM model (a and δ) and deceleration conditions, with engine braking (SV - Eng.Brak.) or coasting (SV - Coasting), comparing to the constant speed profile with the same average speed of the speed variation speed profile (CS - Coasting or CS - Eng.Brak. respectively). 4th gear is chosen for acceleration. Deceleration gears are indicated in the graphics legend.

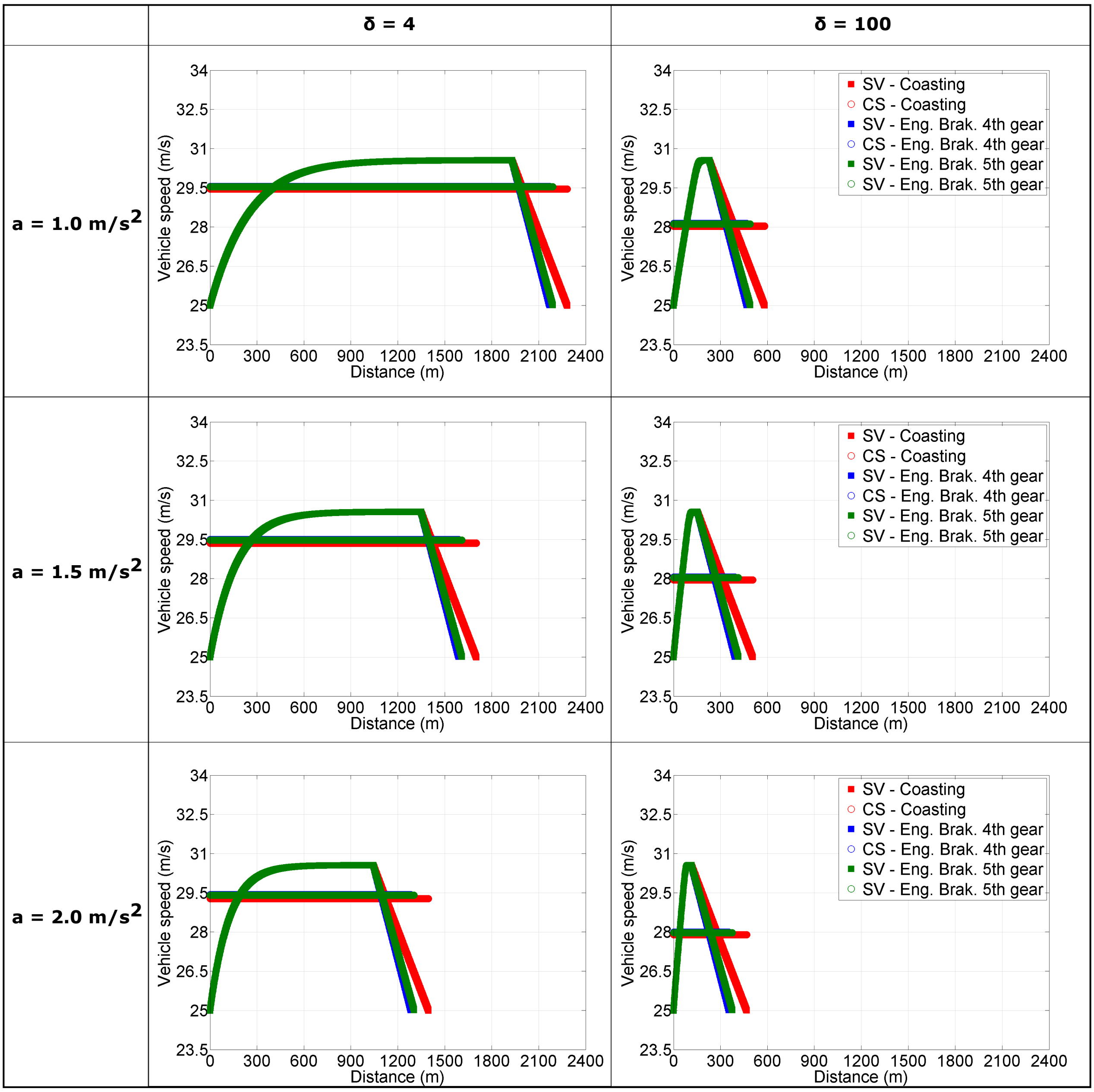


Figure 4.9: Speed variations simulated with the simplified ICEV model for 90-110 km/h, and the vehicle whose parameters are listed on Table A.1. Speed profiles and fuel consumption are given for different acceleration parameters from IDM model (a and δ) and deceleration conditions, with engine braking (SV - Eng.Brak.) or coasting (SV - Coasting), comparing to the constant speed profile with the same average speed of the speed variation speed profile (CS - Coasting or CS - Eng.Brak. respectively). 4th gear is chosen for acceleration. Deceleration gears are indicated in the graphics legend.

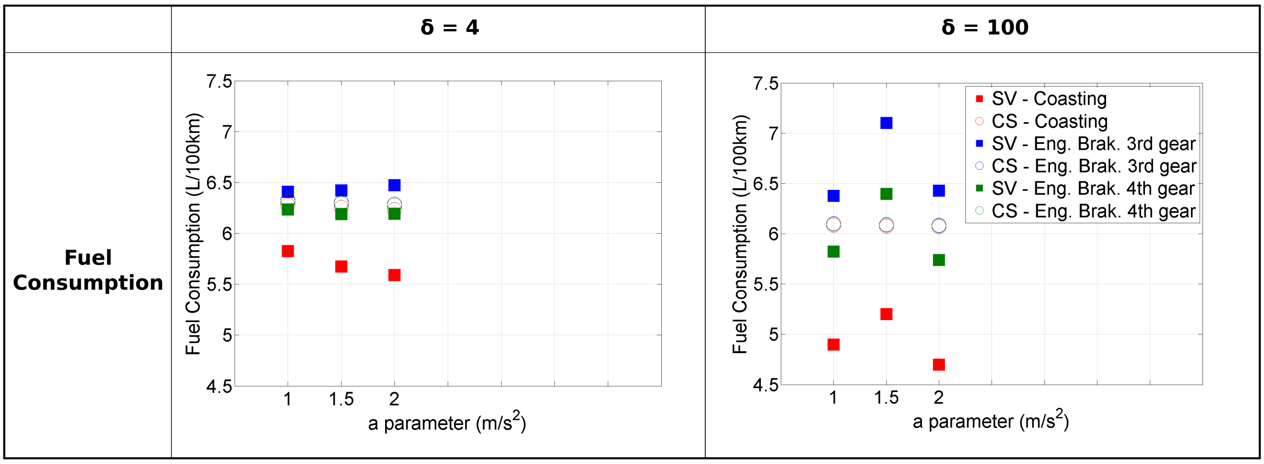


Figure 4.10: Fuel consumption calculated for speed profiles simulated with the simplified ICEV model for 50-70 km/h shown in Figure 4.7.

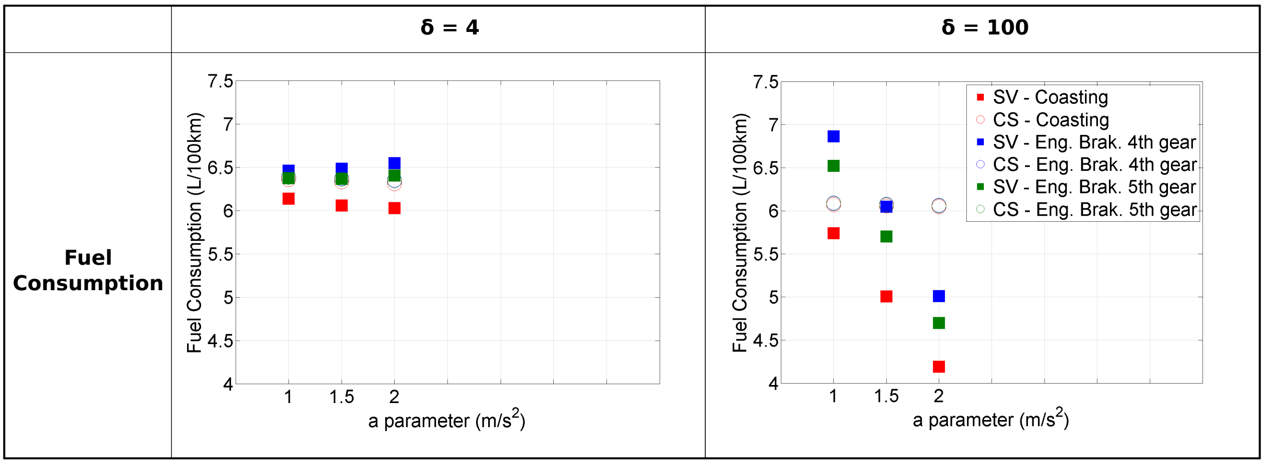


Figure 4.11: Fuel consumption calculated for speed profiles simulated with the simplified ICEV model for 70-90 km/h shown in Figure 4.8.

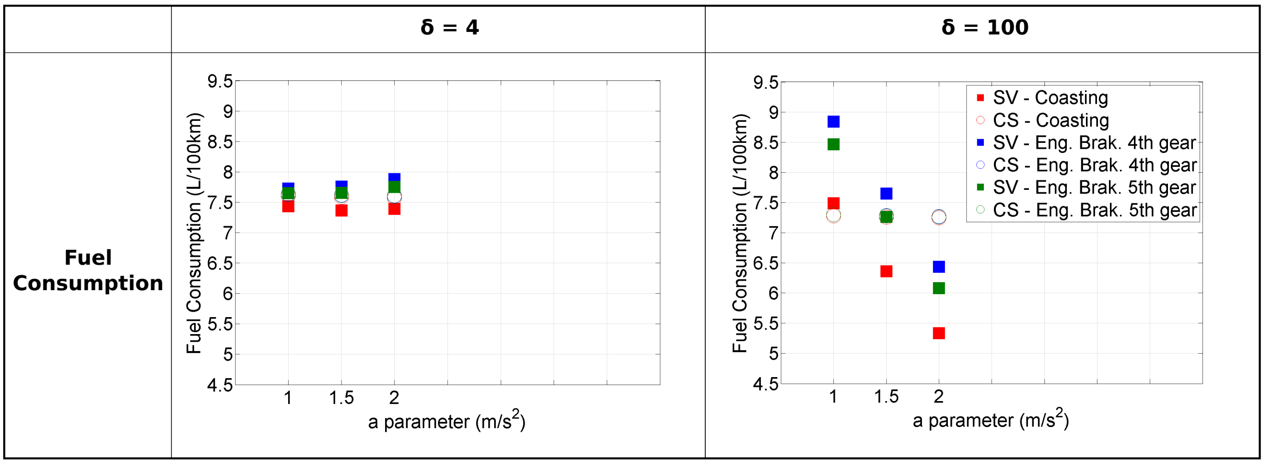


Figure 4.12: Fuel consumption calculated for speed profiles simulated with the simplified ICEV model for 90-110 km/h shown in Figure 4.9.

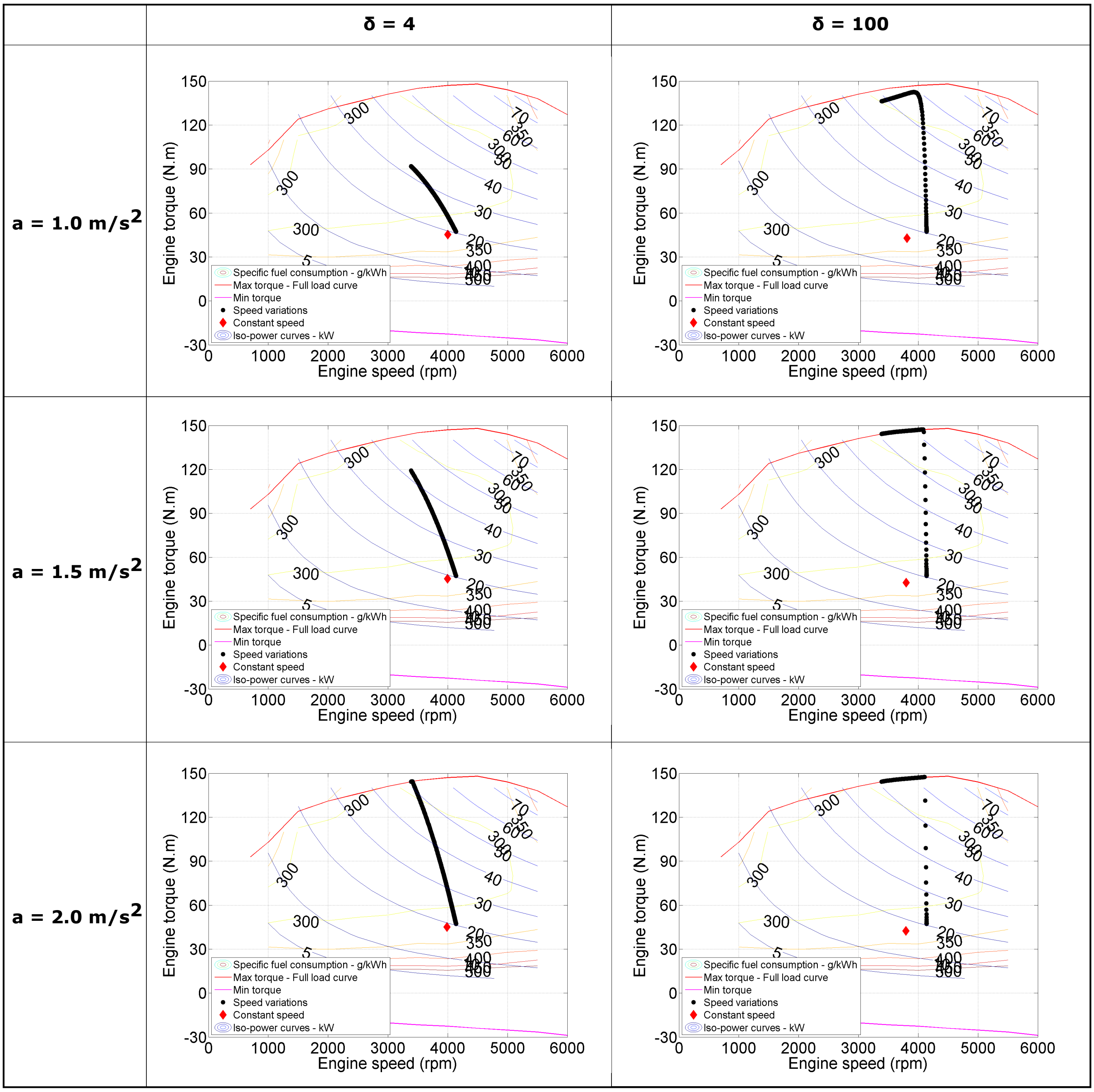


Figure 4.13: Engine maps with the operating points (engine torque and engine speed) obtained for the acceleration phase of speed variations from 90 to 110 km/h simulated with the simplified ICEV model with 4th gear engaged during acceleration (using the acceleration part of the speed profiles shown on Figure 4.9).

Table 4.2: Cases simulated using the simplified ICEV model for different speed variations conditions. Six parameters defined each case: (I) the speed variation initial speed, chosen between 50 and 110 km/h with intervals of 5 km/h; (II) the speed variation interval (maximum of 20 km/h); (III) the gear ratio of the acceleration phase; (IV) the gear ratio of the deceleration phase; (V) the parameter a of IDM model for the speed profile of the acceleration phase and (VI) the parameter delta of IDM model for the speed profile of the acceleration phase. The vehicle parameters are defined at Table A.1 and rolling resistance coefficient, C_{RR}, is considered as 0.018, and road grade is supposed to be null.

Speed variation initial speed (in km/h) **(I)**	(I).1 – 50 (I).2 – 55 (I).3 – 60 (I).4 – 65 (I).5 – 70	(I).6 – 75 (I).7 – 80 (I).8 – 85 (I).9 – 90 (I).10 – 95 (I).11 – 100 (I).12 – 105 (I).13 – 110
Speed variation interval (in km/h) **(II)**	(II).1 – 5 (II).2 – 10 (II).3 – 15 (II).4 – 20	
Gear ratio of the acceleration phase **(III)**	For cases (I).1 until (I).5 (III).1 – 3rd gear (III).2 – 4th gear	For cases (I).6 until (I).13 (III).1 – 4th gear (III).2 – 5th gear
Gear ratio of the deceleration phase **(IV)**	(IV).1 – Neutral gear (Coasting) (IV).2 – Same gear as acceleration phase (Engine braking) (IV.3) – Gear of acceleration phase+1 (Engine braking)	
IDM a *parameter* **(V)**	(V).1 – 1 m/s^2 (V).2 – 1.5 m/s^2 (V).3 – 2 m/s^2	
IDM δ *parameter* **(VI)**	(VI).1 – 4 (VI).2 – 100	

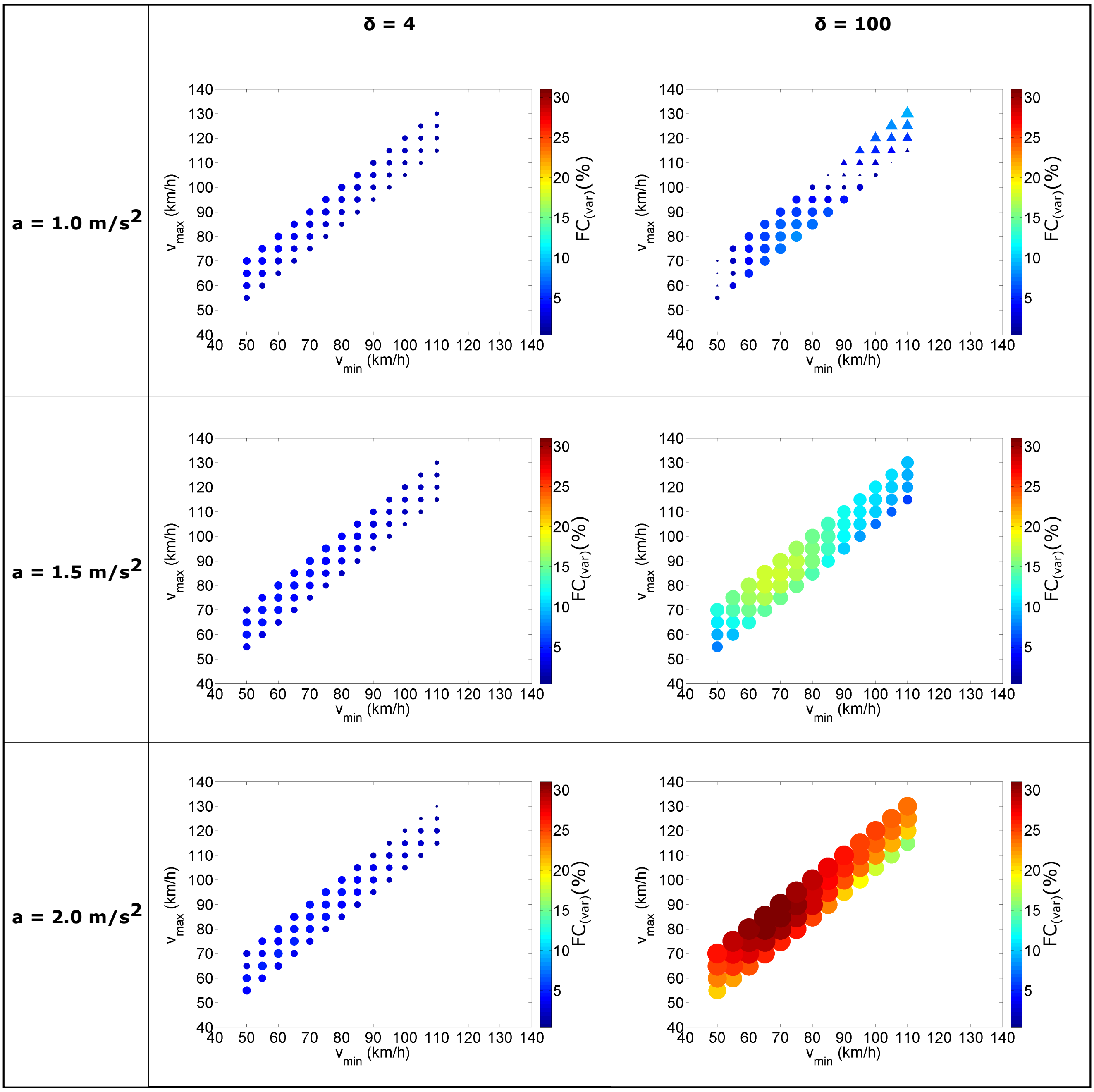


Figure 4.14: Fuel consumption reduction obtained for the speed variations conditions of v_{min} and v_{max} listed on Table 4.2 simulated with the simplified ICEV model with 4th gear engaged during acceleration and coasting during deceleration. The triangles represent negative values of FC_{red} ($C_{fuel} > C_{fuel_{avg-speed}}$) while the circles represent non negative values ($C_{fuel} \leq C_{fuel_{avg-speed}}$). Vehicle parameters used in simulations are listed on Table A.1. Fuel consumption reduction values are given for different acceleration parameters from IDM model (a and δ).

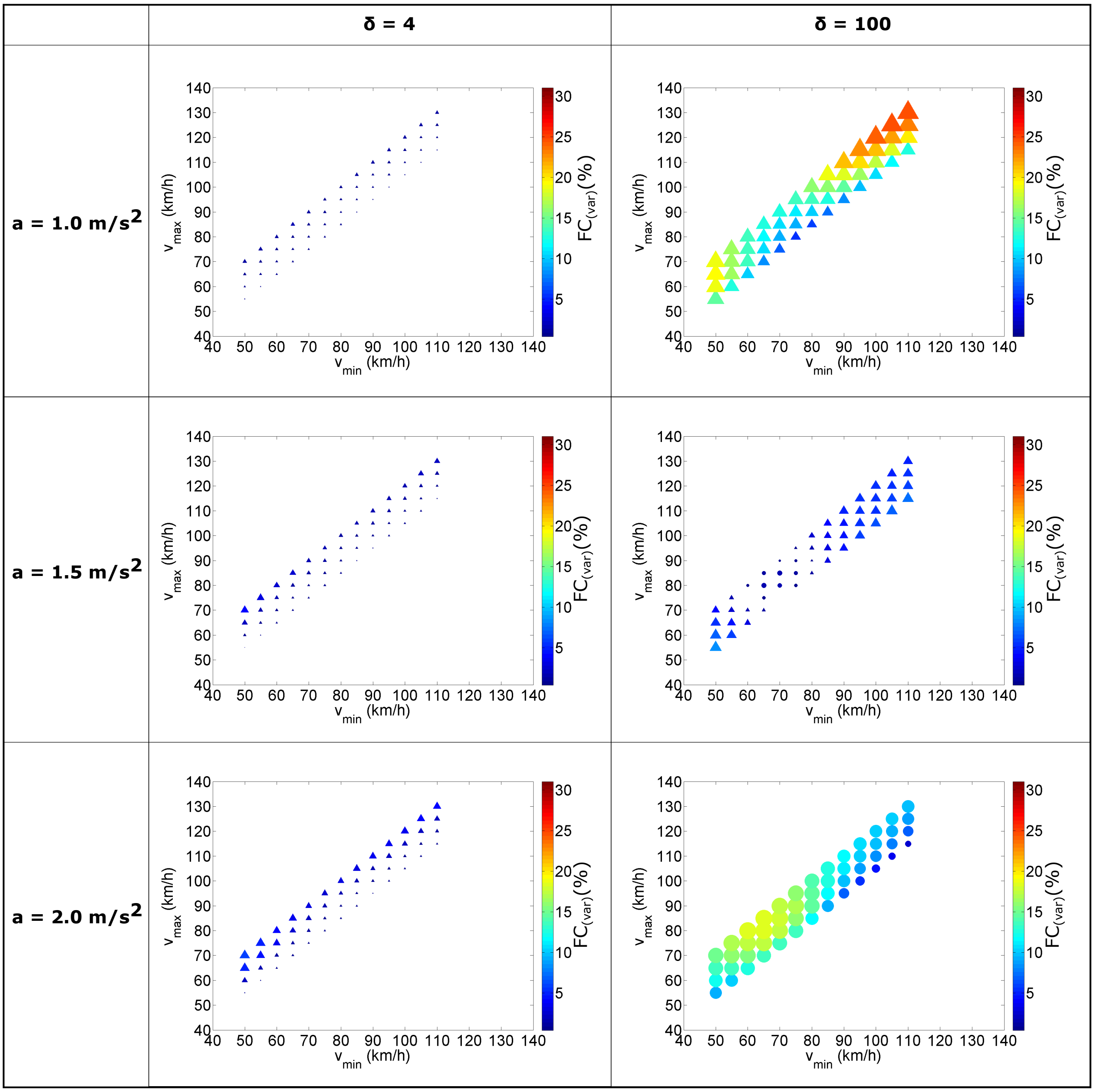


Figure 4.15: Fuel consumption reduction obtained for the speed variations conditions of v_{min} and v_{max} listed on Table 4.2 simulated with the simplified ICEV model with 4th gear engaged during acceleration and the same gear during deceleration (engine braking). The triangles represent negative values of FC_{red} ($C_{fuel} > C_{fuel_{avg-speed}}$) while the circles represent non negative values ($C_{fuel} \leq C_{fuel_{avg-speed}}$). Vehicle parameters are listed on Table A.1. Fuel consumption reduction values are given for different acceleration parameters from IDM model (a and δ).

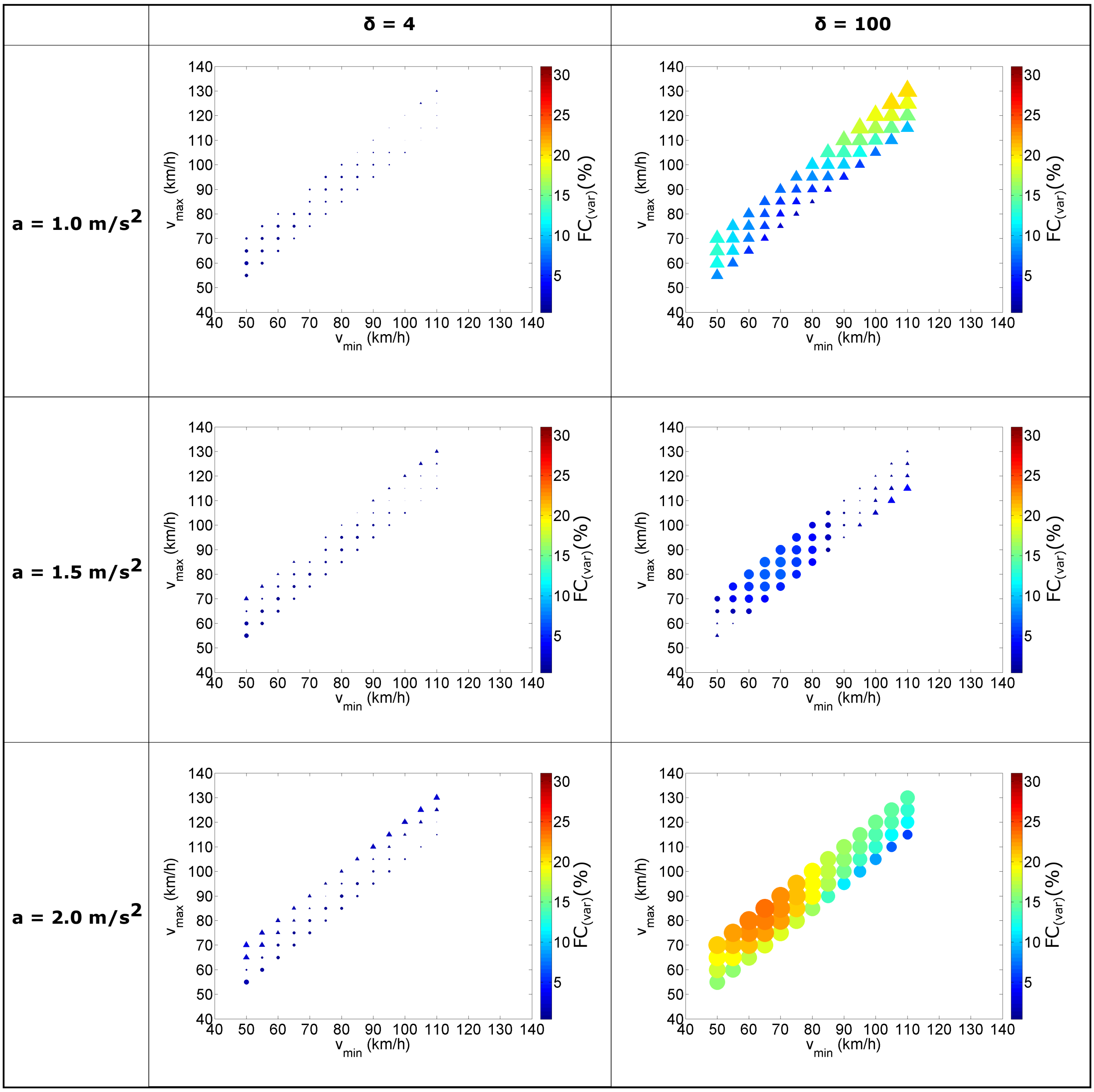


Figure 4.16: Fuel consumption reduction obtained for the speed variations conditions of v_{min} and v_{max} listed on Table 4.2 simulated with the simplified ICEV model with 4th gear engaged during acceleration and 5th gear during deceleration (engine braking). The triangles represent negative values of FC_{red} ($C_{fuel} > C_{fuel_{avg-speed}}$) while the circles represent non negative values ($C_{fuel} \leq C_{fuel_{avg-speed}}$). Vehicle parameters are listed on Table A.1. Fuel consumption reduction values are given for different acceleration parameters from IDM model (a and δ).

4.4.3 Experimental evaluation of the concept in ICEVs

The theoretical evaluation of the potential of speed variations shown in the previous section was completed by an experimental evaluation. Lee et al. (2009) only used numerical simulations for evaluating the benefits for conventional internal combustion engine vehicles, and did dynamometer tests for the hybrid electric vehicle. The aim of this experimental verification is to verify the feasibility of the concept of speed variations in real driving conditions and to evaluate the real fuel consumption benefits obtained.

The vehicle used for the experimental tests is a Renault Clio 3 Eco 2 vehicle[30]. The parameters of this vehicle were those already applied in the simulations made with the simplified ICEV model. This vehicle is a gasoline estate car of the B-segment, with a 5 gears manual transmission. It is equipped with CAN[31] fuel consumption sensors. The fuel consumption is acquired from the CAN Bus channel with a 80 mm^3 resolution. The vehicle is also equipped with sensors for capturing the longitudinal speed, the engine speed, the position of the acceleration pedal and with an inertial navigation system. These sensors allow the measurement of the vehicle position, instantaneous speed, cumulated distance and the cumulated fuel consumption. RTMAPS (©INTEMPORA, France) is used for real data logging.

The same driver realized all the tests[32]. These tests were realized in days having similar weather conditions to ensure comparability. All tests were realized in the Satory test track, in France. This test track, called the "speed test track", is a 2 km long dedicated road (Figure 4.17), with altitude and slope profiles indicated in Figure 4.18.

4.4.3.1 Scenarios analyzed with the experimental setup

Similarly to the comparisons made in the simulations using the simplified ICEV model (Section 4.4.2.4), the aim of the experimental setup was to compare two driving conditions: the speed variation condition (with engine braking or coasting in the deceleration phase) and a constant speed profile having approximately the same average speed as the speed variation condition. Two speed intervals were tested

[30] The vehicle is shown in Figure 4.4.

[31] CAN is the abbreviation of controller area network. The CAN bus interconnects the different electronic control units in automobiles, as presented in the original 1986 SAE paper by Robert Bosch GmbH engineers (Kiencke et al., 1986).

[32] The author would like to thank M. Benoît Lusetti for the realization of these experimental tests.

Figure 4.17: Satellite view of the Satory "speed test track". The balloons indicate the west (W) and east (E) directions of the test track.

in the experimentations: 50 to 70 km/h (a typical semi–urban speed variation[33]) and 90-110 km/h (a typical extra-urban speed variation[34]). All tests were realized three times in both directions of the test track (from east-to-west (abbreviated E–W) and from west-to-east (abbreviated W–E), in order to reduce the effects of road slope and wind in the results.

Four different test strategies were made for each of the two speed intervals:

- **Test strategy 1** : The driver accelerates from the minimum speed (v_{min}) until reaching the maximum speed (v_{max}) with a chosen gear engaged. The gas pedal is released and the gear is put in neutral position. The vehicle decelerates in the neutral gear until minimum speed is reached. This strategy is an adaptation of the "Pulse and Glide" strategy described by Lee et al. (2009) to a conventional car in which turning off the engine is not possible.

- **Test strategy 2** : The driver accelerates from the minimum speed (v_{min}) until reaching the maximum speed (v_{max}) with a chosen gear engaged. The gas pedal is released and the vehicle decelerates (with the same gear as the one engaged for acceleration or with a superior gear if possible). This strategy uses vehicle inertia and engine braking to decelerate the vehicle.

[33] According to the French traffic code (Code de la route, 2016) in urban areas the speed is limited at 50 km/h, and 70 km/h in the Boulevard Périphérique that surrounds Paris

[34] According to the French traffic code (Code de la route, 2016) the speed is limited at 130 km/h in freeways, 110 km/h in the 4–lanes expressways and 90 km/h in other roads

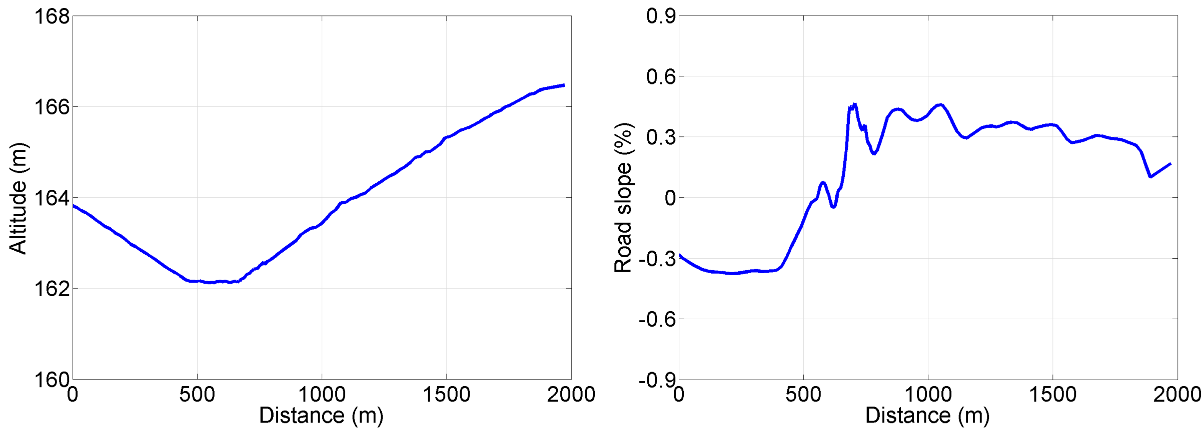


Figure 4.18: Altitude and slope profiles of the Satory "speed test track" in the direction from east-to-west (these directions are those indicated in Figure 4.17)

- **Test strategy 3** : The driver maintains a constant speed. The speed limiter of the vehicle is set to the desired speed. A difference of 2-5 km/h was observed between the speed set in the speed limiter and the speed recorded with the sensors that equipped the vehicle.

- **Test strategy 4** : The driver maintains a constant speed. The speed limiter of the vehicle is set to the desired speed. The constant speed is the speed of test strategy 3 plus 10 km/h. This increase is chosen because variations of the mean speed of the speed variations profiles (Test strategy 1 and 2) is not superior to 10 km/h.

The gears used in each speed intervals were 3rd and 4th gear for the 50-70 km/h and 4th and 5th gear for the 90-110 km/h test. These gears correspond to usual gears used with these speeds. For the engine braking phase, in the 50-70 km/h case, we used the same gear as the one in acceleration phase. However, in the 90-110 km/h, we have used for the acceleration in 4th gear, a deceleration in 5th gear. This change is taken into account in the analysis of the results obtained with the experimentations. Changing for a superior gear increases the distance made in the engine braking phase (Figures 4.6 to 4.9) which benefits the fuel consumption savings made with engine braking. However, the simulations show that engine braking in most cases do not allow fuel consumption savings except when changing for a superior gear, such as 4th to 5th gear in 70-90 km/h and 90-110 km/h - Figures 4.8 and 4.9 fuel consumption column.

In test strategies 1 and 2, the starting point of the test was the stabilization by the driver of the lower speed (v_{min}) during some seconds. The acceleration pattern to reach the maximum speed was chosen by the driver, providing a panel of acceleration patterns achievable with the same driver. The only limitation given to the driver was not to reach the maximum acceleration (avoiding a too steep acceleration slope). The driver speed reference for these two tests was the speedometer, leading to a slight difference of 2-5 km/h in the recorded speed when compared to the speed specified in the experimental protocol.

Therefore, the experimental plan relies on three main controlled factors in the two scenarios (50-70 km/h and 90-110 km/h): *(i)* The test strategy, *(ii)* the gear engaged and *(iii)* the direction of the test track. Tables 4.3 and 4.4 detail the conditions (gear, test-track directions, strategy) of each test realized in each of the two scenarios (6 tests are realized for each test strategy, in both directions, totaling 48 tests).

Table 4.3: Tested conditions for the scenario with speed variation from 50 until 70 km/h. Three trials were realized for each test.

Strategy	Acceleration & decel. in neutral ("coasting") 50–70 km/h				Acceleration & decel. engine braking ("same gear") 50–70 km/h				Constant speed lower avg. speed bound 60 km/h				Constant speed upper avg. speed bound 70 km/h			
Gear of the test	3		4		3		4		3		4		3		4	
Track directions	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W

Table 4.4: Tested conditions for the scenario with speed variation from 90 until 110 km/h. Three trials were realized for each test.

Strategy	Acceleration & decel. in neutral ("coasting") 90–110 km/h				Acceleration & decel. engine braking ("gear + 1") 90–110 km/h				Constant speed lower avg. speed bound 100 km/h				Constant speed upper avg. speed bound 110 km/h			
Gear of the test	4		5		4		5		4		5		4		5	
Track directions	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W

4.4.3.2 Results of the experimental evaluation of the "pulse and glide" strategy

Figure 4.19 shows the recorded speed profiles and fuel consumption for speed variations with deceleration in neutral (Test strategy 1) and in engine braking (Test strategy 2) for 50–70 km/h case with the 4th gear engaged and for the 90–110 km/h with the 5th gear engaged[35]. Two aspects are worth observing in these figures: *(i)* The driver has chosen different acceleration patterns in the repetitions[36], reflecting real driving conditions and *(ii)* The fuel consumption in the engine braking case was approximately zero, because of fuel cut-off during deceleration with engine braking, while neutral gear

[35] The speed and fuel consumption profiles obtained for the other tests and conditions (strategy, gear and directions) are detailed in Appendix B.

[36] As explained previously, the driver did not receive any specific instruction for acceleration, only not to accelerate at the maximum rate.

produces a fuel consumption equivalent to fuel consumption at idle. The fuel consumption and speed profiles recorded for the lower and upper bottom of constant speed (60 km/h and 70 km/h for the 50-70 km/h and 100 and 110 km/h for the 90-110 km/h) are also given as an indication of their values and comparison with the speed variation profiles.

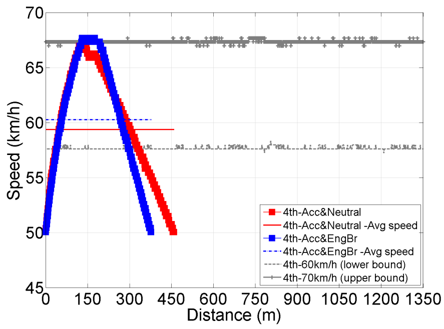
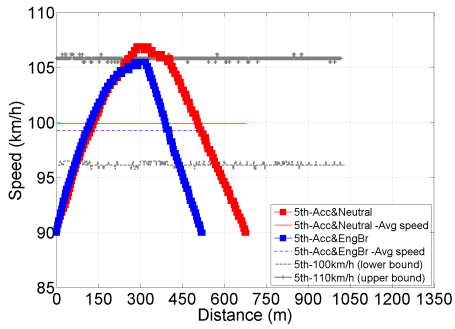
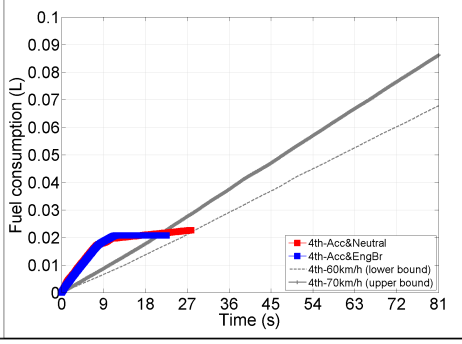
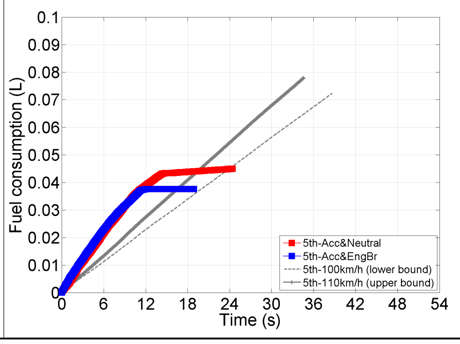
	50-70 km/h *4th gear acceleration* *Test nb 3 (neutral) - W-E* *Test nb 3 (eng. brake) - W-E*	**90-110 km/h** *5th gear acceleration* *Test nb 1 (neutral) - W-E* *Test nb 1 (eng. brake) - W-E*
Speed Profile		
Cumulative Fuel consumption		

Figure 4.19: Speed profiles and fuel consumption recorded within the expermiments realized at Satory "speed test track" with the Renault Clio 3 vehicle. For the two speed variations conditions (50–70 km/h and 90–110 km/h), 4 tests are represented: test 3 in W–E direction for engine braking and neutral deceleration for the first condition and test 1 for both two cases of the second conditions. The constant speed profiles and fuel consumption data were also chosen for the same test numbers and same direction, in both speed conditions, the lower bound (LB) of 60 km/h and the upper bound of 70 km/h for the 50-70 km/h and 100 and 110 km/h for the 90-110 km/h scenario.

Table 4.5 summarizes the results obtained for all the tests of the 50-70 km/h scenario and Table 4.6 for the 90-110 km/h. These two tables have two extra lines, showing the calculated FC_{var}, fuel consumption variation, calculated using the mean fuel consumption of the upper and lower average speed bound for each speed track direction, respectively.

The results of the two scenarios (speed variations from 50 until 70 km/h and from 90 until 110 km/h)

Table 4.5: Mean results – average speed and fuel consumption – obtained in the tests realized for the speed variation scenario from 50 until 70 km/h.

Strategy	Acceleration & decel. in neutral ("coasting") 50–70 km/h				Acceleration & decel. engine braking ("same gear") 50–70 km/h				Constant speed lower avg. speed bound 60 km/h				Constant speed upper avg. speed bound 70 km/h			
Gear of the test	3		4		3		4		3		4		3		4	
Track directions	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W
Average speed [km/h]	60.0	59.7	60.0	59.5	60.1	60.1	60.5	60.1	57.9	57.7	57.7	57.7	67.2	67.2	67.3	67.3
Fuel consumption [L/100km]	4.6	4.7	4.6	4.1	5.9	6.2	5.2	4.8	6.2	5.8	5.3	4.6	6.8	6.2	5.6	5.0

Table 4.6: Mean results – average speed and fuel consumption – obtained in the tests realized for the speed variation scenario from 90 until 110 km/h.

Strategy	Acceleration & decel. in neutral ("coasting") 90–110 km/h				Acceleration & decel. engine braking ("gear+ 1") 90–110 km/h				Constant speed lower avg. speed bound 100 km/h				Constant speed upper avg. speed bound 110 km/h			
Gear of the test	4		5		4		5		4		5		4		5	
Track directions	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W	W–E	E–W
Average speed [km/h]	99.6	99.0	99.2	98.9	99.8	99.5	99.0	99.4	96.2	96.1	96.2	96.1	105.8	105.8	105.8	105.8
Fuel consumption [L/100km]	6.7	5.9	6.7	5.7	7.7	7.1	7.5	6.9	7.6	7.3	7.0	6.6	8.3	7.4	7.6	7.4

are analyzed using a classic multiway analysis of variance [37]. The measures can be treated as independent measures because the same conditions are used for all the tests (same driver, same test track). Both scenarios show a low variability of the fuel consumption for a single condition. The Bartlett test[38] indicate that the equality of variances can be assumed. Considering the low number of trials for each scenario (only 48 trials are performed) and the difference in experimental protocol observed in test strategy 1 for the 90–110 km/h scenario[39], the significance level used in the classic analysis of variance is considered as 1% instead of the usual 5% in order to avoid false conclusion of the analysis, as suggested in (Johnson, 2013). The analysis of variance consists of searching for significant differences induced by the combination of the three controlled factors (test strategy, gear engaged and direction of the test track).

[37]The author would like to thank M. Guillaume Saint Pierre for his contribution in the realization of the statistical analysis of the experimental data.

[38]The Bartlett test is used to verify the assumption used in analysis of variance (ANOVA) that variances are equal across groups or samples.

[39]The gear in the acceleration phase (4th gear) is different from the gear used in deceleration phase in engine braking (5th gear)

For the 50–70 km/h scenario, the ANOVA shows that all the main effects are significant ($p < 10e-5$), and that there are two significant interactions: strategy *x* gear ($p = 0.00092$) and gear *x* direction ($p = 0.0083$). A Tukey Honestly Significant Difference (Tukey HSD) test can then be applied to verify between which factors the interactions are significant. It shows that strategy 1 is associated with significantly lower fuel consumption than all the other strategies, while strategies 3 (lower bound of constant speed) and 2 (engine braking) are shown to be similar. Direction W–E slightly increases fuel consumption, and the 3rd gear has significantly higher fuel consumption when compared to 4th gear. Figure 4.20 shows the fuel consumption boxplots for the three factors in this scenario.

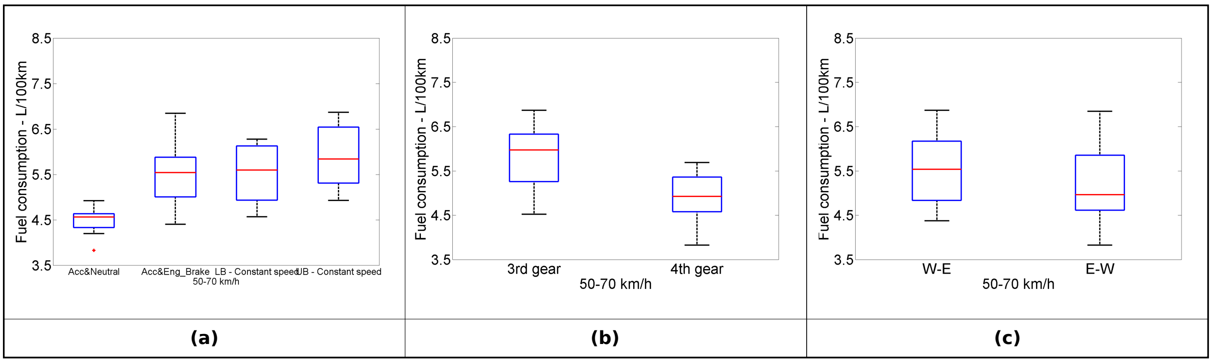


Figure 4.20: Fuel consumption boxplots for (a) the four strategies, (b) the two gears, and (c) the two directions of the 50–70 km/h scenario.

For the 90–110 km/h scenario, the ANOVA shows that all the main effects are significant only at a 1% level. The conclusions with regards to the interactions after performing a Tukey HSD test are essentially the same as those for the first scenario (strategy 1 having a significantly lower fuel consumption than all the other strategies and strategies 2 and 3 showing similar performances). However, in this scenario, interactions are not significant. Additional tests are required to uncover such less important effects. Figure 4.21 shows the fuel consumption boxplots for the three factors in this scenario.

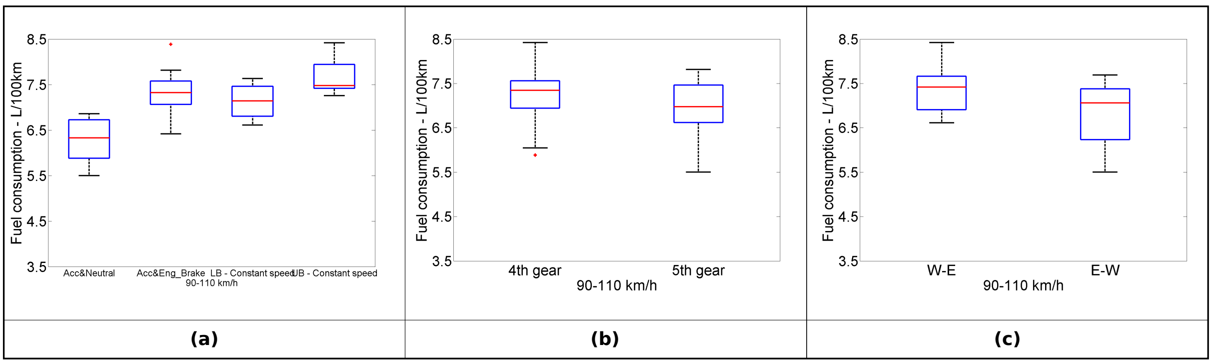


Figure 4.21: Fuel consumption boxplots for (a) the four strategies, (b) the two gears, and (c) the two directions of the 90–110 km/h scenario.

4.5 Conclusion: speed variations simulations and experimental evaluation

The aim of this chapter was to verify whether the speed variations strategies applied by athletes during long distance courses could benefit automobile fuel consumption (reduce its fuel consumption). In order to start this study, a literature review on the subject is realized, showing that the strategy of speed variations is not unknown to automotive engineers (patents and articles were published in the mid-1980s and in the end of 2000s), but could receive a deeper analysis, mainly for its benefits on conventional internal combustion engine vehiclesICEVs.

This deeper analysis included the realization of simulations using a simplified ICEV model elaborated using quasi-static models from literature and data of an existing vehicle used for tests in the LIVIC laboratory and the realization of tests in a real test track. The tests simulated the conditions of speed variation described by Lee et al. (2009), with a speed profile composed of an acceleration part and a deceleration part that could be made with engine braking (vehicle inertia and engine stops the vehicle) or coasting (vehicle inertia only stops the vehicle). While Lee et al. (2009) considers that in a conventional ICEV the engine can be turned off in coasting, the tests and simulations considered that the gear was set in neutral position and that engine operates at idle. Even with this limitation, the simulations and tests show that the speed variations produce interesting results, with a significant fuel consumption reduction when compared to a constant speed profile when the deceleration is made at coasting mode. This fuel consumption reduction comes from the fuel consumption during the deceleration phase that is lower than in a constant speed profile and from the use of better operating points of the engine during the acceleration phase when compared to the deceleration phase. When deceleration is made in engine braking mode, the results does not show a significant difference of fuel consumption when compared to the constant speed case.

Electric vehicles and hybrid vehicles were not included in the analysis presented in this chapter. Firstly, electric vehicles use electric motors for propulsion. An electric motor has a better energy efficiency than an internal - combustion engine (energy efficiency ranging from 70 to 94%, according to data presented by Sundström et al. (2008)), neutralizing the effect observed in acceleration phase (more fuel consumption but with better efficiency) and energy is already recovered during braking phases thanks to regenerative braking (the electric motor works as a generator and recharges the battery[40]). Secondly, hybrid electric vehicles also presented fuel consumption gains when realizing speed variations (Lee et al., 2009), however, the experimental setup for realizing tests with a hybrid

[40] See Box 4.1.

vehicle was not available during the realization of this research. Further work should include these tests and theoretical simulations with hybrid vehicles for completing the analysis.

Chapter 5

Discussion

Chapter contents

This chapter discusses three important aspects of the work described in the previous chapters. The first aspect is the role of biological knowledge in the design process, studied in Chapter 2. The second aspect is the application of the biologically inspired design for a company specific innovation field and its practical aspects, studied in Chapter 3. The third aspect is the modeling and evaluation of a bio-inspired concept detailed in Chapter 4.

These aspects were studied to provide answers to the two research questions related to the research problem of this thesis. The first research question being related to the role of the biological inspiration in the generation of disruptive concepts and the second to the results brought by the application of the bio-inspired design to a specific innovation field of automotive research: the reduction of CO_2 emissions produced by passenger cars.

5.1 Biologically inspired design: more than analogies

As shown in the literature review of Chapter 2, biological knowledge, the knowledge about all the living forms, has been used by humankind to develop technologies and to explain phenomena. The recent trend involving the so-called “biologically inspired design” or “biomimicry” refers to a more systematic use of biological phenomena during the design process. This use is characterized in scientific literature about design as an analogical process: biology is the source domain and the human designs are the target domain.

The modeling of the design process of the four examples chosen from literature using the C–K theory framework and operators showed that biologically inspired design goes *beyond analogies*: biological knowledge is not only a source domain for analogies. It generates concepts, expands and revises knowledge – the partitions created in the concepts space using the biological knowledge provoke an expansion (activation of new knowledge bases that would not be spontaneously activated) and a revision (a new interpretation for the existing knowledge) of the scientific (non-biological) knowledge bases in order to become knowledge.

Disentangling this other role of the biological knowledge during the design process required the use of a general design theory such as C–K theory that could model the activity of problem solving (analogies are a part of this activity) and that could understand how the knowledge bases are related and evolve during the design process.

This observation brings some elements allowing formulating an answer to the first research question of this research work: *How does biological inspiration stimulate the generation of disruptive concepts during the design process?* Biological knowledge has interesting properties that can generate expanding partitions in the concepts space and these expanding partitions guide the exploration of scientific and biological knowledge bases.

Another aspect that was disentangled with the analysis of the case examples from literature with C–K theory is the organization of this process in practice. In all cases, engineers and biologists worked together, but this interaction was more than a simple knowledge transfer from biology to engineering. Biological bases were also revised with the tools and bases of the scientific knowledge that were activated during the design process. For example, in the Flectofin®case, different models of plants movements were studied with physical models, the Bird of paradise flower was considered an interesting model for exploration as it involved a known failure mode that did not produce material failure (the buckling). Biologically-inspired design can be considered “mutually inspirational” because of this mutual expansion of knowledge bases, biological and scientific (non-biological), using properties found in each base.

5.2 Application of the biologically inspired design to a specific innovation field

The second research question of this research is related to the application of bio-inspiration to a specific field and its outcome: *Does the concepts generated using biological inspiration allow CO_2 emissions reduction for passenger cars?*

Answering this second question required the application of bio-inspiration to a specific innovation field of the automotive company where this research was realized: the “low carbon vehicle” or the reduction of CO_2 emissions produced by passenger cars. The C–K model for bio-inspiration that described in four steps the biologically inspired design is the model used in this application of bio-inspiration, as shown in Figures 5.1 and 5.2.

C-K model for bio-inspiration General steps	C-K model for bio-inspiration Application to the low carbon vehicle innovation field
1 Identification of design paths for which concept partitioning is required	- **Construction of the C-K diagram** for the "low carbon vehicle" innovation field only with scientific (non-biological) knowledge from company experts and literature about automotive research. - **Identification of design paths** for applying bio-inspiration. The chosen path is "*the energy use during the use phase of passenger cars - energy transformations (the engine) and energy recovery and reuse*".
2 Activation of biological knowledge	- Research in **general biology textbooks** about "*energy in nature*" - Identification of "**human physiology"** as an interesting knowledge base
3 Expansions in both biological and scientific knowledge bases	**- Human physiology:** *energy pathways; *activation of pathways during exercice; *limits of the different energy pathways; *methods for improving performance; *adaptations for anticipating energy requirements. **- Automotive research** *powertrain architectures; *energy management systems in hybrid vehicles; *engine design and working principles; *energy recovery methods (regenerative braking, exhaust heat energy recovery);
4 Return to the scientific knowledge bases	- Choice of a bio-inspired concept to **evaluate using scientific methods** (modeling and experimentations): * "*use of **speed variations** to save energy when the vehicle is in use*"

Figure 5.1: Application of biologically inspired design to the low carbon vehicle innovation field, based on the general steps of the C–K model for bio-inspiration developed in Chapter 2.

The use of this general model does not imply that other methods described in literature for biologi-

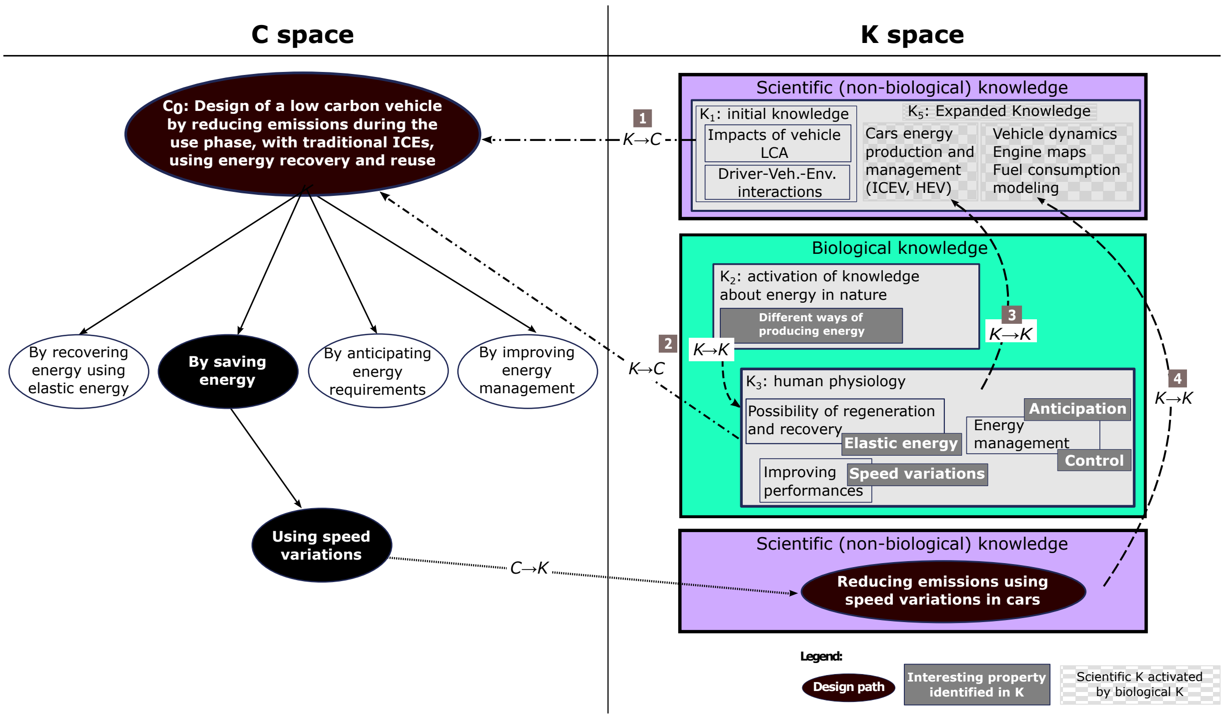


Figure 5.2: Application of biologically inspired design to the low carbon vehicle innovation field, based on the general steps of the C–K model for bio-inspiration developed in Chapter 2, represented using a C–K framework.

cally inspired design are not used during the design process: the natural language approach proposed by Shu (2010) was used to identify the first biological knowledge bases about "energy in nature" and consultations with experts (a researcher on human physiology and the company and laboratories engineering experts) were also required. The author has also used the AskNature database for gathering more information about other systems in nature that could have interesting properties besides humans.

One of the difficulties of this process was finding a suitable concept for development using bio-inspiration. Hybrid vehicles and their energy management strategies seemed a particularly interesting field for applying biological inspiration. However, this field proved to be very complex to develop during only one thesis. It would require a larger amount of time in designing new strategies inspired from human energy management systems and will be developed in further work in the research company.

Another field that could not be analyzed during this research work but that seems promising is the elastic energy recovery in vehicles. Humans and other animals use this kind of energy recovery to reduce energy expenditure during activities such as running, and cars or any rolling machine such as motorcycles or bicycles could certainly benefit from this system.

5.3 Evaluation of one bio-inspired concept using scientific methods

In this thesis, one bio-inspired concept was evaluated using scientific methods (theoretical modeling and experimentations). This concept was the use of speed variations for reducing fuel consumption when the vehicle is in use. It is interesting to notice that the analogy in this case seems very straightforward: the speed variations pattern is applied to vehicles. However, in humans, speed variations are used as a means of keeping a constant time to exhaustion (constant anaerobic energy reserves), while in vehicles it has the effect of saving fuel by making the engine work at better energy efficiency points during acceleration and not consuming or consuming only the idle fuel consumption during deceleration. In both cases, we can say that the technique allows completing a course: in the humans case completing long distances runs with less fatigue, in the cars case, complete a given journey consuming less fuel.

The speed variations application to cars was not a completely new concept, but for the engineers involved in the project, it allowed the activation of knowledge bases that would not be spontaneously activated. At the beginning of the bio-inspiration process, they did not know that speed variations could indeed provide fuel consumption reductions. This technique does not appear in the usual reviews about strategies to reduce fuel consumption of passenger cars.

The results obtained in modeling and experimentally seem promising. When compared to a journey made with constant speed during a certain amount of time, a journey having the same average speed as the constant speed journey but made with speed variations can achieve reductions up to 20% when deceleration is in coasting mode. These results are the first results of experimental trials using this protocol, and tests are required to ensure their repeatability and reproducibility with more conditions of speed variations and acceleration patterns tested. Moreover, the acceptability of speed variations to drivers and the impacts of the application of this technique in real-world traffic conditions (with other vehicles) should also be the subject of a rigorous analysis, as they will condition the applicability of speed variations to passenger cars. The safety issues related to the use of coasting mode also deserve a better characterization. Besides, this deeper study could have a comparison between the conditions in which experimentations and simulations were realized. The theoretical model has simplified assumptions about road slope and rolling resistance between the car tires and the road, and would benefit from the introduction of parameters similar to those of the experimentations, namely for these two parameters.

The speed variations were modeled and tested experimentally for ICEVs. Lee et al. (2009) also verified its interest for a hybrid vehicle tested in a dynamometer, using the same principle modeled for ICEVs: acceleration and deceleration in coasting mode. However, hybrid vehicles can be operated in different modes that could produce the same effects of speed variations (reaching better engine efficiency points) thanks to the possibility of working with two engines, the electric and the internal combustion engine. In hybrid vehicles, the internal combustion engine can be charged to operate in the best efficiency operating zones, while the electric motor completes the required torque at the wheels. In this case we would variate the engine torque at constant speed. This hybrid operating mode can possibly produce energy efficiency gains similar to those obtained with the speed variations in ICEVs. This hypothesis could be tested in further work.

Chapter 6

Conclusions and perspectives for future work

The aim of the research work and the results obtained

This research work aimed at better understanding the role of biological inspiration in the design process and applying biological inspiration to a specific innovation field of an automotive company.

The analysis of existing examples of biologically inspired design with a general design theory, the C–K theory, allowed us to disentangle two main aspects of the role of biological-inspiration during the design process, the first one is its role as a generator of expanding partitions in the concepts space, the second one is its role as a "guide" allowing the expansion and revision of biological and non-biological knowledge bases.

The application of the biologically inspired design process to the specific innovation field of the "low carbon vehicle" followed the steps provided by the analysis of examples using C–K theory (Figure 5.1). It showed that bio-inspiration can indeed help formulating bio-inspired concepts that can potentially contribute for designing the low carbon vehicle (with lower CO_2 emissions). The evaluation of one concept, the speed variations, showed that the biological knowledge does indeed have a role of activating knowledge bases that would not otherwise be activated. Speed variations for conventional cars are a concept that can be found in literature but that is not applied by automobile manufacturers. Moreover, the modeling and experimental results have promising first results allowing fuel consumption and emissions reduction.

Research implications of this thesis

The main research implications of this work for the research on biologically inspired design are:

- It provides a general framework to "guide" the steps involved in the BID process. This framework can be very useful for cases in which different design paths can benefit from biological inspiration, as it represents in the same framework concepts and knowledge bases.
- It provides explanations on the role of biological knowledge and its relation with the generation of disruptive concepts.
- It identifies a knowledge base that can provide inspiration for developing innovative vehicle energy management systems and components: human physiology.

The results obtained for the bio-inspired concept coming from the bio-inspired design process described in this work seem promising for reducing CO_2 emissions produced by passenger cars. A more complete evaluation of this concept, including evaluating speed variations in other conditions of speed intervals and acceleration patterns would provide a more accurate quantification of the benefits that this concept would bring for fuel consumption and CO_2 emissions reduction. Moreover, the framework for biological inspiration with the C–K theory is applied to the case developed in the thesis. Applying this framework in other innovation fields could corroborate the observations made in this thesis in terms of its help in the organizational aspects of the BID activity.

Perspectives for further work

This research work opens new research possibilities in two research fields: the design field and the automotive research field. The design field could continue the work started with the interpretation of bio-inspiration with C–K theory, in order to better disentangle the role of analogies in the design process, and the impact of analogies from different fields in the creativity aspects. The automotive research could continue on the development of bio-inspired energy management systems, applying speed and torque variations to hybrid vehicles, and developing the systems related to the other bio-inspired concepts, such as elastic energy recovery or anticipation of energy requirements. Moreover, this research also indicates that human physiology could also benefit from the existing models of vehicle energy management to better model and understand the energy management system of humans.

Bibliography

Abidin, Z., Arshad, M., Ngah, U., 2015. An introduction to swarming robotics: application development trends. Artificial Intelligence Review 43, 501–514.

Agogué, M., Hooge, S., Arnoux, F., Brown, I., 2014a. An Introduction to Innovative Design: Elements and Applications of C-K theory. Presses des MINES.

Agogué, M., Kazakçi, A., Hatchuel, A., Le Masson, P., Weil, B., Poirel, N., Cassotti, M., 2014b. The impact of type of examples on originality: Explaining fixation and stimulation effects. The Journal of Creative Behavior 48, 1–12.

Alazemi, J., Andrews, J., 2015. Automotive hydrogen fuelling stations: An international review. Renewable and Sustainable Energy Reviews 48, 483 – 499.

Alexander, R.M., 1984. Walking and running: Legs and leg movements are subtly adapted to minimize the energy costs of locomotion. American Scientist 72, 348–354.

Amditis, A., Pagle, K., Joshi, S., Bekiaris, E., 2010. Driver–vehicle–environment monitoring for on-board driver support systems: Lessons learned from design and implementation. Applied Ergonomics 41, 225 – 235. Special Section: Behavioural Effects and Drive-Vehicle-Environment Modelling in Modern Automotive Systems.

Amsterdamer, Y., Molin, H., 2011. Les experts leaders face à l'innovation de rupture : des méthodes de construction et de gestion de l'expertise. Rapport de Stage - Option IC. Mines ParisTech.

ANFAC, 2013. European motor vehicle parc 2011. Technical Report. ANFAC. Accessed on 10.05.2015. Available at:. http://www.acea.be/uploads/statistic_documents/2013_ANFAC_Report.pdf.

Atabani, A., Badruddin, I.A., Mekhilef, S., Silitonga, A., 2011. A review on global fuel economy standards, labels and technologies in the transportation sector. Renewable and Sustainable Energy Reviews 15, 4586 – 4610.

Autumn, K., 2006. L'inusable adhésif des pattes du gecko. Pour la science (originally published in American Scientist, vol.94, Number 2, March-April 2006, page 124, How gecko toes stick) , 82 – 88.

Autumn, K., Liang, Y.A., Hsieh, S.T., Zesch, W., Chan, W.P., Kenny, T.W., Fearing, R., Full, R.J., 2000. Adhesive force of a single gecko foot-hair. Nature 405, 681 – 684.

Avins, J., 1978. Automatic control of free wheeling. US Patent 4,084,672.

Avins, J., 1983. Automotive control systems for improving fuel consumption. US Patent 4,408,293.

Badarnah Kadri, L., 2012. Towards the LIVING envelope – Biomimetics for building envelope adaptation. Ph.D. thesis. Technische Universiteit Delft.

Badin, F., 2013. Les véhicules hybrides. Editions Technip. chapter L'hybridation. pp. 285–380.

Bar-Cohen, Y., 2006. Biomimetics - using nature to inspire human innovation. Bioinspiration & Biomimetics 1, P1.

Bar-Cohen, Y., 2012. Biomimetics: nature based innovations. CRC press.

Barkenbus, J.N., 2010. Eco-driving: An overlooked climate change initiative. Energy Policy 38, 762 – 769.

Baron, E., Pescarou, P., 2013. Transmissions dans l'automobile - influence sur la consommation du véhicule, in: Techniques de l'Ingénieur. volume BM2584.

Barthlott, W., 1997. Self-cleaning surfaces of objects and process for producing same. European Patent EP 0772514 B1.

Barthlott, W., Neinhuis, C., 1997. Purity of the sacred lotus, or escape from contamination in biological surfaces. Planta 202, 1–8.

Barthlott, W., Neinhuis, C., 2000. Method of producing self-cleaning detachable surfaces.

Bartlett, M.D., Croll, A.B., King, D.R., Paret, B.M., Irschick, D.J., Crosby, A.J., 2012. Looking beyond fibrillar features to scale gecko-like adhesion. Advanced Materials 24, 1078–1083.

Baumgartner, A., Harzheim, L., Mattheck, C., 1992. SKO (soft kill option): the biological way to find an optimum structure topology. International Journal of Fatigue 14, 387 – 393.

Bellu, S., 1998. Histoire mondiale de l'automobile. Flammarion.

Benyus, J.M., 1997. Biomimicry: innovation inspired by nature. William Morrow and Co.

Bhushan, B., 2009. Biomimetics: lessons from nature - an overview. Philosophical Transactions of the Royal Society A: Mathematical,Physical and Engineering Sciences 367, 1445–1486.

Billat, V., 2012. Physiologie & méthodologie de l'entraînement: de la théorie à la pratique. De Boeck.

Billat, V., 2013. VO_2 max à l'épreuve du temps. De Boeck.

Billat, V., Hamard, L., Koralsztein, J.P., Morton, R.H., 2009. Differential modeling of anaerobic and aerobic metabolism in the 800–m and 1,500–m run. Journal of Applied Physiology 107, 478–487.

Biomimicry3.8, 2015a. Biomimicry design lens: Life's principles. Accessed on 06.09.2015. Available at:. http://biomimicry.net/about/biomimicry/biomimicry-designlens/lifes-principles/.

Biomimicry3.8, 2015b. Biomimicry design lens: Biomimicry thinking. Accessed on 06.09.2015. Available at:. http://biomimicry.net/about/biomimicry/biomimicry-designlens/biomimicry-thinking/.

Boer, E.R., Hoedemaeker, M., 1998. Modeling driver behavior with different degrees of automation: A hierarchical decision framework of interacting mental models, in: Conference on human decision making and manual control, Valenciennes, December 14-16, 1998, LAMIH.

Boesel, L.F., Greiner, C., Arzt, E., del Campo, A., 2010. Gecko-inspired surfaces: A path to strong and reversible dry adhesives. Advanced Materials 22, 2125–2137.

Bonnans, J., Aftalion, A., 2013. Optimization of running strategies based on anaerobic energy and variations of velocity. Technical Report. INRIA.

Bonser, R.H., 2006. Patented biologically-inspired technological innovations: A twenty year view. Journal of Bionic Engineering 3, 39 – 41.

Bowyer, D., Akçelik, R., Biggs, D., 1985. Guide to Fuel Consumption Analysis for Urban Traffic Management. Special Report 32. ARRB Transport Research Ltd., Vermont South, Australia.

Braha, D., Reich, Y., 2003. Topological structures for modeling engineering design processes. Research in Engineering Design 14, 185–199.

Börjesson, S., Elmquist, M., Hooge, S., 2014. The challenges of innovation capability building: Learning from longitudinal studies of innovation efforts at Renault and Volvo Cars. Journal of Engineering and Technology Management 31, 120 – 140.

Brook, R., Brook, J., Rajagopalan, S., 2003. Air pollution: The "heart" of the problem. Current Hypertension Reports 5, 32–39.

Burgess, S., Choi, J., 2003. A parametric study of the energy demands of car transportation: a case study of two competing commuter routes in the uk. Transportation Research Part D: Transport and Environment 8, 21 – 36.

Cade, R., Packer, D., Zauner, C., Kaufmann, D., Peterson, J., Mars, D., Privette, M., Hommen, N., Fregly, M.J., Rogers, J., 1992. Marathon running: physiological and chemical changes accompanying late-race functional deterioration. European Journal of Applied Physiology and Occupational Physiology 65, 485–491.

Campbell, R.W., Hunsberger, J.R., 1962. Energy recovery incentive for regenerative braking. SAE Technical Paper .

Carey, H.V., Andrews, M.T., Martin, S.L., 2003. Mammalian hibernation: Cellular and molecular responses to depressed metabolism and low temperature. Physiological Reviews 83, 1153–1181.

Chakrabarti, A., 2014. Biologically Inspired Design: Computational Methods and Tools. Springer-Verlag London. chapter Supporting analogical transfer in biologically inspired design. pp. 201 – 220.

Chakrabarti, A., Sarkar, P., Leelavathamma, B., Nataraju, B., 2005. A functional representation for aiding biomimetic and artificial inspiration of new ideas. Artificial Intelligence for Engineering Design, Analysis and Manufacturing 19, 113–132.

Chan, C., 2007. The state of the art of electric, hybrid, and fuel cell vehicles. Proceedings of the IEEE 95, 704–718.

Chang, D., Morlok, E., 2005. Vehicle speed profiles to minimize work and fuel consumption. Journal of Transportation Engineering 131, 173–182.

Cheng, Qi, N.L.O.O., 2013. A piecewise vehicle fuel consumption model for eco-driving assistance system, in: IAVSD 2013.

Chiu, I., Shu, L.H., 2005. Bridging cross-domain terminology for biomimetic design. ASME Conference Proceedings. ASME Int. Design Engineering Technical Conf., Long Beach, CA, September 24–28 2005, 93–101.

Clarke, P., Muneer, T., Cullinane, K., 2010. Cutting vehicle emissions with regenerative braking. Transportation Research Part D: Transport and Environment 15, 160 – 167.

Code de la route, 2016. Articles R413-2 to R413-3. Légifrance. Accessed on 06.01.2016. Available at:. https://www.legifrance.gouv.fr/.

Coiret, A., Vandanjon, P.O., Bosquet, R., Jullien, A., 2012. Energy consumption induced by operation phase of railways and road infrastructures, in: CETRA 2012, 2nd International Conference on Road and Rail Infrastructure.

Colvile, R., Hutchinson, E., Mindell, J., Warren, R., 2001. The transport sector as a source of air pollution. Atmospheric Environment 35, 1537 – 1565.

Continental, 2014. Giving engines a break: Continental's "48-volt eco drive" technology significantly reduces fuel consumption. Accessed on 08.08.2015. Available at:. http://www.continental-corporation.com/www/pressportal_com_en/themes/press_releases/3_automotive_group/powertrain/press_releases/pr_2014_11_12_48_volt_vox_en.html.

Crew, H., De Salvio, A., 1914. trans. Dialogues Concerning Two New Sciences by Galileo Galilei. The Macmillian Company.

Daimler, 2011. The future of the original. the research cars of mercedes-benz. Accessed on 13.10.2014. Available at:. http://www.daimler.com/downloads/en.

Damm, D.L., Fedorov, A.G., 2008. Conceptual study of distributed CO_2 capture and the sustainable carbon economy. Energy Conversion and Management 49, 1674 – 1683.

Dawson, C., Vincent, J.F.V., Rocca, A.M., 1997. How pine cones open. Nature 390, 668.

Dawson, T.J., Taylor, C.R., 1973. Energetic cost of locomotion in kangaroos. Nature 246, 313–314.

Degraeuwe, B., Beusen, B., 2013. Corrigendum on the paper "using on-board data logging devices to study the longer-term impact of an eco-driving course". Transportation Research Part D: Transport and Environment 19, 48 – 49.

Deldin, J.M., Schuknecht, M., 2014. Biologically inspired design: computational methods and tools. Springer-Ver. chapter The AskNature Database: Enagling Solutions in Biomimetic Design. pp. 17–27.

Desai, C., Williamson, S.S., 2009. Comparative study of hybrid electric vehicle control strategies for improved drivetrain efficiency analysis, in: Electrical Power & Energy Conference (EPEC), IEEE. pp. 1–6.

Dincer, I., Acar, C., 2015. Review and evaluation of hydrogen production methods for better sustainability. International Journal of Hydrogen Energy 40, 11094 – 11111.

Direnzi, N.J., 2011. The Use of Elastically-Based Mechanical Energy Storage in Motor Vehicles. Ph.D. thesis. University of Dayton.

Durand, H., Larrieu, C., Hubert, C., 2012. Étude sur la contribution du biomimétisme à la transition vers une économie verte en France : état des lieux, potentiel, leviers. Technical Report. Ministère de l'Ecologie, du Développement Durable, des Transports et du Logement - Comissariat Général au Développement Durable.

Eloy, C., 2011. Leonardo's rule, self-similarity, and wind-induced stresses in trees. Phys. Rev. Lett. 107, 258101.

Enke, K., 1979. Possibilities for improving safety within the driver-vehicle- environment control loop, in: Proceedings of the 7th Int. Experimental Safety Vehicles Conference.

ESA, 2015. ESA - Advanced Concepts Team Biomimetics. Accessed on 17.01.2015. Available at:. http://www.esa.int/gsp/ACT/bio/.

European Commission, 2013. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. com(2013) 216 edition.

Faiz, A., Weaver, C.S., Walsh, M.P., 1996. Air pollution from motor vehicles: Standards and technologies for controlling emissions. The World Bank.

Farley, C.T., Glasheen, J., McMahon, T.A., 1993. Running springs: speed and animal size. Journal of Experimental Biology 185, 71–86.

Fish, F.E., Battle, J.M., 1995. Hydrodynamic design of the humpback whale flipper. Journal of Morphology 225, 51–60.

Fish, F.E., Weber, P.W., Murray, M.M., Howle, L.E., 2011. The tubercles on humpback whales' flippers: Application of bio-inspired technology. Integrative and Comparative Biology 51, 203–213.

Fonseca, N., Casanova, J., Valdés, M., 2011. Influence of the stop/start system on CO_2 emissions of a diesel vehicle in urban traffic. Transportation Research Part D: Transport and Environment 16, 194 – 200.

Fontaras, G., Samaras, Z., 2010. On the way to 130 gCO_2/km–estimating the future characteristics of the average european passenger car. Energy Policy 38, 1826 – 1833.

Freitas Salgueiredo, C., Hatchuel, A., 2014. Modeling biologically inspired design with the C–K design theory, in: Marjanovic, D., Storga, M., Pavkovic, N., Bojcetic, N. (Eds.), Proceedings of the DESIGN 2014 13th International Design Conference, pp. 23 – 32.

Freitas Salgueiredo, C., Hatchuel, A., 2016. Beyond analogy: A model of bioinspiration for creative design. Artificial Intelligence for Engineering Design, Analysis and Manufacturing 30, 159 – 170.

Freitas Salgueiredo, C., Orfila, O., Saint Pierre, G., Coiret, A., Vandanjon, P.O., Doublet, P., Doncieux, S., Glaser, S., 2014. Overview of strategies for reducing CO_2 emissions during the use phase of passenger cars. Proceedings of the Transport Research Arena 2014 (TRA2014), Paris, France .

Fulton, L., Cazzola, P., Cuenot, F., 2009. IEA Mobility Model (MoMo) and its use in the ETP 2008. Energy Policy 37, 3758 – 3768. Carbon in Motion: Fuel Economy, Vehicle Use, and Other Factors affecting CO_2 Emissions From Transport.

Gastin, P., 2001. Energy system interaction and relative contribution during maximal exercise. Sports Medicine 31, 725–741.

Gattuso, J.P., Allemand, D., Frankignoulle, M., 1999. Photosynthesis and calcification at cellular, organismal and community levels in coral reefs: A review on interactions and control by carbonate chemistry. American Zoologist 39, 160–183.

Geim, A.K., Dubonos, S.V., Grigorieva, I.V., Novoselov, K.S., Zhukov, a.a., Shapoval, S.Y., 2003. Microfabricated adhesive mimicking gecko foot-hair. Nature Materials 2, 461–463.

Gentner, D., 1983. Structure-mapping: A theoretical framework for analogy. Cognitive Science 7, 155 – 170.

Gerard, D., Lave, L.B., 2005. Implementing technology-forcing policies: The 1970 clean air act amendments and the introduction of advanced automotive emissions controls in the united states. Technological Forecasting and Social Change 72, 761 – 778.

Gillespie, T.D., 1992. Fundamentals of vehicle dynamics. Society of Automotive Engineers.

Glaser, S., Rakotonirainy, A., Gruyer, D., Nouveliere, L., 2007. An integrated driver-vehicle-environment model to assess crash risks, in: Proceedings of the 2007 Australasian Road Safety Research, Policing and Education Conference.

Gleich, A.v., Pade, C., Petschow, U., Pissarskoi, E., 2009. Potentials and trends in biomimetics. Springer.

Goel, A.K., Vattam, S., Wiltgen, B., Helms, M., 2014. Biologically Inspired Design: Computational Methods and Tools. Springer-Verlag London. chapter Information processing theories of biologically inspired design. pp. 127 – 152.

Goldstein, A., 1997. Facets : new perspectives on the history of semiconductors. IEEE Center for the History of Electrical Engineering. chapter Jack Avins: the essence of engineering. pp. 133 — 214.

Guglielmo, C.G., 2010. Move that fatty acid: Fuel selection and transport in migratory birds and bats. Integrative and Comparative Biology , 1–10.

Guzzella, L., Sciarretta, A., 2005. Vehicle propulsion systems. Springer.

Harkness, J.M., 2002. In appreciation – a lifetime of connections: Otto herbert schmitt, 1913 - 1998. Physics in Perspective 4, 456–490.

Harrison, G., Shepherd, S., 2014. An interdisciplinary study to explore impacts from policies for the introduction of low carbon vehicles. Transportation Planning and Technology 37, 98–117.

Hatchuel, A., Le Masson, P., Weil, B., 2011. Teaching innovative design reasoning: How concept–knowledge theory can help overcome fixation effects. Artificial Intelligence for Engineering Design, Analysis and Manufacturing 25, 77–92.

Hatchuel, A., Masson, P.L., Reich, Y., Weil, B., 2011b. A systematic approach of design theories using generativeness and robustness, in: Culley, S., Hicks, B., McAloone, T., Howard, T., Reich, Y. (Eds.), Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, pp. 87–97.

Hatchuel, A., Weil, B., 2003. A new approach of innovative design: an introduction to C–K theory, in: Proceedings of the 14th International Conference on Engineering Design (ICED'03), Stockholm, Sweden, pp. 109–124.

Hatchuel, A., Weil, B., 2009. C–K design theory: an advanced formulation. Research in Engineering Design 19, 181–192.

Hatchuel, A., Weil, B., Masson, P., 2012. Towards an ontology of design: lessons from C–K design theory and forcing. Research in Engineering Design , 1–17.

Hawkins, T.R., Gausen, O., Stromman, A., 2012. Environmental impacts of hybrid and electric vehicles – a review. The International Journal of Life Cycle Assessment 17, 997–1014.

He, Y., Chowdhury, M., Ma, Y., Pisu, P., 2012. Merging mobility and energy vision with hybrid electric vehicles and vehicle infrastructure integration. Energy Policy 41, 599 – 609. Modeling Transport (Energy) Demand and Policies.

Helfman Cohen, Y., Reich, Y., Greenberg, S., 2011. What can we learn from biological systems when applying the law of system completeness? TRIZ future 2011, Dublin, Ireland .

Helfman Cohen, Y., Reich, Y., Greenberg, S., 2012. Substance field analysis and biological functions. TRIZ future 2012, Lisbon, Portugal .

Helfman Cohen, Y., Reich, Y., Greenberg, S., 2014. Biomimetics: Structure–Function Patterns Approach.

Journal of Mechanical Design 136, 111108.

Helms, M., Goel, A., 2012. Analogical problem evolution in biologically inspired design, in: Gero, J.S. (Ed.), Design Computing and Cognition ’12. Springer Netherlands, pp. 3–19.

Helms, M., Vattam, S.S., Goel, A.K., 2009. Biologically inspired design: process and products. Design Studies 30, 606 – 622.

Hesselberg, T., 2007. Biomimetics and the case of the remarkable ragworms. Naturwissenschaften 94, 613–621.

Heywood, J., 1988. Internal Combustion Engine Fundamentals. McGraw-Hill, New York.

Hochachka, P.W., 1985. Fuels and pathways as designed systems for support of muscle work. Journal of Experimental Biology 115, 149–164.

Holland, S.P., 2008. Modeling peak oil. The Energy Journal 29, pp. 61–79.

Holyoak, K.J., 1985. The psychology of learning and motivation. Academic Press. volume 19. chapter The pragmatics of analogical transfer. pp. 59–87.

Hooker, J., 1988. Optimal driving for single-vehicle fuel economy. Transportation Research Part A: General 22, 183 – 201.

Hu, J., Wu, Y., Wang, Z., Li, Z., Zhou, Y., Wang, H., Bao, X., Hao, J., 2012. Real-world fuel efficiency and exhaust emissions of light-duty diesel vehicles and their correlation with road conditions. Journal of Environmental Sciences 24, 865 – 874.

ICCT, 2014. European Vehicle Market Statistics - Pocketbook 2014. Technical Report. International Council on Clean Transportation.

Ickx, J., 1971. Ainsi naquit l’automobile. Edita S.A. Lausanne.

IEA, 2012a. Technology Roadmap: fuel economy of road vehicles. Technical Report. International Energy Agency.

IEA, 2012b. Energy Technology Perspectives. Technical Report. International Energy Agency.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC.

ISO standard, 2006. Environmental management – life cycle assessment – principles and framework.

Jacobson, S.H., King, D.M., 2009. Fuel saving and ridesharing in the us: Motivations, limitations, and opportunities. Transportation Research Part D: Transport and Environment 14, 14 – 21.

Johnson, V.E., 2013. Revised standards for statistical evidence. Proceedings of the National Academy of Sciences 110, 19313–19317.

JRC, 2014. WELL-to-WHEELS Report version 4a. Technical Report. Joint Research Centre - EUCAR - CONCAWE.

Kato, Y., Otsuka, K., Liu, C., 2005. Carbon dioxide zero-emission hydrogen carrier system for fuel cell vehicle. Chemical Engineering Research and Design 83, 900 – 904. 7th World Congress of Chemical Engineering.

Katrašnik, T., 2011. Energy conversion phenomena in plug-in hybrid-electric vehicles. Energy Conversion and Management 52, 2637 – 2650.

Kennedy, J., Eberhart, R., 1995. Particle swarm optimization, in: Neural Networks, 1995. Proceedings., IEEE International Conference on, pp. 1942–1948 vol.4.

Kessler, C., Etemad, A., Alessandretti, G., Heinig, K., Selpi, Brouwer, R., Cserpinsky, A., Hagleitner, W., Benmimoun, M., 2012. European Large–Scale Field Operational Tests on In-Vehicle Systems, EuroFOT, Final Report. Technical Report.

Kiencke, U., Dais, S., Litschel, M., 1986. Automotive serial controller area network. SAE Technical Paper .

Kirsch, D.A., 1997. The electric car and the burden of history: Studies in automotive systems rivalry in america,1890-1996, in: Business and economic history, Business history conference, pp. 304–310.

Knippers, J., Speck, T., 2012. Design and construction principles in nature and architecture. Bioinspiration & Biomimetics 7, 015002.

Koch-Groeber, H., Wang, J., 2014. Criteria for coasting on highways for passenger cars. SAE Technical Paper .

Korzenietz, P., 2013. Requirements analysis for a universal system architecture for ecological and economical driver assistance systems, in: Maurer, M., Winner, H. (Eds.), Automotive Systems Engineering. Springer Berlin Heidelberg, pp. 63–79.

Krinke, S., BoBdorf-Zimmer, B., Goldmann, D., 2005. Executive Summary -Life cycle assessment of end-of-life vehicle treatment. Technical Report. Volkswagen AG.

Kroll, E., Le Masson, P., Weil, B., 2014. Steepest-first exploration with learning-based path evaluation: un-covering the design strategy of parameter analysis with C–K theory. Research in Engineering Design 25, 351–373.

Lamp, P., Tachtler, J., Finkenwirth, O., Mukerjee, S., Shaffer, S., 2003. Development of an auxiliary power unit with solid oxide fuel cells for automotive applications. Fuel Cells 3, 146–152.

Lapola, D.M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C., Priess, J.A., 2010. Indirect land-use changes can overcome carbon savings from biofuels in brazil. Proceedings of the National Academy of Sciences 107, 3388–3393.

Larsson, H., Ericsson, E., 2009. The effects of an acceleration advisory tool in vehicles for reduced fuel consumption and emissions. Transportation Research Part D: Transport and Environment 14, 141 – 146.

Leduc, G., Mongelli, I., Uihlein, A., Nemry, F., 2010. How can our cars become less polluting? an assessment of the environmental improvement potential of cars. Transport Policy 17, 409 – 419.

Lee, J., 2009. Vehicle Inertia Impact on Fuel Consumption of Conventional and Hybrid Electric Vehicles Using Acceleration and Coast Driving Strategy. Ph.D. thesis. Virginia Polytechnic Institute and State University.

Lee, J., Nelson, D.J., Lohse-Busch, H., 2009. Vehicle inertia impact on fuel consumption of conventional and hybrid electric vehicles using acceleration and coast driving strategy, in: SAE World Congress & Exhibition, SAE International.

Lenau, T., Dentel, A., Ingvarsdottir, P., Gudlaugsson, T., 2010. Engineering design of an adaptive leg prosthesis using biological principles, in: Marjanovic, D., Storga, M., Pavkovic, N., Bojcetic, N. (Eds.), Proceedings of DESIGN 2010, the 11th International Design Conference, Dubrovnik, Croatia, pp. 331 – 340.

Lenau, T., Helten, K., Hepperle, C., Schenkl, S., Lindemann, U., 2011. Reducing Consequences of Car Collision using Inspiration from Nature. TU Delft.

Lenau, T.A., Keshwani, S., Chakrabarti, A., Ahmed-Kristensen, S., 2015. Biocards and level of abstraction, in: Proceedings of the 20th International Conference on Engineering Design (ICED15), Design Society.

Lepora, N.F., Verschure, P., Prescott, T.J., 2013. The state of the art in biomimetics. Bioinspiration & Biomimetics 8, 013001.

Levine, B.D., 2008. Vo2max: what do we know, and what do we still need to know? The Journal of Physiology 586, 25–34.

Li, S.E., Peng, H., 2012. Strategies to minimize the fuel consumption of passenger cars during car-following scenarios. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 226, 419–429.

Lienhard, J., Poppinga, S., Schleicher, S., Masselter, T., Speck, T., Knippers, J., 2009. Abstraction of plant movements for deployable structures in architecture, in: Proceedings of the 6th Plant Biomechanics Conference, pp. 389–397.

Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T., Knippers, J., 2011. Flectofin: a hingeless flapping mechanism inspired by nature. Bioinspiration & Biomimetics 6, 045001.

Lindemann, U., Gramann, J., 2004. Engineering design using biological principles, in: D., M. (Ed.), Proceedings of DESIGN 2004, the 8th International Design Conference, Dubrovnik, Croatia, pp. 355 – 360.

Lindström, B., Karlsson, J., Ekdunge, P., Verdier, L.D., Häggendal, B., Dawody, J., Nilsson, M., Pettersson, L., 2009. Diesel fuel reformer for automotive fuel cell applications. International Journal of Hydrogen Energy 34, 3367 – 3381.

López Avila, L.A., 2014. Incorporating the Innovation Process in a Product Development Organi. Master's thesis. Massachusetts Institute of Technology.

Lutsey, N., 2012. A technical analysis of model year 2011 us automobile efficiency. Transportation Research Part D: Transport and Environment 17, 361 – 369.

Luu, H.T., 2010. Développement de méthodes de réduction de la consommation en carburant d'un véhicule dans un contexte de sécurité et confort : un compromis entre économie et énergie. Ph.D. thesis. Université d'Evry-Val-d'Essonne.

Ma, H., Balthasar, F., Tait, N., Riera-Palou, X., Harrison, A., 2012. A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal combustion vehicles. Energy Policy 44, 160 – 173.

MacCurdy, E., 1955. trans. The notebooks of Leonardo da Vinci. George Braziller.

Maderson, P.F.A., 1964. Keratinized Epidermal Derivatives as an Aid to Climbing in Gekkonid Lizards. Nature 203, 780–781.

Mak, T., Shu, L., 2008. Using descriptions of biological phenomena for idea generation. Research in Engineering Design 19, 21–28.

Manzie, C., Watson, H., Halgamuge, S., 2007. Fuel economy improvements for urban driving: Hybrid vs. intelligent vehicles. Transportation Research Part C: Emerging Technologies 15, 1 – 16.

Margaria, R., 1972. The sources of muscular energy. Scientific American 226, 84–91.

Margheri, L., Laschi, C., Mazzolai, B., 2012. Soft robotic arm inspired by the octopus: I. from biological functions to artificial requirements. Bioinspiration & Biomimetics 7, 025004.

Markel, T., Brooker, A., Hendricks, T., Johnson, V., Kelly, K., Kramer, B., O'Keefe, M., Sprik, S., Wipke, K., 2002. Advisor: a systems analysis tool for advanced vehicle modeling. Journal of Power Sources 110, 255 – 266.

Martin, D.E., 1995. Physiology – its role in explaining athletic performance. New Studies in Athletics 10, 9 – 12.

Masselter, T., Barthlott, W., Bertling, J., Cichy, F., Hermann, M., Knippers, J., Luchsinger, R., Mattheck, C., Milwich, M., Neinhuis, C., 2012. Biomimetics: nature based innovations. CRC press. chapter Biomimetic Products. pp. 377–429.

Matini, M., Knippers, J., 2008. Application of "abstract formal patterns" for translating natural principles into the design of new deployable structures in architecture, in: Brebbia, C. (Ed.), Design and Nature IV, Comparing Design in Nature with Science and Engineering, pp. 147 – 156.

Mayer, H., 1999. Air pollution in cities. Atmospheric Environment 33, 4029 – 4037.

Mazzolai, B., Margheri, L., Cianchetti, M., Dario, P., Laschi, C., 2012. Soft-robotic arm inspired by the octopus: Ii . from artificial requirements to innovative technological solutions. Bioinspiration & Biomimetics 7, 025005.

Mc Gilvery, R., 1975. The use of fuels for muscular work, in: Howald, H., Poortmans, J. (Eds.), Metabolic Adaptation to Prolonged Physical Exercise. Birkhäuser Basel, pp. 12–30.

Menon, C., Ayre, M., Ellery, A., 2006. Biomimetics-a new approach for space system design. ESA bulletin 125, 20–26.

Michon, J.A., 1985. A critical view of driver behavior models: What do we know, what should we do?, in: Evans, L., Schwing, R. (Eds.), Human Behavior and Traffic Safety. Springer US, pp. 485–524.

Mitchell, William J.& Borroni-Bird, C.E.L.D., 2010. Reinventing the automobile: Personal urban mobility for the 21st century. The MIT press.

Mock, P., Kühlwein, J., Tietge, U., Franco, V., Bandivadekar, A., German, J., 2014. The WLTP: How a new test procedure for cars will affect fuel consumption values in the EU. Technical Report. ICCT.

Moroney, J.V., Ynalvez, R.A., 2009. Algal Photosynthesis. John Wiley & Sons, Ltd.

Morton, R., 2006. The critical power and related whole-body bioenergetic models. European Journal of Applied Physiology 96, 339–354.

Morton, R., Billat, L., 2004. The critical power model for intermittent exercise. European Journal of Applied Physiology 91, 303–307.

Murray, J., King, D., 2012. Climate policy: Oil's tipping point has passed. Nature 481, 433 – 435.

Murray, K.D., Murray, K.A., 2010. Captured CO2 from atmospheric, industrial and vehicle combustion waste. US Patent 7,914,758.

Musardo, C., Rizzoni, G., Staccia, B., 2005. A–ECMS: An adaptive algorithm for hybrid electric vehicle energy management, in: Decision and Control, 2005 and 2005 European Control Conference. CDC-ECC '05. 44th IEEE Conference on, pp. 1816–1823.

Nagel, J.K., Nagel, R.L., Stone, R.B., McAdams, D.A., 2010. Function-based, biologically inspired concept generation. Artificial Intelligence for Engineering Design, Analysis and Manufacturing 24, 521–535.

Nagel, J.K., Stone, R.B., 2012. A computational approach to biologically inspired design. Artificial Intelligence for Engineering Design, Analysis and Manufacturing 26, 161–176.

Nagel, J.K., Stone, R.B., McAdams, D.A., 2014. Biologically inspired Design: Computational Methods and Tools. Springer-Verlag London. chapter Function-based biologically inspired design. pp. 95 – 125.

Nature, 1932. Regenerative braking on trains. Nature 129, 864.

Nègre, L., 2011. Structuration de la filière des véhicules décarbonés. Rapport. Sénat (France).

Newsholme, E., Leech, T., 2010. Functional biochemistry in health and disease. Wiley-Blackwell.

NRC, 2011. Assessment of Fuel Economy Technologies for Light-Duty Vehicles. Technical Report. National Research Council,Committee on the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy.

Orfila, O., Pierre, G.S., Andrieu, C., 2012. Gear shifting behavior model for ecodriving simulations based on experimental data. Procedia - Social and Behavioral Sciences 54, 341 – 348. (Proceedings of EWGT2012 - 15th Meeting of the EURO Working Group on Transportation, September 2012, Paris).

Ort, D.R., Kramer, D., 2009. Photosynthesis. John Wiley & Sons, Ltd.

Paganelli, G., Delprat, S., Guerra, T., Rimaux, J., Santin, J., 2002. Equivalent consumption minimization strategy for parallel hybrid powertrains, in: Vehicular Technology Conference, 2002. VTC Spring 2002. IEEE 55th, pp. 2076–2081 vol.4.

Pahl, A.K., Beitz, W., 1988. Engineering Design – A Systematic Approach. Springer-Verlag 1977.

Pahl, G., Beitz, W., 1977. Konstruktionslehre (english title: Engineering design). Springer Berlin Heidelberg.

Peters, T., 2011. Nature as measure: The biomimicry guild. Architectural Design 81, 44–47.

Porsche, 2015. Porsche caymann - coasting - porsche cars north america. Access on 08.08.2015. Available at:. http://www.porsche.com/usa/models/cayman/cayman/drive/coasting/.

Pourkhesalian, A.M., Shamekhi, A.H., Salimi, F., 2010. Alternative fuel and gasoline in an SI engine: A comparative study of performance and emissions characteristics. Fuel 89, 1056 – 1063.

Powers, S.K., Lawler, J., Criswell, D., Dodd, S., Grinton, S., Bagby, G., Silverman, H., 1990. Endurance-training-induced cellular adaptations in respiratory muscles. Journal of Applied Physiology 68, 2114–2118.

Priest, T., 2014. Hubbert's peak: The great debate over the end of oil. Historical Studies in the Natural Sciences 44, 37 – 79.

PSA Peugeot Citroën, 2013. Hybrid air, an innovative full hybrid gasoline system. Accessed on 17.01.2015. Available at:. http://www.psa-peugeot-citroen.com/en/automotive-innovation/innovation-by-psa/hybrid-air-engine-full-hybrid-gasoline.

Rapoport, B.I., 2010. Metabolic factors limiting performance in marathon runners. PLoS Comput Biol 6, 1–13.

Reich, Y., 1995. A critical review of general design theory. Research in Engineering Design 7, 1–18.

Reich, Y., Hatchuel, A., Shai, O., Subrahmanian, E., 2012. A theoretical analysis of creativity methods in engineering design: casting and improving ASIT within C–K theory. Journal of Engineering Design 23, 137–158.

Reif, K., Dietsche, K.H., 2014. Automotive Handbook. Robert Bosch GmbH.

Renault, 2011. Fluence and Fluence Z.E. – life cycle assessment. Technical Report. Renault.

Renault, 2014. With 1 litre/100 km, EOLAB is a showcase for Renault's innovations in favour of the environment and rises to the challenge of ultra low fuel consumption (press kit). Electronic. Accessed on: 03.05.2015. Available at:. http://media.renault.com/download/media/specialfile/61732_1_5.aspx.

Renault, 2015. Renault CLIO brochure. Renault. Accessed on 13.12.2015. Available at:. http://www.renault.fr/e-brochure/CL4_1/pdf/fullPDF.pdf.

Riebesell, U., Zondervan, I., Rost, B., Tortell, P.D., Zeebe, R.E., Morel, F.M.M., 2000. Reduced calcification of marine plankton in response to increased atmospheric CO_2. Nature 6802, 364–367.

Rollier, J.D., Gonzalez-Aguilar, J., Petitpas, G., Darmon, A., Fulcheri, L., Metkemeijer, R., 2008. Experimental study on gasoline reforming assisted by nonthermal arc discharge. Energy & Fuels 22, 556–560.

Romm, J., 2006. The car and fuel of the future. Energy Policy 34, 2609 – 2614.

Rus, D., Tolley, M., 2015. Design, fabrication and control of soft robots. Nature 521, 467 – 475.

Sadava, D., Hillis, D.M., Heller, H.C., Berenbaum, M.R., 2011. Life: The Science of Biology. Sinauer Associates, Inc.

Saerens, B., 2012. Optimal Control Based Eco-Driving – Theoretical Approach and Practical Applications. Ph.D. thesis. Katholieke Universiteit Leuven.

Saidur, R., Rezaei, M., Muzammil, W., Hassan, M., Paria, S., Hasanuzzaman, M., 2012. Technologies to recover exhaust heat from internal combustion engines. Renewable and Sustainable Energy Reviews 16, 5649 – 5659.

Salomo, S., Talke, K., Strecker, N., 2008. Innovation field orientation and its effect on innovativeness and firm performance. Journal of Product Innovation Management 25, 560–576.

Santucci, A., Sorniotti, A., Lekakou, C., 2014. Power split strategies for hybrid energy storage systems for vehicular applications. Journal of Power Sources 258, 395 – 407.

Sartori, J., Pal, U., Chakrabarti, A., 2010. A methodology for supporting ”transfer” in biomimetic design. Artificial Intelligence for Engineering Design, Analysis and Manufacturing 24, 483–506.

Schenau, G.I., Cavanagh, P., 1990. Power equations in endurance sports. Journal of Biomechanics 23, 865 – 881.

Schipper, L., 2011. Automobile use, fuel economy and CO_2 emissions in industrialized countries: Encouraging trends through 2008? Transport Policy 18, 358 – 372.

Schwarzkopf, A., Leipnik, R., 1977. Control of highway vehicles for minimum fuel consumption over varying terrain. Transportation Research 11, 279 – 286.

Sciarretta, A., 2013. Les véhicules hybrides – des composants au système. Editions Technip. chapter Supervision des véhicules hybrides. pp. 381–426.

Scientific American, 1918. Electricity recovering from electric traction lines. Scientific American 86, 152.

Scientific American, 1920. Electric truck with regenerative braking. Scientific American , 201.

Scott Turner, J., Soar, R.C., 2008. Beyond biomimicry: What termites can tell us about realizing the living building, in: Proceedings of the 1st International Conference on Industrialised, Integrated, Intelligent Construction (I3CON), Loughborough, UK, 14-16 May, pp. 221 – 237.

Shai, O., Reich, Y., 2004. Infused design. i. theory. Research in Engineering Design 15, 93–107.

Shine, K.P., D.R., Wuebbles, D.J., M.J., 1990. Climate Change - The IPCC Scientific Assessment. Cambridge University Press. chapter Radiative forcing of climate. pp. 41 – 68.

Shu, L., 2010. A natural-language approach to biomimetic design. Artificial Intelligence for Engineering Design, Analysis and Manufacturing 24, 507–519.

Shu, L., Ueda, K., Chiu, I., Cheong, H., 2011. Biologically inspired design. CIRP Annals - Manufacturing Technology 60, 673 – 693.

Singh, A.V., Rahman, A., Kumar, N.S., Aditi, A., Galluzzi, M., Bovio, S., Barozzi, S., Montani, E., Parazzoli, D., 2012. Bio-inspired approaches to design smart fabrics. Materials & Design 36, 829 – 839. Sustainable Materials, Design and Applications.

Sivak, M., Schoettle, B., 2012. Eco-driving: Strategic, tactical, and operational decisions of the driver that influence vehicle fuel economy. Transport Policy 22, 96 – 99.

Smokers, R., Fraga, F., Verbeek, M., 2011. Support for the revision of Regulation (EC) No 443/2009 on CO_2 emissions from cars. Technical Report. European Commission.

Sorrell, S., Speirs, J., Bentley, R., Brandt, A., Miller, R., 2010. Global oil depletion: A review of the evidence. Energy Policy 38, 5290 – 5295. Special Section on Carbon Emissions and Carbon Management in Cities with Regular Papers.

Sovran, G., Blaser, D., 2006. Quantifying the potential impacts of regenerative braking on a vehicle's tractive-fuel consumption for the us, european, and japanese driving schedules. SAE Technical Paper .

Speck, T., Speck, O., 2008. Process sequences in biomimetic research, in: Brebbia, C. (Ed.), Design and Nature IV, WIT Press. pp. 3–11.

Steer, K.C., Wirth, A., Halgamuge, S.K., 2009. The rationale behind seeking inspiration from nature, in:

Chiong, R. (Ed.), Nature-Inspired Algorithms for Optimisation. Springer Berlin Heidelberg. volume 193 of *Studies in Computational Intelligence*, pp. 51–76.

Suh, N., 1990. Principles of Design. Oxford University Press.

Sundström, O., Guzzella, L., Soltic, P., 2008. Optimal hybridization in two parallel hybrid electric vehicles using dynamic programming, in: Proceedings of the 17th IFAC world congress, pp. 4642–4647.

Tchobansky, L., Kozek, M., Schlager, G., Jörgl, H., 2003. A purely mechanical energy storing concept for hybrid vehicles. SAE Technical Paper .

Tie, S.F., Tan, C.W., 2013. A review of energy sources and energy management system in electric vehicles. Renewable and Sustainable Energy Reviews 20, 82 – 102.

Torres, J., Gonzalez, R., Gimenez, A., Lopez, J., 2014. Energy management strategy for plug-in hybrid electric vehicles. a comparative study. Applied Energy 113, 816 – 824.

Treiber, M., Hennecke, A., Helbing, D., 2000. Congested traffic states in empirical observations and microscopic simulations. Phys. Rev. E 62, 1805–1824.

Tsang, K., Hung, W., Cheung, C., 2011. Emissions and fuel consumption of a euro 4 car operating along different routes in hong kong. Transportation Research Part D: Transport and Environment 16, 415 – 422.

Ullman, D.G., 1991. The status of design theory research in the united states. Design Studies 12, 204 – 208.

Vandevenne, D., Caicedo, J., Verhaegen, P.A., Dewulf, S., Duflou, J., 2013. Webcrawling for a biological strategy corpus to support biologically-inspired design, in: Chakrabarti, A. (Ed.), CIRP Design 2012. Springer London, pp. 83–92.

Vandewalle, H., Vautier, J., Kachouri, M., Lechevalier, J., Monod, H., 1997. Work-exhaustion time relationships and the critical power concept. a critical review. The Journal of Sports Medicine and Physical Fitness 37, 89–102.

Vattam, S.S., Helms, M.E., Goel, A.K., 2010. A content account of creative analogies in biologically inspired design. Artificial Intelligence for Engineering Design, Analysis and Manufacturing 24, 467–481.

Velcro®, 2014. Velcro industries history and George de Mestral. Accessed on 13.10.2014. Available at:. http://www.velcro.com/About-Us/History.aspx.

Vincent, J.F., 2014. Biologically inspired Design: Computational Methods and Tools. Springer-Verlag London. chapter An Ontology of Biomimetics. pp. 269 – 285.

Vincent, J.F., Bogatyreva, O.A., Bogatyrev, N.R., Bowyer, A., Pahl, A.K., 2006. Biomimetics: its practice and theory. Journal of The Royal Society Interface 3, 471–482.

Vinot, E., Trigui, R., 2013. Optimal energy management of HEVs with hybrid storage system. Energy Conversion and Management 76, 437 – 452.

Volkswagen, 2014. The e-Golf: Environmental Commendation - Background Report. Technical Report. Volkswagen AG.

Wagner, P., 1996. Determinants of maximal oxygen transport and utilization. Annual Review of Physiology 58, 21 – 50.

Wang, L.C.H., Lee, T.F., 2010. Comprehensive Physiology. John Wiley & Sons, Inc.. chapter Torpor and Hibernation in Mammals: Metabolic, Physiological, and Biochemical Adaptations. pp. 507 – 532.

Weber, J.M., 2009. The physiology of long-distance migration: extending the limits of endurance metabolism. Journal of Experimental Biology 212, 593–597.

Wesfreid, E., Billat, V.L., Meyer, Y., 2005. Multifractal analysis of heartbeat time series in human races. Applied and Computational Harmonic Analysis 18, 329 – 335.

Williams, M.H., Anderson, D.E., Rawson, E.S., 2013. Nutrition for Health, Fitness, and Sport. McGraw Hill Higher Education.

Wilson, J.O., Rosen, D., Nelson, B.A., Yen, J., 2010. The effects of biological examples in idea generation. Design Studies 31, 169 – 186.

Wiltgen, B., Goel, A., Vattam, S., 2011. Representation, indexing, and retrieval of biological cases for biologically inspired design, in: Ram, A., Wiratunga, N. (Eds.), Case-Based Reasoning Research and Development. Springer Berlin Heidelberg. volume 6880 of *Lecture Notes in Computer Science*, pp. 334–347.

Xu, S., Li, S.E., Zhang, X., Cheng, B., Peng, H., 2015. Fuel-optimal cruising strategy for road vehicles with step-gear mechanical transmission. IEEE Transactions on Intelligent Transportation Systems 16, 3496–3507.

Yoshikawa, H., Uehara, K., 1985. Design theory for CAD/CAM integration. CIRP Annals - Manufacturing Technology 34, 173 – 178.

Zielinski, M., Wala, H., Szerejko, D., Rynne, D.G., 2012. Method and apparatus for removal of carbon dioxide from automobile, household and industrial exhaust gases. Patent WO/2012/145303.

Appendix A

Simplified modeling for an internal combustion engine powertrain

A.1 Internal combustion engine vehicle parameters used in modeling

The parameters for the Renault Clio3 Estate used in the vehicle simulations are given in the table below. The values are the same as the ones presented in the Appendix A of Luu (2010). We adapted some of the values given by this author considering the manufacturer data. These adaptations are indicated between parenthesis (*) in Table A.1.

Symbol	**Description**	**Value**	**Units**
$A_f C_d$	aerodynamic drag	0.725 (*0.706)	m^2
C_{RR}	rolling resistance coefficient	0.020	-
I_{engine}	inertia of the engine	0.2630 (*0.150)	$kg.m^2$
I_d	inertia of the transmission	0.115	$kg.m^2$
I_w	inertia of the wheels	2.8 (for the 4 wheels)	$kg.m^2$
m_v	vehicle mass	1269	kg

continued …

…continued

Symbol	Description	Value	Units
N_f	final drive ratio	4.092	-
N_t	transmission ratio	1st gear – 3.7272 2nd gear – 2.0476 3rd gear – 1.3929 4th gear – 1.0294 5th gear – 0.8205	-
η_{tf}	final drive and transmission combined efficiency	1st gear – 0.85 2nd gear – 0.90 3rd gear – 0.93 4th gear – 0.95 5th gear – 0.97	-
r_w	wheel radius	0.297	m
P_emax	maximum engine power	74	W
T_emax	maximum engine torque (@ engine speed)	145 (@3000)	N.m (@rpm)
ω_{idle}	engine speed at idle	800 (83.8)	rpm (rad.s^{-1})

Table A.1: Vehicle parameters used in simulations.

The general parameters used in the simulation are listed in Table A.2:

Symbol	Description	Value	Units
FC_{idle}	fuel consumption at idle	0.45	$kg.s^{-1}$ (**see Section A.2.4)
g	acceleration of gravity	9.8	$m.s^{-2}$
ρ_a	air density	1.205	$kg.m^{-3}$
ρ_{fuel}	gasoline density	747	$kg.m^{-3}$
$H_{fuel-lcv}$	fuel lower heating value	42.8	$MJ.kg^{-1}$

Table A.2: General parameters used in simulations.

A.2 Equations used for modeling of ICEV subsystems

The ICEV simplified model shown in Figure 4.3 reproduced in this Appendix has different subsystems. In this Appendix, we will detail the constructs and equations of each subsystem. These equations are based on the quasi-static backward approach, conceived by Guzzella and Sciarretta (2005) and applied on vehicle powertrain modeling papers such as Sundström et al. (2008).

A.2.1 Driving cycle

This subsystem receives as inputs the speed and road profile (speed as a function of time, road slope profile and gear ratios engaged), and gives as outputs the vehicle acceleration for each time interval, and the speed and grade vectors, with the desired time step (that can be different from the time step on which the initial speed profile is given). The distance covered by the vehicle for the given speed profile is calculated by integrating speed over time.

Inputs

- Speed profile : $v(t)$ – [m.s−1]; $t(t)$ – [s]
- Road profile : $grade(t)$ – [rad]
- Gear ratio engaged : $gear(t)$

Algorithm

1. Set the vectors for the desired time step, h – [s]. In our case, linear regressions are used to achieve this change in time step ($v(t)$, $t(t)$, $grade(t)$, $gear(t)$)
2. Vehicle acceleration is calculated using the new speed and time vectors:

$$a(t) = \frac{(v'(t+h) - v'(t))}{h} \tag{A.1}$$

3. The distance covered by the vehicle during time step (h):

$$x(t) = \int_{t_i}^{t_{i+h}} v'(t)\,\mathrm{d}t \tag{A.2}$$

Outputs

- Speed profile with time step h: $v'(t)$ – [m.s−1]; $t'(t)$ – [s]
- Road profile: $grade'(t)$ – [rad]
- Gear ratio engaged: $gear'(t)$
- Distance covered by the vehicle: $x(t)$ – [m]
- Vehicle acceleration: $a(t)$ – [m.s^{-2}]

A.2.2 Vehicle

This subsystem receives as inputs the outputs of the "driving cycle" subsystem and uses the vehicle longitudinal dynamics equations to calculate the torque and rotational speed of the wheels. We also consider that the vehicle wheels may have additional resistance forces, due to brake drag[1]. We considered an additional resistance of approximately 20 N (17 N in this vehicle).

Inputs

- Speed profile : $v(t)$ – [m.s−1]; $t(t)$ – [s]
- Road profile : $grade(t)$ – [rad]
- Vehicle acceleration: $a(t)$ – [m.s^{-2}]

Algorithm

1. Forces calculations:
   - Rolling resistance: $F_{roll} = C_{RR} m_v g \cos(grade'(t))$ (Equation 3.2)
   - Aerodynamic resistance: $F_{aero} = \frac{1}{2}\rho_a A_f C_d v'(t)^2$ (Equation 3.3)
   - Gravitational force: $F_g = m_v g \sin\alpha$ (Equation 3.4)
   - Additional resistance forces: $F_{add_{res}} = constant$
   - Tractive force: $F_{TR} = (F_{roll} + F_{aero} + F_g + F_{add_{res}}) + (m_v + 4[\frac{I_w}{r_w^2}])a(t)$ (Equation 3.5)

2. Torque at the wheels:

$$T_{wh}(t) = F_{TR}(t) * r_w \tag{A.3}$$

3. Wheel rotational speed, assuming no wheel slip:

$$\omega_{wh}(t) = \frac{v'(t)}{r_w} \tag{A.4}$$

4. Wheel rotational acceleration, assuming no wheel slip:

$$\mathrm{d}\omega_{wh}(t) = a(t) * r_w \tag{A.5}$$

Outputs

- Torque at the wheels:$T_{wh}(t)$ – [N]
- Wheel rotational speed: $\omega_{wh}(t)$ – [rad.s^{-1}]
- Wheel rotational acceleration: $\mathrm{d}\omega_{wh}(t)$ – [rad.s^{-2}]

[1]Brake drag may be caused by "sliding friction of disk braking pads on rotors when the brakes are not engaged" (NRC, 2011).

A.2.3 Gearbox

This subsystem receives as inputs the different gear ratios engaged along the speed profile[2], the torque at the wheels and the wheels rotational speed and acceleration. It calculates the torque on the clutch side of the gearbox and the crankshaft rotational speed. These calculations involve the use of the gear ratios, defined by the vehicle manufacturer (Table A.1). The final transmission ratio, N_{tf}, is the product of the final drive ratio N_f and the corresponding transmission ratio N_t $(gear'(t))$.

Inputs

- Gear ratio engaged: $gear'(t)$
- Torque at the wheels:$T_{wh}(t)$ – [N]
- Wheel rotational speed: $\omega_{wh}(t)$ – [rad.s^{-1}]
- Wheel rotational acceleration: $\mathrm{d}\omega_{wh}(t)$ – [rad.s^{-2}]

Algorithm

1. Torque on the clutch side of the gearbox:

$$T_{gb}(t) = \frac{T_{wh}(t)}{\eta_{tf}(i) \cdot N_{tf}(i,t)}, if\ T_{wh} \geq 0 \tag{A.6}$$

$$T_{gb}(t) = \frac{T_{wh}(t) \cdot \eta_{tf}(i)}{N_{tf}(i,t)}, if\ T_{wh} < 0 \tag{A.7}$$

2. Crankshaft rotational speed:

$$\omega_{gb}(t) = N_{tf}(i,t) \cdot \omega_{wh} \tag{A.8}$$

3. Crankshaft rotational acceleration:

$$\mathrm{d}\omega_{wh}(t) = a(t) * r_w \tag{A.9}$$

Outputs

- Torque on the clutch side of the gearbox:$T_{gb}(t)$ – [N]
- Crankshaft rotational speed: $\omega_{gb}(t)$ – [rad.s^{-1}]
- Crankshaft rotational acceleration: $\mathrm{d}\omega_{gb}(t)$ – [rad.s^{-2}]

[2]If the gear ratios are not available, experimental approaches such as those developed by (Orfila et al., 2012) can allow a simple approximation for estimating the gears engaged.

A.2.4 Internal Combustion Engine (ICE)

This subsystem calculates the engine fuel consumption, considering the torque and speed required at the crankshaft. This calculations involve in our model, the use of engine maps, i.e. tables that relate the engine torque and speed to values of instantaneous fuel consumption. One example of engine map is given in Figure 3.9. The engine map used in our calculations was obtained experimentally (LIVIC laboratory archieves). We also needed to estimate the idle fuel consumption for our calculations. Previous works of the LIVIC laboratory using the same vehicle, considered the engine speed at idle(ω_{idle}) as 800 rpm.

Luu (2010) proposes the use of the approximation of Bowyer et al. (1985, p.83) model (Equation A.10). This approximation, gives the fuel consumption at idle,FC_{idle} in mL/s as a function of engine capacity EC in L:

$$FC_{idle}\text{mL}/\text{s} = 0.220EC\text{L} - 0.0193EC^2 \tag{A.10}$$

For the Renault Clio 3 vehicle, the engine capacity is of 1.149 L (1149 cm^3). The idle fuel consumption calculated using equation A.10 is 0.23 $mL.s^{-1}$ or 0.61 $kg.h^{-1}$ (considering the gasoline density as 0.747 $kg.L^{-1}$). An experimental test was made at the laboratory (Qi Cheng and Olivier Orfila, unpublished) in order to measure the fuel consumption at idle. This test consisted in putting the vehicle at idle, and measuring using CAN measurements of the cummulated fuel consumption. Considering the consumption at idle measured with a "hot" vehicle (linear portion of the curve of Figure A.1, the value of fuel consumption estimated is of 0.17 $mL.s^{-1}$ or 0.45 $kg.h^{-1}$. This value is inferior to the values obtained with Equation A.10, and is closer to values measured by the vehicle manufacturer on more recent vehicles (between 0.3 and 0.5 kg/h). We will use the value of **0.45 $kg.h^{-1}$**, as the estimation for the value of idle fuel consumption in our simulation model.

The calculations of fuel consumption involved the use of interpolations of the engine fuel consumption map. These interpolation were performed using linear interpolations. Other approaches have been developed for calculating fuel consumption based on the engine torque and speed operating points, one example using the same vehicle and engine, Cheng (2013) developed a piecewise polynomial approximation for computing the engine fuel consumption given an instantaneous engine torque and speed. For periods of idle, the estimated value of 0.45 $kg.h^{-1}$ was used. When the engine torque calculated was higher than the maximum torque of the engine for a given engine speed, we assumed that the

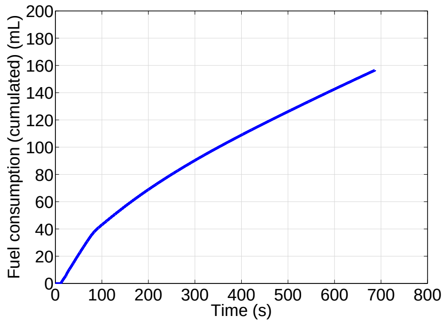


Figure A.1: The fuel consumption at idle, recorded using the Renault Clio 3 Eco2 Estate vehicle (Orfila and Cheng)

operating point was at the maximum engine torque for the calculation of fuel consumption.

We also introduced in our model the *fuel cutoff*, i.e. the injection of fuel in the engine is shutoff during braking phases. We assumed then that there was no fuel consumption in braking phases. The only exception are braking phases in which the vehicle transmission is in neutral gear position. The fuel consumption considered during these phases is the fuel consumption at idle.

Inputs

- Torque on the clutch side of the gearbox:$T_{gb}(t)$ – [N]
- Crankshaft rotational speed: $\omega_{gb}(t)$ – [rad.s^{-1}]
- Crankshaft rotational acceleration: d$\omega_{gb}(t)$ – [rad.s^{-2}]

Algorithm

1. Engine torque, considering the engine drag torque:

$$T_{engine}(t) = T_{drag}(t) + T_{gb}(t) \tag{A.11}$$

$$T_{drag}(t) = I_{engine} \cdot d\omega_{gb}(t) \tag{A.12}$$

2. Engine speed:

$$\omega_{engine}(t) = \omega_{gb}(t) \tag{A.13}$$

3. Instantaneous fuel consumption, using linear interpolation on the engine fuel consumption map, and taking into account the torque and speed requirements (braking phases have no fuel consumption, idle phases have the fuel consumption at idle:

$$\dot{m}_{fuel} = f(T_{engine}, \omega_{engine}, engine\ map)$$

4. Power provided by the fuel, considering the power required by the auxiliaries:

$$P_{fuel} = \dot{m}_{fuel} \cdot H_{fuel-lcv} + P_{aux} \tag{A.14}$$

Outputs

- Power provided by the fuel:$P_{fuel}(t)$ – [W]

A.2.5 Fuel Tank

In this subsystem, the total fuel consumption is calculated, using the Power provided by the fuel and the distance made by the vehicle during the speed profile.

Inputs

- Power provided by the fuel:$P_{fuel}(t)$ – [W]

Algorithm

1. Total fuel energy used during the speed profile

$$E_{fuel} = \int_{t_0}^{t_f} P_{fuel}(t)\,\mathrm{d}t \tag{A.15}$$

2. Converting Energy into L of fuel, using fuel density and lower heating value:

$$V_{fuel} = \frac{E_{fuel}}{H_{fuel-lcv} \cdot \rho_{fuel}} \tag{A.16}$$

3. Calculating fuel consumption in L/100km ($V_f uel$ – [L] and $x(t)$ – [m]) :

$$C_{fuel} = 10^5 \cdot \frac{V_{fuel}}{\sum_{t_0}^{t_f} x(t)} \tag{A.17}$$

Outputs

- Total fuel consumption : V_{fuel} – [L]
- Average fuel consumpttion: C_{fuel} – [L/100km]

A.3 Validating the ICEV model using experimental data

The model is a simplification. It allows the calculation of the fuel consumption, however, we must keep in mind that its outcomes are the result of a simple model, that does not take into account a series of factors, such as the vehicle auxiliary consumption (air conditionning, radio, electrical systems) and that has assumptions such as a constant rolling resistance coefficient, that may induce some differences between the model calculations and the real life fuel consumption measures. The backward approach is also less precise than the forward approach, but was used here for its simplicity.

The data we used to evaluate the precision of our model is data recorded for the experimentation described and analyzed in Orfila et al. (2012) article: 21 drivers were asked to travel along the same extra-urban route. The trip was made by each driver twice, once in their normal driving conditions and in the second using eco-driving tips. Vehicle speed and cummulated fuel consumption were recorded during these experiments, and the road grade was also known at each time step. These speed profiles constituted the inputs that were used in our simplified ICEV model, and the cumulated fuel consumption was the target to be reached.

When building the model, we considered a constant rolling resistance coefficient. This coefficient depend essentially on tire pressure. As the tire pressure was not measured for each of the trips, we considered that we should test the effect of different rolling resistance coefficients on the results. We have also assumed that smoothing the recorded speed and acceleration would not be required in this case.

We calculated the error between the total fuel consumption estimated using the model and measured during the 42 trips, calculated according to equation A.18. This error is calculated only considering the final fuel consumption measured in the experimentations and the cumulated fuel consumption estimated by the model, and is represented with boxplots in Figure A.2.

$$Error = 100 \cdot \frac{FC_{measured}(t = t_{end}) - FC_{model}(t_{end})}{FC_{measured}(t = t_{end})} \quad \text{(A.18)}$$

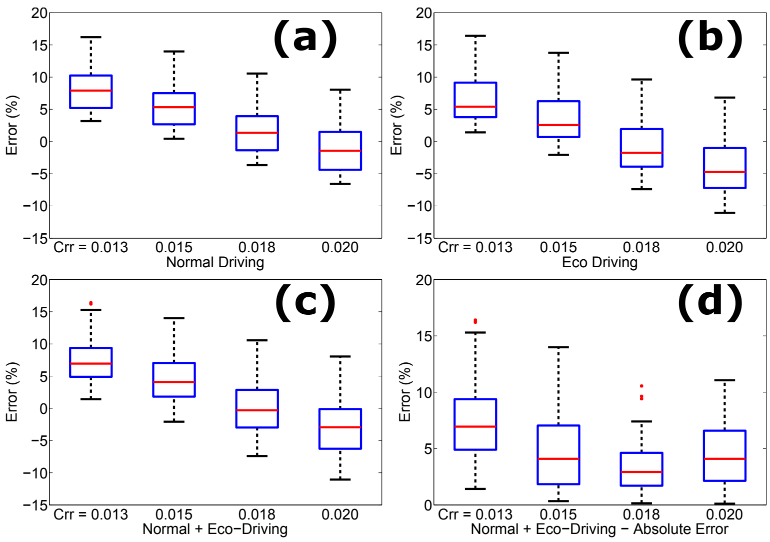


Figure A.2: Errors between the total fuel consumption measured experimentally and the ones obtained with the model, using different values of the rolling resistance coefficient. (a) With the 21 drivers driving normally, (b) With the 21 drivers following eco-driving tips, (c) for all the drivers, (d) the absolute errors for all the drivers.

This figure shows that the model calculates the fuel consumption, but the distance to the measured values depend on the vehicle driving patterns (there is a difference between the values with normal-driving and eco-driving) and also on the rolling resistance coefficient: the higher the rolling resistance, the higher the fuel consumption estimated by the model (errors with negative values). The absolute errors are not superior to 15%, and the median absolute errors are between 3 and 7%.

An example of driving profile for the same driver, with and without eco-driving and the calculated fuel consumption are shown in Figure A.3.

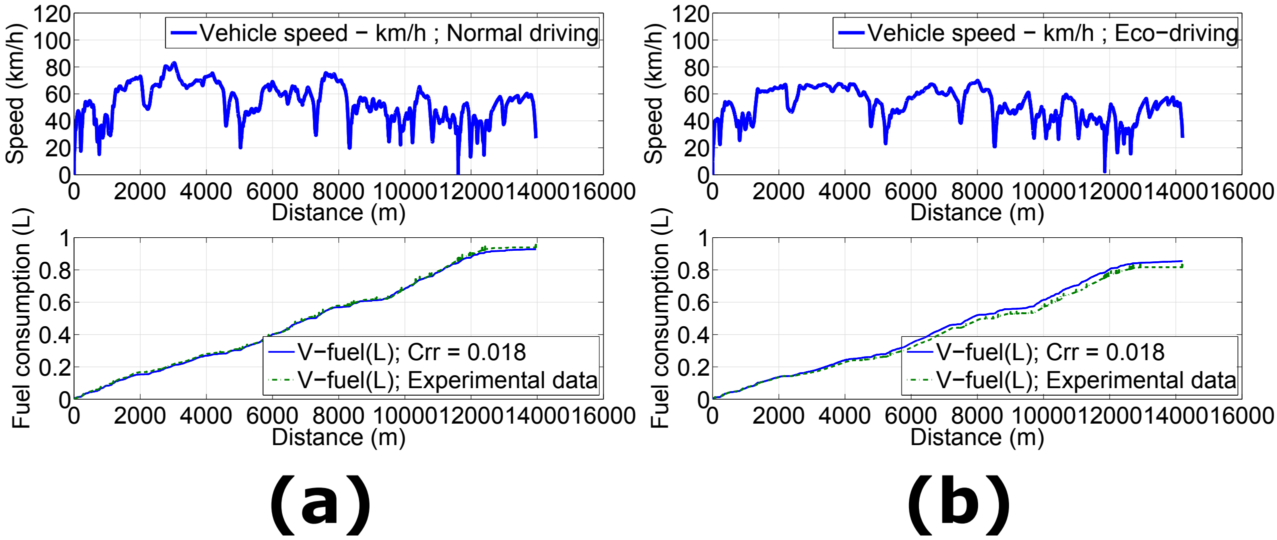


Figure A.3: Vehicle speed and cumulated fuel consumption measured in the experimentations and calculated with the model using a rolling resistance coefficient of 0.018. (a) Driver with a normal driving style (b) The same driver driving with eco-driving tips.

Appendix B

The results obtained in experimentations for evaluating the concept of speed variations

Figures B.1 to B.4 detail the results obtained in the different experimental tests realized at the Satory "speed test track"[1] for evaluating the concept of speed variations using a conventional ICEV.These tests were realized by the same driver with one only and unique passenger in the vehicle.

[1]See figures 4.17 and 4.18 for details about this test track.

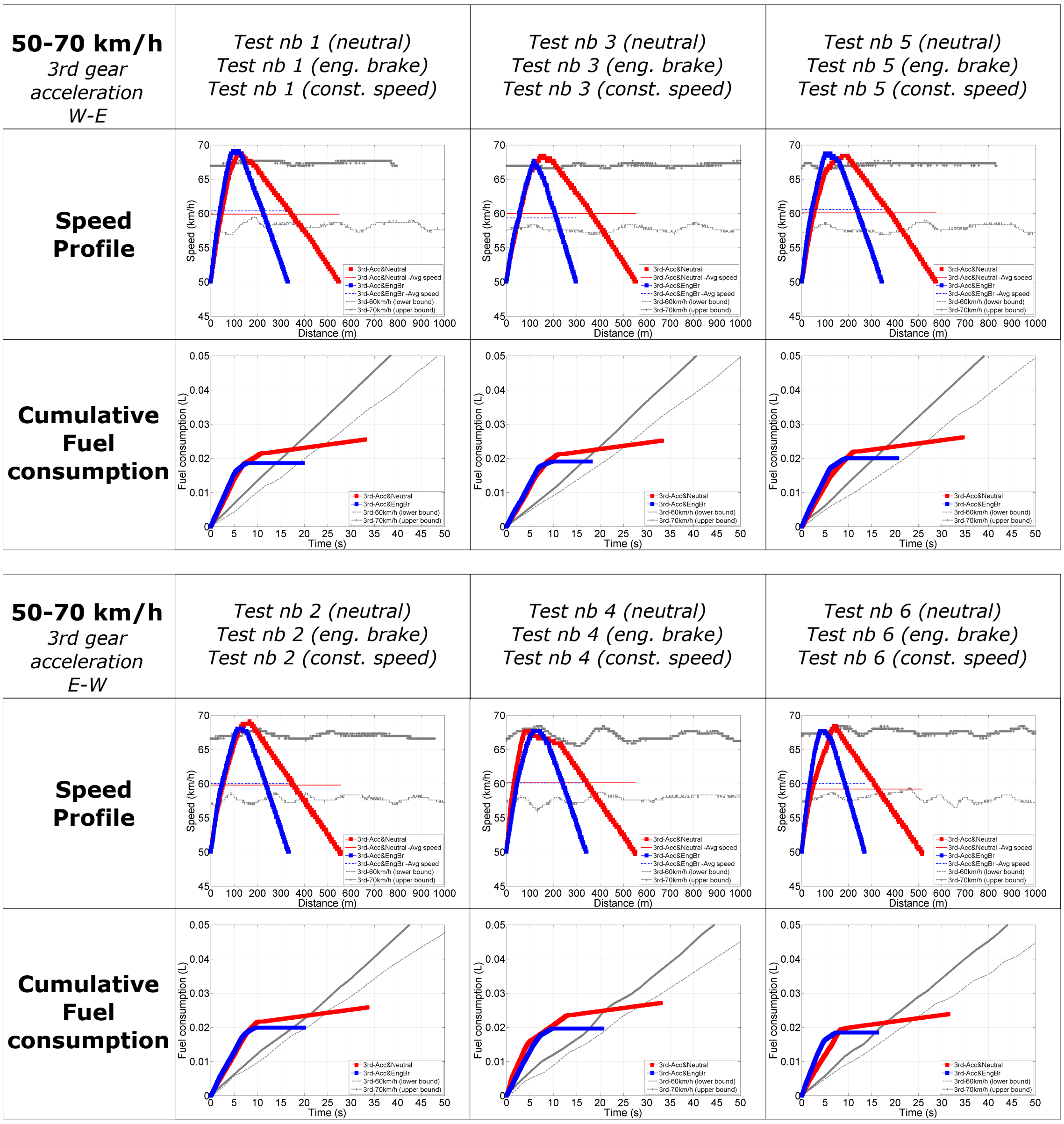


Figure B.1: Speed profiles and fuel consumption recorded within the expermiments realized at Satory “speed test track” with the Renault Clio 3 vehicle for the 50-70 km/h condition with the 3rd gear used in acceleration phase and engine braking. The constant speed profiles and fuel consumption data were also chosen for the same test numbers and same direction, in both speed conditions, the lower bound (LB) of 60 km/h and the upper bound of 70 km/h.

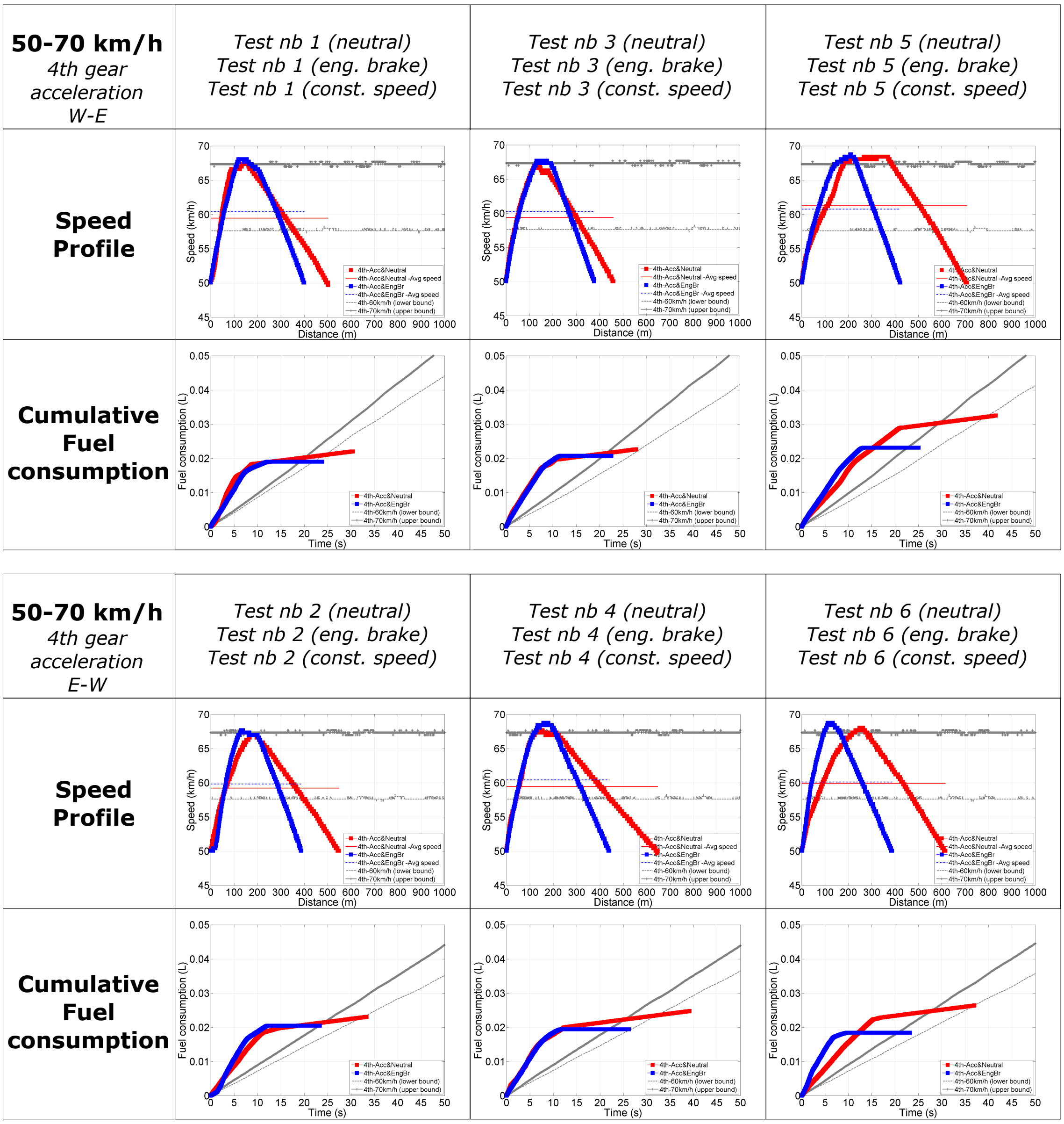


Figure B.2: Speed profiles and fuel consumption recorded within the expermiments realized at Satory "speed test track" with the Renault Clio 3 vehicle for the 50-70 km/h condition with the 4th gear used in acceleration phase and engine braking. The constant speed profiles and fuel consumption data were also chosen for the same test numbers and same direction, in both speed conditions, the lower bound (LB) of 60 km/h and the upper bound of 70 km/h.

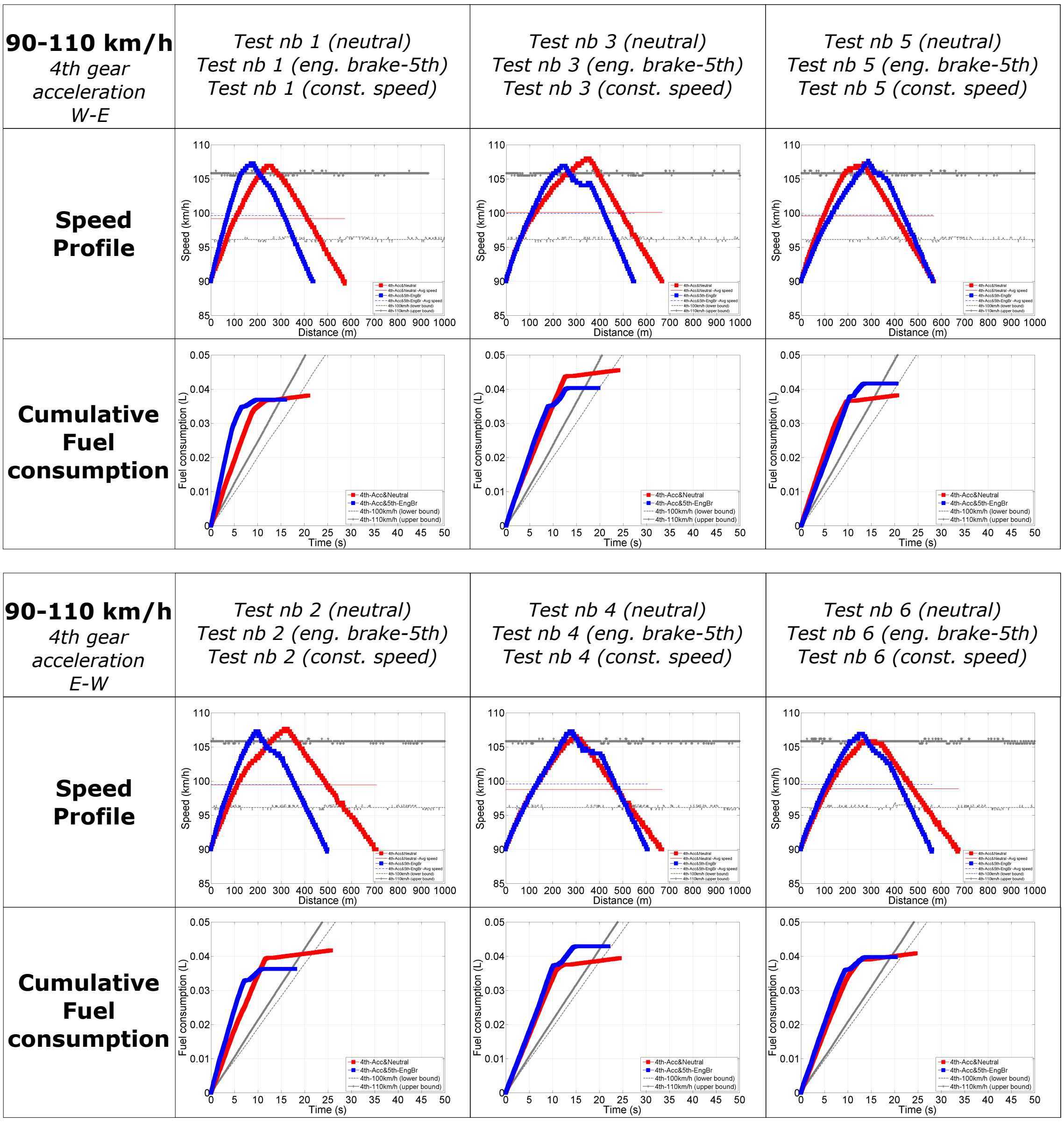


Figure B.3: Speed profiles and fuel consumption recorded within the expermiments realized at Satory "speed test track" with the Renault Clio 3 vehicle for the 90-110 km/h condition with the 4th gear used in acceleration phase and 5th gear in engine braking phase. The constant speed profiles and fuel consumption data were also chosen for the same test numbers and same direction, in both speed conditions, the lower bound (LB) of 100 km/h and the upper bound of 110 km/h.

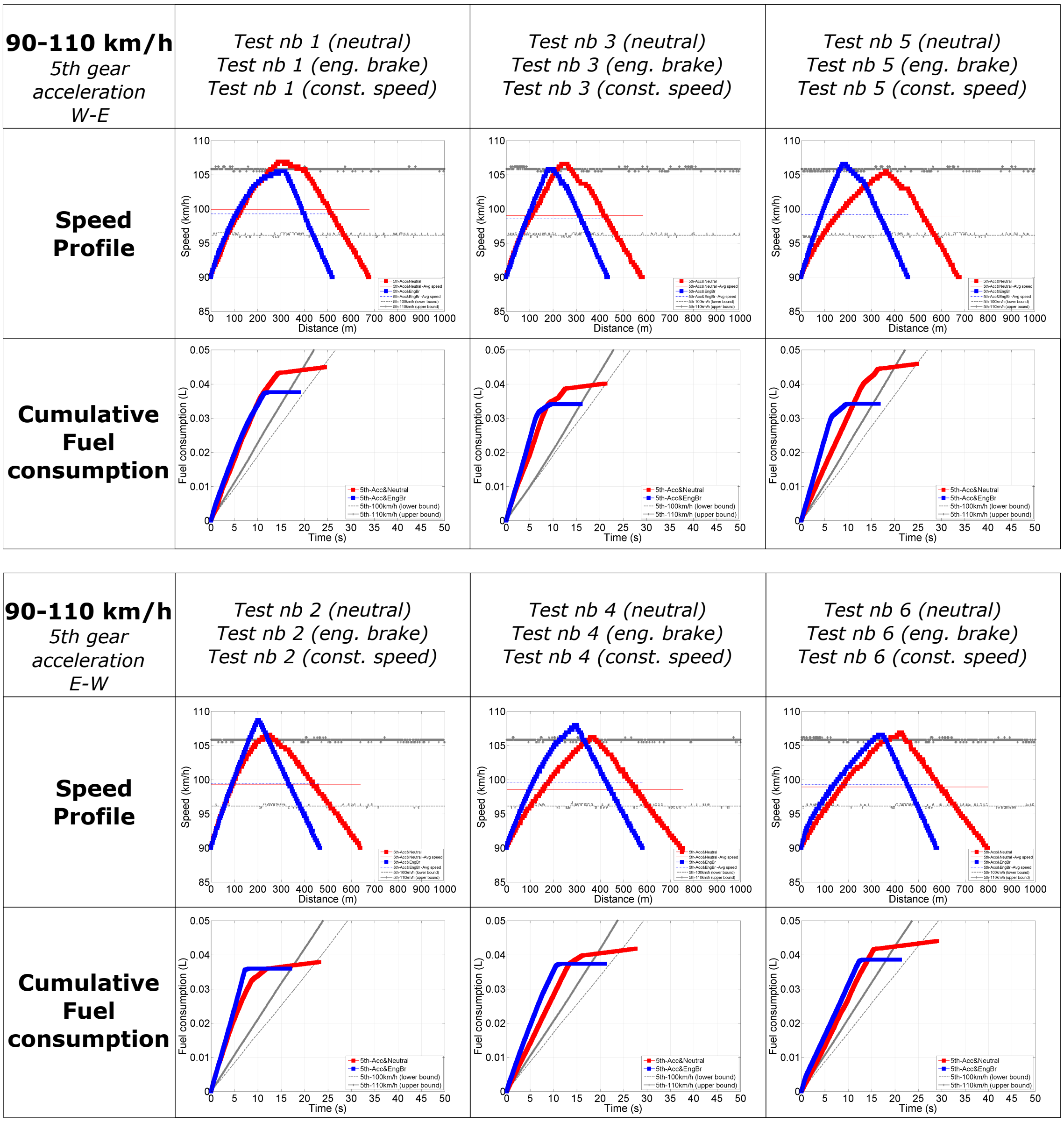


Figure B.4: Speed profiles and fuel consumption recorded within the expermiments realized at Satory "speed test track" with the Renault Clio 3 vehicle for the 90-110 km/h condition with the 5th gear used in acceleration phase and engine braking. The constant speed profiles and fuel consumption data were also chosen for the same test numbers and same direction, in both speed conditions, the lower bound (LB) of 100 km/h and the upper bound of 110 km/h.

ÉCOLE DOCTORALE
Sciences et technologies de l'information et de la communication (STIC)

Titre : Biomimétisme et Véhicule Décarboné : génération de concepts innovants bio-inspirés à partir de la méthode C-K

Mots clés : innovation, bioinspiration, automobile, décarboné

Résumé : Le biomimétisme ou conception bio-inspirée est une approche qui propose l'utilisation du vivant en tant que source d'inspiration pour améliorer ou concevoir de nouvelles technologies. Intégrer la conception bio-inspirée au processus d'innovation des entreprises pourrait ainsi permettre la génération de concepts à la fois innovants et durables. Cette thèse, réalisée au sein de Renault avait deux objectifs : comprendre les mécanismes de la conception bio-inspirée et les appliquer à un cas concret dans l'automobile pour stimuler la génération de concepts en rupture. Pour comprendre les mécanismes de la bio-inspiration, nous nous sommes appuyés sur la littérature scientifique ainsi que sur les inventions et concepts bio-inspirés. Pour analyser le raisonnement de conception de ces exemples, nous avons choisi une théorie de la conception, la théorie C-K. Le cadre issu de la théorie C-K nous a permis de proposer un modèle général pour la conception bio-inspirée. Nous avons appliqué ce modèle au champ d'innovation du véhicule décarboné. Ce champ traite des questions liées au développement d'innovations permettant aux véhicules de réduire leur empreinte environnementale, principalement par la réduction des émissions de dioxyde de carbone (CO_2), un puissant gaz à effet de serre qui contribue également au phénomène du changement climatique. L'identification des voies où la rupture serait nécessaire a débuté par la réalisation d'un arbre des concepts, à l'aide des connaissances internes disponibles en entreprise auprès des experts leaders. Un travail de réorganisation de ces concepts et la création d'une base de connaissances rassemblant articles scientifiques et expertises sur le sujet des émissions de gaz à effet de serre ont été effectués. Ce travail a permis de cartographier le champ d'innovation du véhicule décarboné. Les véhicules multi-énergies ont été la voie choisie pour la recherche de concepts bio-inspirés.

Une recherche générale sur l'énergie dans le vivant nous a conduits à identifier l'énergie dans les cellules animales et particulièrement chez les humains comme une base de connaissances biologiques particulièrement intéressante. L'énergétique humaine possède un certain nombre de propriétés qui pourraient permettre une révision des connaissances sur les véhicules multi-énergie, notamment sur le stockage et la transformation d'énergie. La performance sportive humaine s'est aussi révélée être une base de connaissances intéressante par les différentes techniques utilisées pour les entrainements et en course afin de mieux mobiliser des sources d'énergie. L'application du modèle du processus de bio-inspiration avec C-K nous a conduit à formuler un concept inspiré des observations réalisées sur des coureurs pendant des courses supérieures à 1 500 m. En effet, les profils de vitesse enregistrés pour des athlètes indiquent qu'une variation de vitesse est choisie par le coureur pour lui permettre de mieux utiliser ses réserves anaérobies limitées. Pour un véhicule, ceci pourrait impliquer qu'une variation de vitesse pourrait conduire à des meilleurs résultats en termes de consommation de carburant qu'une vitesse stabilisée. Ce concept a été exploré dans cette thèse à l'aide de la réalisation d'essais sur piste et des simulations avec des modèles numériques. Ces explorations montrent le potentiel de ce concept pour des véhicules conventionnels et aussi ses limitations. Ces travaux ouvrent des perspectives pour la gestion d'énergie des véhicules considérant la façon dont l'énergie est produite, stockée et utilisée chez le vivant. Les systèmes énergétiques étudiés par la physiologie humaine représentent un terrain intéressant pour le développement de véhicules adaptables à différents cas d'utilisation. De plus, l'étude du processus de la bio-inspiration a permis d'éclairer les raisons de faire appel à cette démarche et les conditions qui permettraient son application plus systématique dans les processus d'innovation en entreprise.

Title : Biomimicry and the low carbon vehicle: generation of innovative bio-inspired concepts using the C-K theory

Keywords : innovation, bioinspiration, automobile, low-carbon

Abstract : Biologically inspired design, also called bioinspired design, biomimetics or biomimicry proposes the use of Nature, or biological knowledge, as a source of inspiration to improve or conceive new designs. Integrating the biologically inspired design approach into the innovation process of companies could then allow the generation of more innovative and sustainable concepts. This thesis, realized during three years at a French automaker (Renault) research and development department had two objectives: to understand the mechanisms of the biologically inspired design and to apply this approach to a case belonging to an innovation field of the automotive sector. In order to understand the mechanisms of biologically inspired design we studied the literature about bio-inspired concepts and inventions. We have chosen a design theory, the C-K theory, to analyse the design process of these literature examples. This allowed us to propose a model for bio-inspiration. We applied this model inspired by the C-K theory to the low carbon vehicle innovation field. This field includes the development of innovations allowing passenger cars to reduce their environmental footprint, mainly the reduction of carbon dioxide (CO_2) emissions. The carbon dioxide is a greenhouse gas, contributing to the climate change phenomena. The identification of the path where concept partitioning is required in this field began with the construction of a concepts space, using knowledge of company experts on the subject. Reorganizing these concepts and building a knowledge base on the strategies for CO_2 emissions allowed us to map this innovation field. The vehicles with more than one energy source, such as electrified internal combustion engine vehicles and hybrid vehicles were the path chosen for the research of bio-inspired concepts.

A research about energy in nature led us to identify the energy in animal cells, particularly those in humans as an interesting biological knowledge base. Human energy properties such as cells with more than one kind of energy storage, with at least two metabolic pathways to recharge these stores are interesting to revise the knowledge about energy store and conversion in multi-energy vehicles. Besides, the human sportive performance has appeared to be an interesting knowledge base, as the training techniques and the running techniques during a race can influence the way athletes use their energy. These two biological bases have led us to formulate a bio-inspired concept based on the running patterns observed in runners during races superior to 1 500 m. The speed profiles recorded show a spontaneous speed variation chosen by the runner, in order to better use its limited anaerobic energy stores. For a vehicle, this could mean that varying its speed could allow a lower fuel consumption than using a constant speed. This bio-inspired concept was explored in this thesis with the realization of tests in a dedicated test track and simulations. These tests show the potential of this concept for conventional vehicles and its limitations. This work opens the way for analysing the vehicle energetics in the light of human energetics. The versatility of human activities could help on the development of vehicles adapting to different use cases. Further research could also use the knowledge about the dynamic modelling of energy in vehicles to complete the empirical approaches used to model the human energy management, allowing a better optimization of running strategies. The study of the bio-inspiration process using a design theory also allowed a better comprehension of the reasons for using this approach and of the conditions for successfully applying it in the innovative process of a company.

Université Paris-Saclay
Espace Technologique / Immeuble Discovery
Route de l'Orme aux Merisiers RD 128 / 91190 Saint-Aubin, France