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Gaylord KABONGO BOOTO

Using life cycle thinking approach to support environmental sustainability in big linear infrastructure projects

Alignment modelling, optimization and evaluation for reducing impacts to the natural environment

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of Philosophiae Doctor
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To my children Lordina KABONGO BOOTO and Lordson DUGOGI BOOTO*,*
I loved you before knowing you and with you, life really makes sense

To my wife Benedicte MPUTU KAPINGA*, your belief in me has never been shacked and your courage remains unparalleled*

To my mother, Rosalie MASALA MAKENGA, *you were able to raise us with too little material goods, sacrificing your life for us,*

and

To my beloved father, ally, mentor, and friend, DUGOGI BOOTO MBAKA Leon Basile, *you taught us LOVE while loving us more than nobody else did. Your soul in peace, in the beyond realm.*

All I have and will always have to say is “True LOVE”.

When education serves for a better world, technological development takes place in a truly sustainable way. Then, and only then, the term "innovation" reasonably makes sense to be used.

Using life cycle thinking approach to support environmental sustainability in big linear infrastructure projects.
Alignment modelling, optimization, and evaluation for reducing impacts to the natural environment.

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Abstract

This thesis focuses on environmental optimization of the vertical alignment in large linear infrastructure projects, at early design stage. Two categories of problems are investigated: “modification of the existing alignment” and “generation of a new alignment”. The road is modelled with fixed geometrical parameters. Several models are developed which relate the road gradients, for each constituting segment of the road, to three elements retained as influential factors in this study i.e. the earthwork cost, the energy cost and the emission cost. Two concepts are introduced to support the constructed methods: the “single level approach (SLA)” and the “multi-layered multi-level approach (MLMLA or ML2A)”. These approaches are based on the performances of test vehicles used as a proxy for characterizing the environmental profile of vertical alignments of linear infrastructures. New metrics for evaluating the performances of the vertical alignments are also introduced based on the life cycle assessment method. The final models of the vertical alignment have implemented piece-wise linearity using lower order spline polynomial techniques to decrease complexity level and maintain robustness. This enables the use of simple linear programming techniques for solving (optimizing) the developed models. The methods have been implemented in MATLAB (for the first problem type) and Python (for the second problem type) environments. Models’ performances are illustrated through simulations and application to real world cases, and validation is performed through benchmarking with results from similar studies found in the literature. Higher and lower gradient limits, powertrains and standard technologies, speed levels, load factors, and vehicle segment have all been investigated throughout this project. It is shown that the developed models can successfully be used to design vertical alignments with reduced environmental impacts and that several other factors that influence the performance of heavy-duty vehicles on highways need to be considered.

Keywords: vertical alignment, LCA, optimization, highways, clean vehicles, HDVs, emissions.

List of appended papers

The following papers formed the basis of the present thesis

I. BOOTO, Gaylord K., BORN, Reyn O., EBRAHIMI, Babak, *et al.* Road Planning and Route Alignment Selection Criteria in the Norwegian Context. In: *IOP Conference Series: Materials Science and Engineering*. IOP Publishing, 2019. p. 062007.

II. Booto, G. K., Bohne, R. A., Vignisdottir, H. R., Pitera, K., Marinelli, G., Brattebø, H., & Ebrahimi, B. (2017). The effect of highway geometry on fuel consumption of heavy-duty vehicles operating in eco-driving mode. In *Proceedings from the 10th International Conference on Bearing Capacity of Roads, Railways and Airfields*.

III. Gaylord Kabongo Booto, Giuseppe Marinelli, Helge Brattebø, Rolf Andre Bohne. Reducing fuel consumption and emissions through optimization of the vertical alignment of a road: A case study of a heavy-duty truck on the Norwegian Highway Route E39. European Transport \ Transporti Europei (2019). Issue 71, Paper No 4, ISSN 1825-3997.

IV. KABONGO BOOTO, Gaylord, RUN VIGNISDOTTIR, Hrefna, MARINELLI, Giuseppe, *et al.* Optimizing Road Gradients Regarding Earthwork Cost, Fuel Cost, and Tank-to-Wheel Emissions. *Journal of Transportation Engineering, Part A: Systems*, 2020, vol. 146, no 3, p. 04019079.

V. Gaylord Kabongo Booto, Helge Brattebø, Giuseppe Marinelli, Rolf Andre Bohne. Performances of different heavy-duty drivetrains on optimized alignment: A life cycle perspective (2019). *Submitted manuscript*.

Author's contribution to the appended papers

In **paper number I**, the author conducted the complete literature search and reviewed all the documents, performed the meta-analysis, and extracted the required information. He designed the study and oversaw the implementation of the proposed method. He drafted the entire manuscript of the full version and coordinated the collaboration work with all the co-authors who helped in structuring the search process, suggesting better approaches, reviewing the manuscripts, and proofreading when needed.

In **paper number II**, the commencement of the project, the development of the method, the processing and analysis of the gathered field data, as well as the modelling tasks were completed by the author. In addition, the author searched the literature, developed the script of the data handling pipeline, wrote the full draft version of the complete manuscript, and organized the collaboration work with the whole team. Co-authors contributed with collection of field data, advising the study design, structuring, and editing the full text and revising it.

In **paper number III**, the author initiated the study, designed it, developed the concept, gathered the required literature, collected the data, developed the employed models, translated the mathematical models into codes, performed simulation and post-processing of results. The full draft version of the entire manuscript was also written by the author. The team supported with text editing and processing, study design improvement, verification of calculation methods, consistency, and compatibility of the conducted analysis. The author performed revision tasks in collaboration with the team.

In **paper number IV**, the author wrote the full draft version of the entire manuscript, initiated and designed the study, developed the concept, put in place the model and coded it, verified the calculations, calibrated and validated the model, ran the simulations and processed the results. Co-authors assisted in structuring the text, organizing the literature, setting the method, and reviewing the final version.

In paper **number V**, the author initiated the project, searched the literature, elaborated the approaches, developed the concept, designed the vehicles, compiled the inventories, developed the models, coded the models, conducted the complete LCA, analyzed and interpreted the results. Also, the entire manuscript was drafted by the Author in its full version. The author organized the collaboration work with the whole team. Team members supported the study design, assisted in interpretation of the results, and helped in structuring and processing the text. They also aided in reviewing the final version of the manuscript.

Acknowledgements

The journey throughout this research project has been challenging but also rich in learning, both scientifically and individually. I really doubt that it could have been achieved without help in many ways from our Heavenly Father and many. So, I am deeply grateful to all.

Let me start by thanking God for all His deeds. He is and will remain TRUE for ever. Then my gratitude is first expressed to the Norwegian Public Road Administration (NPRA or SVV), for funding this research project. It was mainly at the department of Civil and Environmental Engineering (IBM) of the Norwegian University of Science and Technology (NTNU) that most of the work constituting this thesis were conducted. I would like to deeply thank each member of these institutions who contributed to the realization of this project.

On a more personal level, I would like to thank my main advisor, Professor Rolf Andre Bohne, for his unfailing and true commitment in this project. Through his support, in multiple forms, and his coaching, he was always able to get me to the point where I needed to be, especially in the moments where my time counting down was running out. My warmest thanks go to Professor Helge Brattebø, my second advisor, whom through his pronounced taste for research and his rich academic experience, knew how to transfer his passion for science to students, in a rigorous way. Professor Tore Haavaldsen acted as the perfect mentor providing support in almost all aspects during my years at the department. May he find my deep recognize for his handy touch in this part of my life. I thank Dr. Giuseppe Marinelli, Dr. Alemu Moges, Professor Holger Wallbaum and Professor Mohamed Hamdy for having invested time and energy to help me in modelling, optimization, and research structuring tasks, especially when things were getting harder. I cannot say more on the value of the help I got from them and its impact on this thesis. Finally, a big thank to my colleagues, co-authors, and collaboration partners from the Norwegian Ferry-free E39 projects. The completion of this project has benefited a lot from the friendship, brotherhood, discussion, and advises of Hrefna Run Vignisdottir, Ebrahimi Babak and Reyn Joseph O'Born. You guys were more than just a scientific family.

My beloved wife, extraordinary life co-player and true friend, Benedicte MPUTU KAPINGA, and my adorable kids Lordina K. and Lordson D. BOOTO showed so much love, understanding and attention, ceaselessly, to the always in-duty and endlessly busy husband and father that I was. For me you are the meaning of living and the most important people on earth. I am eternally grateful for all your deeds. Many thanks to my brothers and sisters, the BOOTOs, and to my mother Rosalie M. MAKENGA for your everlasting support, trust and prayers for me and my family. You showed how unique and unrivalled the family is for its members.

To close, I must state here that the unexpected disappearance of my father still weighs heavier, every day of my life. How much I would have liked his presence at this time! This thesis is dedicated to him.

Contents

Chapter 1

Introduction

1.1 Background

With the demonstrated evidence of global warming, humanity is facing one of the most critical challenge, never met during its entire existence. The assessed concentration of anthropogenic greenhouse gases (GHG) have reached levels never transcended for no less than 8000 years, while still depicting a firmly increasing trend (Team, Pachauri, & Meyer, 2014). The reactive effects of the natural environment are more and more pronounced, and clear and visible consequences on the earth's climate system are being noticed in almost all geographical zones (I. C. Change, 2014; I. P. o. C. Change, 2018). Hence, it is time that the commitment of countries in the Paris agreement now goes from verbal policies to concrete actions. This implies that well defined strategies regarding how countries will unfold themselves and tackle the growing challenge of global warming, under the COP-21 framework, must be rapidly put in place, with great details and in much more practical fashion.

Transport remains one of the last sectors – if not the last one – that necessitate to undergo a deep decarbonization process (Gota, Huizenga, Peet, Medimorec, & Bakker, 2019; Huizenga, General, & Peet, 2017; Pauw et al., 2018). Its contribution to the earth CO_2 budget is substantial (Huizenga et al., 2017), with a confirmed increasing trend directly supported by the continuing growth in passenger and freight activities, as registered in the past decades (I. P. o. C. Change, 2018; Tongwane, Piketh, Stevens, & Ramotubei, 2015).

Road transport is the subsector that is responsible of the highest share of emissions from the transport sector (Creutzig et al., 2015). It is characterized by a dominant share of fossil fuel burning activities – especially during the operation phase – and releases around 17 % of the total CO_2 globally (Abergel et al., 2017; Santos, 2017), i.e. an extremely confirmed human-induced global warming actor.

While considerable efforts have been made – and are still going on – to curb emissions from transportation of goods and persons via roads, it is alarming to observe that almost all those labors were oriented towards the vehicles (de Souza et al., 2018; Ercan & Tatari, 2015; Franco et al., 2013; Gota et al., 2019; Nordelöf & Arvidsson, 2019; Nordelöf, Grunditz, et al., 2019; Nordelöf, Romare, & Tivander, 2019; Song, Ou, Yuan, Yu, & Wang, 2017), and very little attention has been paid to the infrastructure, despite its proved influence.

Given that the observed actual situation is beyond the safe frontier of climate change and since there is a clear limit in the bearing capacity of the earth system (Biermann et al., 2012; Chylek et al., 2007; Douglass & Christy, 2009; Steffen et al., 2018), imminent reduction in emissions is required and transport sector makes a good candidate for a rapid control of situation. For heavy road transport, it is a strong believe that combining both vehicle and infrastructure-oriented strategies through technological development would bring keys to a manageable solution. Novel design techniques to reshape road vertical alignments towards lower environmental impacts during use phase, may constitute the way out for an extended decarbonization of road transport, especially when combined with clean vehicle technologies.

1.2 Motivation, objectives, and scope

Reducing emissions from heavy road transport is imperative and the contribution of technology to achieve that goal is recognized to be of great importance. As stated in section 1.1, the influence of the infrastructure is significant. More precisely, the arrangement of the road geometrical elements in the vertical plan plays a key role in both the demand of energy and the release of emissions, as it also dictates the driving behavior (G. K. Booto, Vignisdottir, Marinelli, Brattebø, & Bohne, 2020; Heyes, Daun, Zimmermann, & Lienkamp, 2015; Llopis-Castelló, Pérez-Zuriaga, Camacho-Torregrosa, & García, 2018; Walnum & Simonsen, 2015; J. Wang & Rakha, 2017).

The observation that so far, there has been so little attention paid to the infrastructure in the fight against emissions (Davey, Dunstall, & Halgamuge, 2017; Noland & Hanson, 2015; Petro & Konečný, 2017; van der Zwaan, Keppo, & Johnsson, 2013), and the knowledge that the interaction between the vehicle and the road pavement (VPI) contributes to high share in the total vehicle energy demand (Figure 1.1) led to the genesis of this study project. Shortly stated, the questions to investigate grew out of the following ground: combining improvement in vertical alignment design with clean vehicle technologies represent a great potential for savings in both energy consumption and emissions releases. This will in turn contribute substantially to the fight against the unparalleled challenges faced by humanity in the present time.

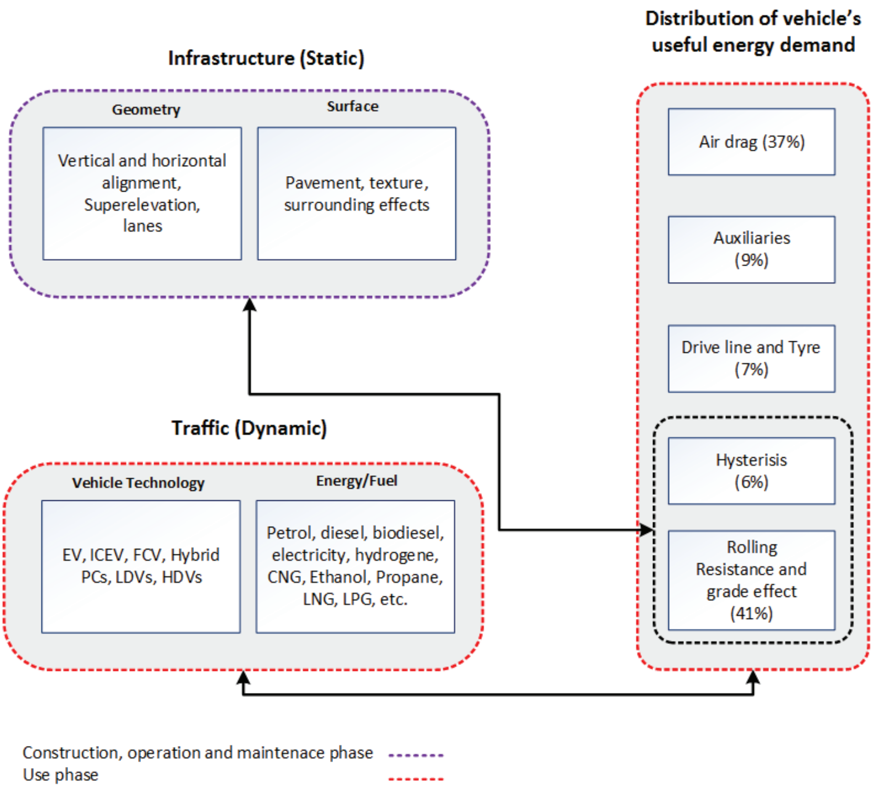

Figure 1.1 Distribution of useful energy demand of a typical truck per component (adapted from Linda Gaines (1998))

This research work pursued the following objectives:

- propose methods to model the interaction between the vertical alignment of a highway and the environmental performances of heavy-duty vehicles using it
- use the developed methods for environmental optimization of the vertical alignment of a highway
- develop metrics for assessing highway's vertical alignment from environmental and efficacy perspective and use them to evaluate those alignments.

The study seeks to understand how the vertical alignment of a highway influences the overall environmental impacts of the activities of a heavy-duty vehicle (HDV). The idea is to balance between the construction and the use phases, by investigating the contribution of the different activities (earthworks, alignment sketching and use) throughout the entire life cycle of a heavy-duty vehicle. In so doing, it will help making informed decisions regarding alternative design options, for a better environmental profile.

The following overarching question is unfolded:

How does the vertical alignment affect the overall environmental profile of the activities of a heavy-duty vehicle and in which ways can a life cycle thinking approach support the sustainability of a vertical alignment for a better environmental profile?

From this main question, the following meticulous questions were framed:

- Which factors are critical in selection and planning of a road project? Is the vertical alignment among the key ones? (Question I)
- Does the vertical alignment of a highway also influence the energy demand of an HDV operated in an environmentally friendly mode? (Question II)
- Which methodological approach can be used to model and optimize vertical alignment towards better sustainability performances? (Question III)
- How do vehicle technologies compose with the impact structure and how do they interplay? (Question IV)

To conduct this research and answer the abovementioned questions, the study focused itself on few components in the entire life cycle of a typical highway project i.e. the construction and the use stages. The main reason for converging to these two phases remains the easiness in formulating the optimization models, since adding more components would substantially increase the complexity of the developed constructs. Notwithstanding, it has been demonstrated in this research work that by appropriately capturing the earthwork cost and linking it to segment slopes and lengths it is possible to generate an arrangement of a vertical alignment of a highway. Figure 1.2 portrays an outline of the road project life cycle, where the two components of interest for this study are shaded in light blue. In most cases, the base context was the Norwegian one, or at least from a country with similar extreme conditions both topological-wise and weather-wise.

1.3 Research approach

The research questions framed in the above section 1.2 express the need for both analyzing numerical data (measuring variables, quantifying effects, mathematical modelling, etc.) and learning more about the key factors influencing the choice of the shape of a route alignment at early design phase of a road. Hence, this study proceeded in a very pragmatic way mixing both qualitative and – to a very large extent – quantitative research methods. The approaches used for the completion of this work comprised an inductive research approach combined with a system thinking approach. A very brief description regarding the motivations for adopting these approaches are unfolded below:

Inductive inference

This approach was selected because the study started from known premises (i.e. the framed research questions), collected relevant data, developed a conceptual framework using suitable techniques to identify themes and patterns, explore phenomena to build and generate theory. This is in line with what is known to be the course of an inductive approach (Bell, Bryman, & Harley, 2018; Crowther & Lancaster, 2012), which typically goes from specific to the general concept. More on the inductive approach can be found in the literature (Bell et al., 2018; Crowther & Lancaster, 2012; Saunders, Lewis, & Thornhill, 2007; Stockman, 2015).

System thinking

Applying system science perspectives to analyze sustainability of organizations, products, processes and/or services has proved to be an efficient approach (Churchman & Churchman, 1968). One of the main motivations for employing this approach is the ability to investigate components and related ties of societal, technical and natural entities from various standpoints (Kratzer, 2018; Nguyen & Bosch, 2013). Consequently, the complex nature (i.e. multi-dimensionality, dynamicity, multi-character, etc.) of sustainability issues seems to be well addressed using a holistic approach, to avoid tradeoffs and problem shifting in the analysis process (Assaraf & Orion, 2005; de Juan, Hewitt, Subida, & Thrush, 2018; Nguyen & Bosch, 2013). The present research work concerns the environmental dimension of sustainability of vertical alignment through performance of the vehicles using that alignment. Vehicles are very complex products made up of several components with multiple technologies and functions grouped in several subsystems.

This approach is adopted in this thesis because all the industrial ecology tools used for conducting the environmental analysis of the framed system are based on a system approach (Bey & McAloone, 2006; de Juan et al., 2018; Khalili, Cheng, & McWilliams, 2017; Kratzer, 2018). A vehicle being complex, is subjected to many factors such as obsolescence, technological change, market trends, discovery of new materials (namely for light weighting), and new designs or innovation, all of which bringing a certain level of complexity in the analysis., thus supporting the assortment of a system thinking approach in this research work.

1.4 Identified gaps

From the performed review (see section 2.5) it was possible to identify certain gaps in the research so far conducted regarding both alignment optimization and LCA of HDVs. The following apertures were selected as the basis for steering the present thesis:

- the consideration of only construction-related costs in formulating alignment optimization models,
- the lack of complete, process based LCA models of (clean) heavy duty trucks,
- the absence of metrics and techniques to evaluate the environmental and efficacy performances of the optimized alignment, throughout the entire life cycle perspective.

Thus, this study first introduces models that extend the traditional earthwork cost formulation for optimizing the vertical alignment by including components and items that links the alignment to emissions, for a given test vehicle. Second, it proposes an approach to develop a streamlined LCA model of heavy road powertrains (from cradle-to-grave), in the absence of industry-related data, providing means to overcome the barriers of the inaccessibility to pertinent information. Last, it

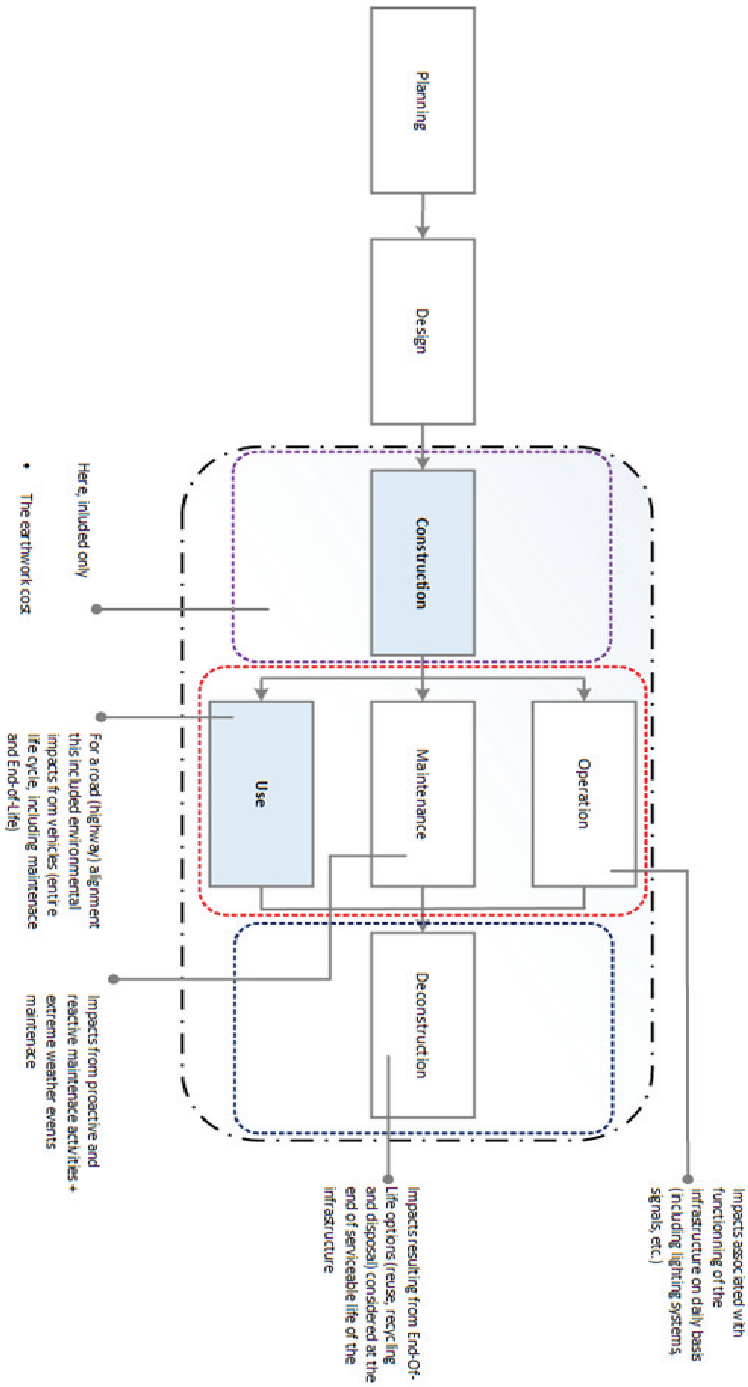

Figure 1.2 Road project life cycle stages of concern in this study

enriches the environmental toolbox with few metrics developed for evaluating performances of alignments during operation of vehicles.

The integration of gradient-related emission cost items to the vertical alignment model has been materialized in the papers III, IV and V. The key difference between each piece of those works rely in that paper III considered modifying an existing alignment and so no earthwork cost was involved in the models developed there, while in the papers IV and V, the developed models involved earthwork cost items, with the alteration that paper IV implemented the emission cost item for only one vehicle where the model developed in paper V allows for working with more than one vehicle and several emission types at the same time. The streamlined truck LCA models were developed in paper V. The alignment performance evaluation metrics were worked out in papers III and V.

In total, the work performed in this research project resulted in five papers, which tackled the research questions posed in section 1.2 in a complimentary fashion, to bridge the identified research gaps. Summarized information as of which paper dealt with which aspect are compacted in Table 1.1

1.5 Structure of the thesis

As a final step in this project, the work enclosed in papers I – V had to be put in a broader context. The contributions needed to be synopsized, the methods had to be evaluated, analyzed, and discussed, and the overall process deserved to undergo a criticism. This is the starring role of the present thesis tasked to resolve the problem stated in section 1.2.

Table 1.1 Papers and targeted questions.

Research Question	Addressed in paper(s)				
	Paper I	**Paper II**	**Paper III**	**Paper IV**	**Paper V**
RQ I	**X**				
RQ II		**X**			
RQ III			**X**	**X**	**X**
RQ IV					**X**

To be explicit, this thesis is spread over seven (7) chapters from end-to-end. Following this introductory one, some theoretical backgrounds are introduced in chapter 2. Chapter 3 unfolds only the methods developed throughout this thesis to try to answer the posed questions in an appropriate manner. Some compacted information on the methodological backgrounds of LCA are also provided. However, the focus is put on what was developed in this work only. Chapter 4 gives brief details on the selected study cases, used to support the methods developed in this research project. Chapter 5 presents the key results obtained applied the developed methods and tools. Then comes Chapter 6 which discusses not only the main findings, but also the adherences, considerations, assumptions, remarks, and reflections made in the course of this research work. The lessons learned and the understanding gotten from blending the content of the five papers appended to this thesis are also discussed in chapter 6. Note beforehand that this compendium does not include summaries of the five appended papers, one-by-one, anywhere in its core. However, when relevant, pertinent aspects of each paper are pointed out and referred to throughout the text making this corpus. The thesis concludes in Chapter 7 with a synthesis of the verdicts in the previous chapter while reflecting on the conclusions of the appended papers, and a prospective look towards the future of the field.

The design of three heavy-duty powertrains constituted a key step in the realization of this research work. Without this step, it would not be possible neither to develop a consequent LCA model of the trucks nor to conduct half of the analysis performed in this thesis. I have taken the real freedom and the joy to append to this thesis a small addendum which reproduces the main steps fetched meticulously in designing the studied test vehicles. The retained approach, the employed equations, and the articulated method to end up with a functional drivetrain are all detailed in this addendum, which is found right after the appendices.

Chapter 2
Theory

2.1 Climate Change

It is now a fact that the earth climate system has drastically changed as a result of human activities, principally connected to the exploitation of fossil, nonrenewable resources. The trend to point out is that counting from the second half of the last century, a lot of attention has been directed towards the growing climate concern, with an increasing public awareness and deeper and stricter engagements from all concerned actors. Considering the widespread media coverage surrounding the likelihood of temperature raise on the earth's surface due to increased greenhouse effects, in one hand, and the high frequencies of occurrence of extreme events so far registered, in the other hand, it is more likely to conclude that the earth changing climate is probably one of the biggest issues that mankind will need to address in the present century and those to come.

Climate change poses a real threat to development globally. It affects the planet and its inhabitants and endangers the ecosystems. This is even more critical in areas with widespread poverty and underdeveloped infrastructure (Schweikert, Chinowsky, Espinet, & Tarbert, 2014). However, unlike extreme consequences that have been observed in known vulnerable areas, the developed world is also concerned with this drama, mostly due to lack of resilience and robustness in their existing systems (Creutzig, Mühlhoff, & Römer, 2012). Climate change is a result of the economic activities as it was shaped since the beginning of the industrial era. It is estimated that its effects negatively affect the global economy with damages amounted to about 2.5 to 3% of the global gross domestic product (GDP), on annual basis ever since (Ciscar et al., 2011; Hallegatte, Hourcade, & Dumas, 2007). Hence the problem is to be considered on global scale and efforts are required from the entire planet to act against one of the most detrimental issues never faced by humanity before.

Several strategies exist today to effectively combat climate change. Some measures are oriented towards mitigating the effects of climate changes while some others focus on adapting mankind's life to the inevitable consequences of global warming (Becken, 2005; Laukkonen et al., 2009; Reckien et al., 2014). Mitigation efforts, such as the several GHG reduction targets imposed by countries or recommended under the COP21 framework constitute the required path to avoid global mean temperature rising of 2 degrees C above the pre-industrial levels by 2100 (da Graça Carvalho, 2012; IPCC, 2014; Reckien et al., 2014), thus guaranteeing living conditions for both actual and future generations on the same earth.

2.2 Infrastructures

Infrastructures provide the fundament for the quality of life within societies. They play a key role in socio-economic development of countries and are righteously considered as the pillars of economies of nations. Infrastructures encompass not only dwellings, heat comforts or convenient lights, but extend to many more assets of very high necessity and paramount to human wellbeing such as drinking water facilities, hospitals, energy generation units, communication and numerical archetypes, and transportation networks.

Infrastructures constitute an important part of the investment portfolio of countries. If they exist, modern and practical infrastructures will be related to economic prosperity and wellbeing, which they enable. Without infrastructure, it would be very difficult to sustain the wider economy in many ways. For example, lacking communication means or experiencing reduced mobility would lead to fewer import or export activities, which may be critical to the correct functioning of societies on daily basis. The need for creating infrastructures goes hand in hand with social demands which are tightly connected to demographic parameters within a given geography. Hence, creating, operating and maintaining infrastructures becomes very challenging, especially under critical conditions. Further, being quite complex systems, infrastructure management must inevitably integrate the Triple Bottom Line approach, to be able to cope with sustainability pre-requisites. This makes it even more challenging as a consistent equilibrium needs to be found between money, nature and people. Well-developed and consistently managed infrastructures will be depending largely on successfully integrating and balancing the different levels of complexity, thus impacting positively the quality of life.

2.2.1 Road infrastructures

Roads are vital in any economy. They are pivotal and constitute the backbone of the economic system, as they enable exchanges in a safer, surer, and secured manners. The transformative role played by road infrastructures in the overall productivity of nations is known to all. The biggest advantage of having well-functioning road infrastructures is the guarantee of fluid transport activities that ensure point-to-point (door-to-door) transport of goods and persons. Road infrastructures are also seen as an economic stimulus. This is to say that they can influence other existing economical inputs and make them more productive, contributing thus to economic growth (Phang, 2003; Pradhan & Bagchi, 2013). The quality of road infrastructures has a strong influence in the quality of trade within regions, while it can also affect economic growth by restructuring the aggregate demand and creating intermediate inputs (Esfahani & Ramírez, 2003; Phang, 2003; Sanchez-Robles, 1998; Shepherd, 2007; Short & Kopp, 2005). However, road infrastructures also have several safety issues mostly related to higher frequency of accidents, a good share of which causes human lives losses (Noland & Oh, 2004; Vieira Gomes, 2013).

2.2.2 Road infrastructures and climate change

Building new roads, expanding or just maintaining existing ones often indicate a healthy economy, social welfare and development (Kessides, 1993). Unlike their extensive use on daily basis, roads are exposed to a number of environmental conditions which make them particularly vulnerable to changes in the climate system (Bollinger et al., 2014; Koetse & Rietveld, 2009). The treat caused by climate change to existing and future road infrastructures have been largely debated in the scientific community and a considerable number of recommendations have been made to escape the drama (Council et al., 2008; Galbraith, Price, & Shackman, 2005; Wooller, 2003).

Among the relevant findings is, for example, the recognition that instantaneous weather-influenced hazards may negatively impact the infrastructure and its operation, inducing higher costs of adaptation and maintenance, while also altering demand for transportation (Bollinger et al., 2014; Hambly, Andrey, Mills, & Fletcher, 2013; Koetse & Rietveld, 2009; Margulis et al., 2010; Nemry & Demirel, 2012). The severity of those weather-related events will vary by geographical locations (climatic zones), and the proportion to which the infrastructure will be impacted will depend on several parameters (design factors, used materials, level of exposition of components, etc.). Further studies attempted to quantify specific impacts of temperature, rain, snow, ice, wind, fog and coastal flooding on road infrastructures (Karl, Melillo, Peterson, & Hassol, 2009). Coastal flooding is tightly related to sea level rise and both have been the focus of many research works which investigated their relative impacts on coastal highways (Burkett, 2002; duVair, Wickizer, & Burer, 2003; Oswald & McNeil, 2013; Savonis, Burkett, & Potter, 2008).

As stated above, episodic extreme weather events induced by climate change will have specific impacts on road infrastructures, proportional to their levels of severity and the degrees of exposure. Such impacts may include, among others, dilatation of bridge joints (i.e. thermal expansion), fluidizing of asphalt pavement (also induced maintenance cost), drains overflow, bridges submersion, landslides leading to road closures. Some of these most relevant impacts are presented in Table 2.1 with their related climate events and the concerned infrastructure components.

It is to underline here that road infrastructures are not only affected by climate change, but they are also contributing to climate change through the release of significantly higher amounts of greenhouse gas (GHG) during their entire life cycle (i.e. construction, operation, maintenance, and decommissioning phases). The largest amount of emissions is released during operation (use) stage as most road users (vehicles) uses hydrocarbons as fuel for their propulsion. The key element here is the vehicle fuel consumption, as the amount of released gas is largely linked to the amount of oxidized fuel. The quantity of consumed fuel per vehicle covered distance is largely influenced by the geometry of the roads and the condition of its surface (Regmi & Hanaoka, 2011). Rough road surfaces will lead to higher fuel consumption as they will tend to make vehicle motion more difficult, uncomfortable, and inefficient. Regular road surfaces will tend to favor uniform velocities, easing accelerations and decelerations, thus improving the operational efficiency of the vehicle. The following section provides some information regarding emissions from road transport activities.

Table 2.1 Potential climate change impacts on road infrastructures (adapted from Regmi and Hanaoka (2011)**)**

Weather event	Potential problem	Component and parameters
Temperature (High)	Surface deterioration; thermal expansion of bridges; steel joints bucling	Pavement (needs stiffness and moisture control)
Temperature (Low)	Snow or ice may affect operations; higher maintenance costs	Steel bridges (control corrosion, expansion of joints, safe materials selection)
Rainfall	Increased flood risk; drainage overload; affect driving conditions; submerge bridges;landslides and mudslides.	Bridges and culverst (design loads, return period); drains (size, shape, slope); Mountaineous road (slope protection, sediment control); pavement (materials, water flashing on surface)
Storms	Flooding risk and inundation causing safety issues (evacuation, alter signs, ect.)	Drans and cross drains (capacity, slope); embankment (control height); signs (design against wind load)
Sea level	Affect coastal roads (may lead to abandon or realigning)	Coastal road (edges, protection walls, signs, realigning)

2.3 Emissions from road transport

Emissions from road transport come from two main sources:

- *the infrastructure*: during construction, operation, maintenance, reparation, extension, decommission, etc.; and
- *the vehicle*: from the combustion of fossil fuel in the internal combustion engine (ICE), mostly during operation.

Relevant emissions from road vehicles can be divided into two main categories i.e. *exhaust emissions* (or *tailpipe emissions*) and *non-exhaust emissions*. The exhaust emissions consist of releases from the operations of the ICE as a result of burning fossil fuels. Two subcategories are distinguished: *cold emissions* and *hot emissions*. Non-exhaust emissions include emissions from *evaporation* of fuel from the tank as well as secretions from *tires and break wears*, and it can occur in both motion and static mode. A typical high-level illustration of emissions' streams from a road vehicle is shown in Figure 2.1.

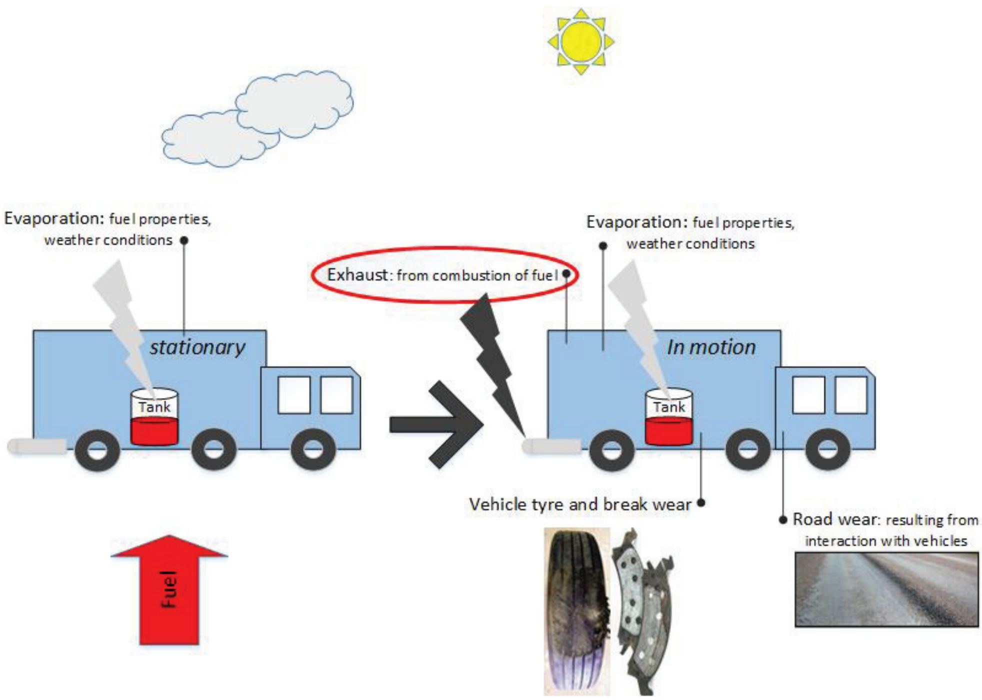

Figure 2.1 Simplified representation of road vehicle's emissions flows

Combustion of any fuel (liquid, solid or gaseous) results in formation of gases and small particles, also referred to as combustion by-products. The form and quantity of these by-products are a function of the fuel type, the air-fuel ratio, the employed combustion appliance, the operating mode, and many other factors. When the burnt fuel is a fossil one (composed mainly of carbon, hydrogen, nitrogen, sulfur and oxygen), it results in a variety of by-products most of which are highly reactive and very detrimental for both human health and the natural ecosystems (Mills et al., 2009; Perera, 2017; Singh et al., 2007). They are therefore designated as "pollutants" or "emitted pollutants" or also "emissions". Pollutants of most concern when burning fossil fuels in a road vehicle include the ozone precursors (i.e. carbon monoxides (CO), nitrogen oxides (NO_x), nom-methane volatile organic compounds (NMVOCs)), greenhouse gases (encompassing carbon dioxides (CO_2), methane (CH_4), nitrous oxides (N_2O)), acidifying substances (comprising sulfur dioxides (SO_2), ammonia (NH_3)), carcinogenic species (embracing polycyclic aromatic hydrocarbons (PAHs), persistent organic pollutants (POPs)), toxic substances (consisting of dioxins and furans), particulate matters (with PM_{10}, $PM_{2.5}$) and heavy metals (Tongwane et al., 2015; Y. Wang, Xing, Xu, & Du, 2016; Q. Zhang et al., 2016). All those pollutants have detrimental effects on human health (Mills et al., 2009). Based on their level of reactivity and the magnitude of their detrimental effects, some pollutants can be regulated while some others cannot (Ayala et al., 2002; Bikas & Zervas, 2007; Broustail, Halter, Seers, Moréac, & Mounaim-Rousselle, 2012; Fontaras et al., 2009; Franco et al., 2013; Weilenmann, Soltic, Saxer, Forss, & Heeb, 2005; Zervas, 2008). A typical example is nitrous oxides (N_2O), although a very detrimental by-product of fossil fuels combustion, yet belongs to the category of nonregulated emissions (Fontaras et al., 2009; Franco et al., 2013).

In general, both the infrastructures and the vehicles generate stressors to the natural environment in each of their life cycle stages. Hence it is advised to adopt a life cycle thinking approach in order to account for environmental impacts of the entire system, holistically. Life cycle assessment (LCA) is the dedicated tool for performing such analysis. The method is known to be not only consistent and robust, but also multidimensional and complete enough for analyzing environmental impacts, from cradle-to-grave. A short description of this method is given the following section. However it is import to mention here that most studies referring to road transport focus mostly on the fuel stream, which is analyzed either from well-to-tank, or tank-to-wheel or well-to-wheel, leaving a side the value chain of the vehicle as well as that of the infrastructure (Atkins & Koch, 2003; Louis, 2001; Ramachandran & Stimming, 2015).

2.4 Life cycle assessment

As mentioned above, produced goods and services do have a life which start from their design and terminate to their end-of-life, passing through extraction of resources, production, and consumption. In each of these life cycle stages one or more activities are performed. To perform those activities, materials, energy, transport, or processes of any kind that combine such resources are required. Hence, all these activities impact the natural environment in one or another way (Finkbeiner, 2013; ISO, 2006; Reap, Roman, Duncan, & Bras, 2008; Rebitzer et al., 2004).

Life cycle assessment (LCA) is a methodological framework for estimating and evaluating the environmental burdens imputable to the entire life cycle of a product, system or service (ISO, 2006). LCA is a tool for measuring the environmental sustainability in a quantitative way. It is widely used by industries, researchers and policymakers, and is substantially employed for decision making, and environmental improvement (Finkbeiner, 2013; Finkbeiner, Inaba, Tan, Christiansen, & Klüppel, 2006; ISO, 2006; Pennington et al., 2004; Reap et al., 2008; Sala, Farioli, & Zamagni, 2013). Several research works provide details on how to apply the LCA method in a wide range of contexts ranging from waste management (Ekvall, Assefa, Björklund, Eriksson, & Finnveden, 2007), energy production (Pehnt, 2006; Varun, Bhat, & Prakash, 2009), food production (Andersson, Ohlsson, & Olsson, 1994; Schau & Fet, 2008), or building (Assiego de Larriva, Calleja Rodríguez, Cejudo López, Raugei, & Fullana i Palmer, 2014; Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014).

The LCA method unfolds in four phases which include the definition of the goal and scope of the study, the analysis of the life cycle inventory, the assessment of the life cycle impacts and the interpretation of the obtained results. The LCA phases are presented in Figure 2.2.

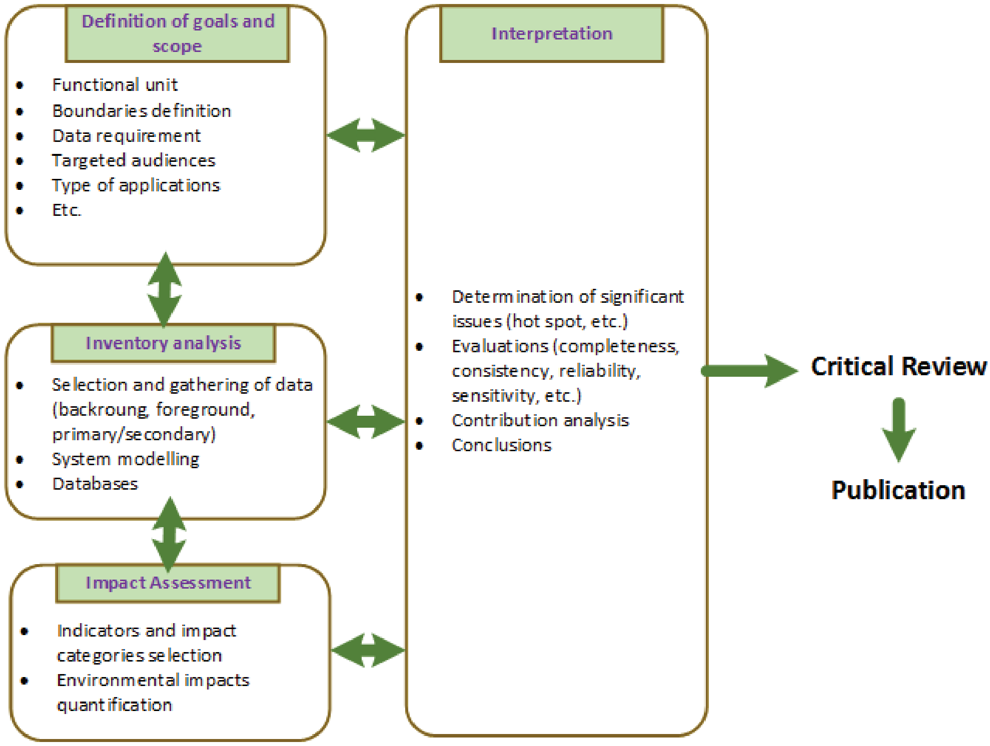

Figure 2.2 Phases of an LCA

According to ISO (2006), the first stage describes the system under study, defines its frontiers and determine a functional unit, which is a metric based on which all calculations will have to refer. The second stage, also seen as the most time-consuming, deals with data collection and budgeting resources entering and leaving the considered system. Accounted flows include consumed resources and generated waste, with respect to their locations of occurrence, size, time period and dynamic. All flows must be modelled consistently within the boundaries defined in the previous phase. Then comes the third stage dedicated to making sense of the inventory i.e. all data collected in the second stage. Specifically, it provides indicators allowing for the analysis of potential contributions of the modelled inventory. The obtained results are then interpreted in the last stage. This stage is not an isolated one as it interacts with all other stages and may influence some iterations of the study already at early stages. Noteworthy to stress here that impact assessment indicators are of two kinds i.e. the midpoint indicators (aka as problem level) and the endpoint indicators (aka as damage level).

To be able to sustainably leverage the power of LCA as a tool it is important to know about the limitations of the method. What comes out of an LCA as results are neither accurate, nor complete. An LCA quantifies potential environmental impacts but is not absolutely objective (Curran, 2013; Ekvall et al., 2007; Finkbeiner et al., 2006; Pennington et al., 2004; Reap et al., 2008; Sala et al., 2013; Y. Zhang, Baral, & Bakshi, 2010; Y. Zhang, Singh, & Bakshi, 2010). Therefore, results from an LCA will largely depend on flexibility in the methodological decisions such as the chosen time perspective, the retained assumptions, the quality of data and related sources, the selected impacts assessment methods, or the type of allocation considered in the analysis. The choices are made by the practitioner, based on the characteristics of the system under study, as defined in the first stage.

An LCA can be conducted in an attributional or a consequential fashion. These two concepts relate to the way the life cycle inventory (LCI) is modelled. An attributional LCI is the one that considers the flows in the environment within a chosen temporal window, while a consequential LCI considers how the flows change in response to decisions that are made (Ekvall et al., 2016). While attributional LCAs (ALCA) are quite common to encounter in practice, consequential LCAs (CLCA) are relatively rare, as it is not really clear when to use such an analysis and for which purpose (Ekvall et al., 2016). An LCA can be conducted using a simple spreadsheet. However, some systems can get quickly complex to model, requiring huge amount of time and a lot of energy to model by hand. Thus, specialized softwares are often employed for such purpose.

2.5 Related literature

Literatures related to this study were reviewed systematically. Several sources were considered, while a specific search sequence was adopted. Two topics of literature were reviewed for the purpose of this work, encompassing "***optimization of vertical alignment***" and "***life cycle assessment of heavy-duty vehicles (HDVs)***". The whole process involved a scoping, literature search, literature sieving, information retrieve, synthesis of collected data and a narrative – mainly the state-of-the-art, insights and gaps. The systematized review procedure is summarized in Figure 2.3 where more details are also given. Insights from the conducted process are compacted below, for each topic:

2.5.1 Vertical alignment optimization studies

Using optimization techniques for efficient shaping of road alignment is not new at all. The idea has been the subject of research works for decades, and the literature is rich of several such related works. Pioneering works date back to the 70s and 80s when the problem was approached either through estimation of total alignment cost (Moavenzadeh & Becker, 1973; Watanatada et al., 1987) or computationally intensive optimization models (Athanassoulis & Calogero, 1973; Hogan, 1973). The focus has shifted ever since, and today's research is mainly directed towards deploying very sophisticated models and algorithms to efficiently tackle large-scale problems in comprehensive time (Hare, Hossain, Lucet, & Rahman, 2014; Ibrahim, Sayed, & Ismail, 2012; Saha & Ksaibati, 2016). The new models often rely on heavy mathematical techniques embracing calculus of variations (Howard, Bramnick, & Shaw, 1968; Shaw & Howard, 1982; Thomson & Sykes, 1988), dynamic programming (Fwa, Chan, & Sim, 2002; Gomaa, Alimin, & Kamarudin, 2011; Nicholson, 1973), mixed integer and linear programming (Said M Easa & Mehmood, 2008; Revelle & Whitlach, 1996). Genetic algorithms, geographic information systems and combined neighborhood heuristic search with mixed integer programming also figure among the employed techniques (Cheng & Lee, 2006; Jha, 2000; Jha & Schonfeld, 2000, 2004; Jian-xin & Qing, 2011; J. Jong, 1998; Kang, Jha, & Schonfeld, 2012). Table 1.1 summarizes the key characteristics of some pertinent studies in this field.

It is worth mentioning that none of the above methods included vehicle emissions or fuel consumption in their models. The focus has been in capturing costs related to the construction phase. Some have tried to consider the use phase cost without explicitly linking it to road gradients (Jha, Jha, Schonfeld, & Jong, 2006; J.-C. Jong & Schonfeld, 1999).

2.5.2 Heavy-duty vehicles life cycle assessment studies

While the number of scientific studies addressing the environmental life cycle assessment of (clean) passenger cars in the literature is significantly high (de Souza et al., 2018; Nordelöf, Messagie, Tillman, Ljunggren Söderman, & Van Mierlo, 2014), methodical researches dealing with heavy road vehicles are relatively scarce (Nordelöf et al., 2014; Nordelöf, Romare, et al., 2019), despite their proved potential for emissions curbing (Sushandoyo & Magnusson, 2014). The few existing studies are mostly concerned with busses addressing mainly the propelling energy on a well-to-wheel (WTW) perspective (Ercan, Noori, Zhao, & Tatari, 2016; Frey, Rouphail, Zhai, Farias, & Gonçalves, 2007; Kliucininkas, Matulevicius, & Martuzevicius, 2012; Lajunen & Lipman, 2016; Ma, Ke, Han, & Tang, 2017; Xu et al., 2015; Xylia et al., 2019; B. Zhou et al., 2016). Some studies use a more complete approach, incorporating the entire value chain of heavy vehicle from cradle-to-grave, while still considering the energy source from well-to-wheel (Cooney, Hawkins, & Marriott, 2013; García Sánchez, López Martínez, Lumbreras Martín, Flores Holgado, & Aguilar Morales, 2013; Harris, Soban, Smyth, & Best, 2018; Nordelöf, Romare, et al., 2019), while others uses a hybrid approach capturing the environmental impacts through combination of country-wide economic matrix and related specific processes' data (Ercan & Tatari, 2015; Ercan, Zhao, Tatari, & Pazour, 2015).

A selected number of heavy-duty trucks LCA exist El Hannach, Ahmadi, Guzman, Pickup, and Kjeang (2019) investigated the economic and environmental impacts of implementing hydrogen and diesel dual-fuel solution in a heavy-duty truck using a WTW perspective for the fuels and the cradle-to-grave approach for the truck. In the same fashion, Rose et al. (2013) compared a diesel and CNG powered refuse collection truck in a Canadian city. Other studies employed either a WTW or a TTW (tank-to-wheel) approach to assess suitability of specific energy carriers as potential fuel for heavy transport (Arteconi, Brandoni, Evangelista, & Polonara, 2010; Cheenkachorn, Poompipatpong, & Ho, 2013; Osorio-Tejada, Llera-Sastresa, & Scarpellini, 2017; Song et al., 2017).

The need for process-based LCA studies encompassing both the entire value chain of a heavy-duty vehicle and the whole propelling energy value chain remains higher (Harris et al., 2018). However, the challenge for conducting such studies remains the access to industry-related data (Cooney et al., 2013; Ercan & Tatari, 2015; Ercan et al., 2015; García Sánchez et al., 2013; Harris et al., 2018; Nordelöf, Romare, et al., 2019).

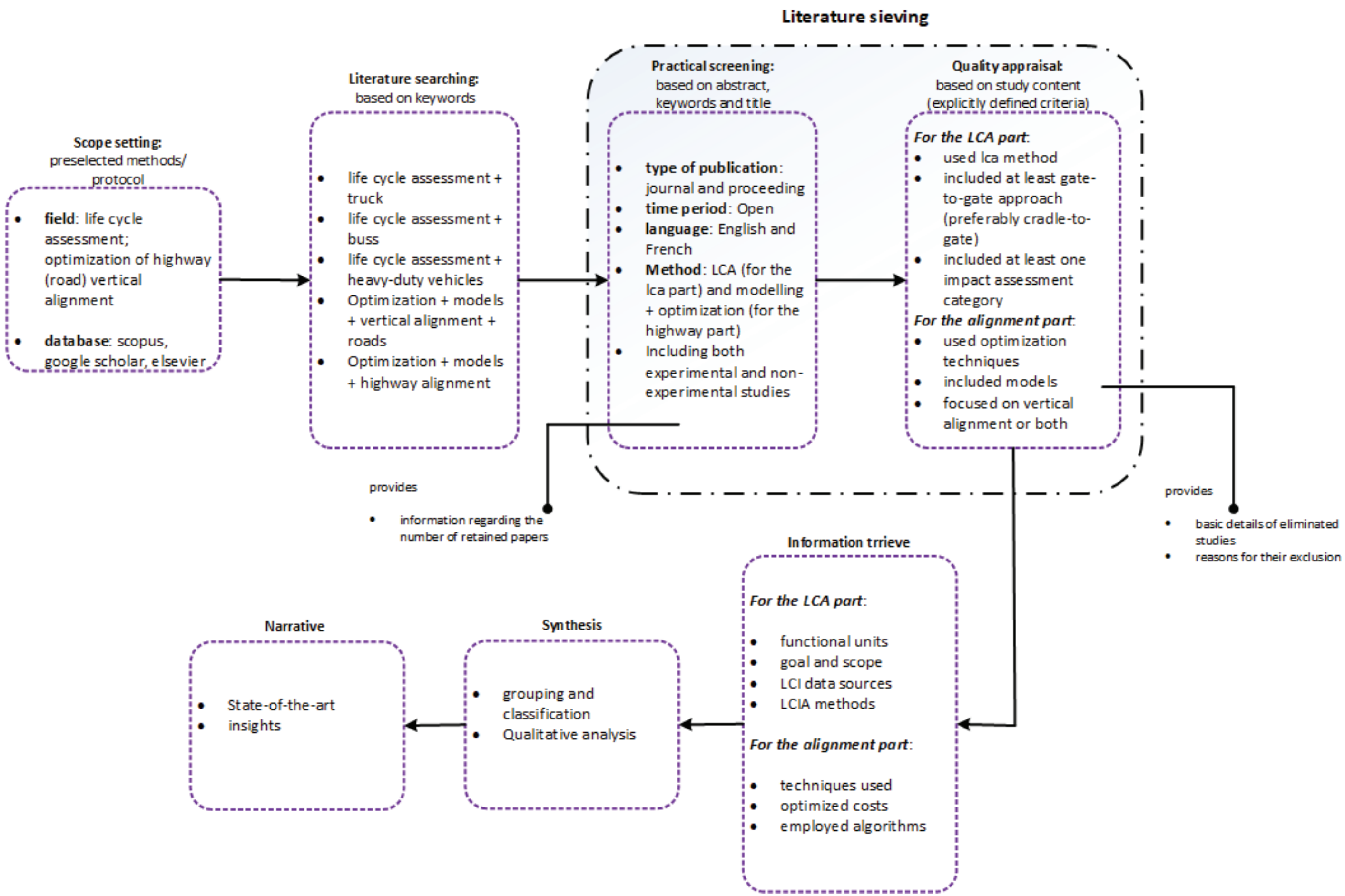

Figure 2.2 Workflow of the study literature review process

Table 2.2 Selected studies in optimization of vertical alignment of a road

Study	Cost items	Model type	Algorithms
(Trypia, 1979)	cut and fill	Mixed integer linear programming (MILP)	
(Schacke, 1972)	earthwork	calculus	Numerical simulation
(Mayer & Stark, 1981)	earthwork	Linear programming (LP)	Numerical search
(Said M. Easa, 1988)	earthwork	Linear programming (LP)	simplex
(Goh & Teo, 1988)	earthwork	Calculus of variation, optimal control	control parametrization technique
(C. J. Goh, E. P. Chew, & T. F. Fwa, 1988), (Göktepe, Altun, & Ahmedzade, 2009), (Goktepe, Lav, & Altun, 2005)	construction, earthwork	Dynamic programming (DP), state parametrization approaches	
(Aljohani & Moreb, 2003; V. R. Koch & Y. Lucet, 2010; A. A. Moreb, 2009; Moreb & Aljohani, 2004)	earthwork, side blocks, etc.	Spline Linear Programming (SLP)	Numerical search, Simplex.
(Moreb, 1996)	earthwork	Linear programming (LP)	simplex
(Goktepe, Lav, & Altun, 2009)	cut, fill	Non-linear programming (NLP), Dynamic programming (DP)	Genetic algorithm, Weighted ground line method (WGLM), Fuzzy logic
(Ghanizadeh & Heidarabadizadeh, 2018)	cut, fill	Non-linear programming (NLP)	Colliding bodies optimization (CBO), genetic algorithm (GA),

particle swarm

optimization (PSO)

Chapter 3 Methods and Materials

This section provides a synopsis of the methods and materials that have been used to tackle the research questions listed in the first chapter of this thesis. For the sake of clarity and objectivity, the methods are just briefly presented here. Detailed related information can be found in the respective papers and the corresponding supplemental materials annexed to this thesis.

3.1 Methods

Based on the purpose of their use, the methods employed in this thesis can be grouped in the following three categories:

- ***Proof of concept***: aiming at capturing the effects of vertical alignment of linear infrastructures on the energy demand of a heavy-duty vehicle that adopts an environmentally friendly driving profile (i.e. operating under eco-driving mode)
- ***Silhouette enhancement***: focusing on optimizing the vertical sketch of linear infrastructures towards improved environmental profile
- ***Silhouette appraisal***: endeavoring to assess the resulting optimized profiles with respect to their environmental and other technical performances (i.e. impacts assessment)

Table 3.1 presents some more information for each of the three categories of the methods mentioned above. While the first category, i.e. the proof of concept, was taken alone in the performed analysis and was enough to stand on its own, the other two categories, i.e. silhouette enhancement and silhouette appraisal, were always combined to come up with scientifically sounds solutions and conclusions for each examined question. Concise details regarding the development of those methods are provided below.

3.1.1 Proof of concept

Eco-driving and in-vehicle driver feedback technologies constitute driving-style changing techniques dedicated to managing road traffic. They were introduced by policy-makers primarily as operational strategies to efficiently handle roadway congestions (Boriboonsomsin & Barth, 2008) but were quickly found to have imminent benefits in reducing vehicle fuel use and related tail-pipe emissions (Barth & Boriboonsomsin, 2009; Boriboonsomsin & Barth, 2009; Boriboonsomsin, Vu, & Barth, 2010). Of the two techniques mentioned above, eco-driving is probably the most popular, and the one that has attracted the most attention of the great public in Europe, North America, Japan and Australia, probably because of its effectiveness in reducing both fuel expenses and GHG emissions (Killian, 2012; MERKiSz, Andrzejewski, & PiELECHA, 2013). As this thesis focuses on the infrastructure side to improve its environmental profile through the performances of its users (i.e. vehicles) during their operations, it was imperative to ascertain that the vertical alignment of those linear infrastructures influences the energy demand and resulting emissions of heavy-duty vehicles, independently of their operating mode (i.e. either they are driven traditionally or eco-friendly).

Driving eco-friendly requires the driver to take a certain number of concrete actions throughout the trip. Such actions may include, among others, to drive less and chain trips, go easy on pedals, turn the engine off for few seconds under specific situations, frequently check tires' pressure,

Table 3.1 Main features of the methods and techniques used in this thesis

Item	Designation of the method		
	Proof of concept	**Silhouette enhancement**	**Silhouette appraisal**
Paper number	**II**	**III, IV,** & **V**	**III, IV** & **V**
Use technique(s)	regression analysis, bi-leveling, split-apply-combine (SAC)	optimization techniques GA & NLP (III); LP (IV & V)	tank-to-wheel analysis, TTW (III & IV); life cycle analysis, LCA (V)
Spatial resolution	50 km road	50 km road (III); 1 km road (IV & V)	50 km road (III); 1 km road (IV & V)
Modelling tool(s)	R and R-studio; ArcMap (ArcGIS)	MATLAB (III); Python (IV & V)	MATLAB (III); Python (IV); OpenLCA (V)
Input data source(s)	Norwegian road databank (NVDB); field data of HDV in eco-driving mode from the Norwegian public road administration (NPRA)	NVDB & EMEP (III); literature & EMEP (IV & V)	NVDB & EMEP (III); literature & EMEP (IV), EMEP, Ecoinvent and ILCD (V)
Input data types	Road segment lengths and slopes, Vehicle GPS positions, instantaneous fuel consumption and speeds	Road segment lengths and slopes, tier-3 EMEP emission factors; road width, initial profile of the terrain profile	Road segment lengths and slopes, tier-3 EMEP emission factors; road width, initial profile of the terrain
Vehicles	40 tons HDV, Volvo FH16 (750 hp).	40 tons articulated HDV; several HDVs	40 tons articulated HDV; several HDVs
Technologies	Euro VI, diesel.	Euro V-SCR diesel, Euro V-SCR & EGR diesel, Euro V diesel.	Euro V-SCR diesel, Euro V-SCR & EGR diesel, Euro V diesel.
Principal outputs	Models of engine fuel rate as a function of road slopes	optimized vertical alignments	optimized vertical alignments

tighten the gas cap, observe specific speed limits, watch over the total vehicle weight before engaging to a trip, adopt a lower air conditioning use profile, etc. This driving mode is way different from the traditional way of driving, often characterized by a certain level of aggressivity in terms of speeds, accelerations, and idling. Therefore, to be able to verify the vertical alignment postulate and prove that concept on HDVs operating on eco-driving mode, a method was developed in this thesis to accurately model the variation of fuel consumption with the road gradients.

To accurately capture the effects of road gradients on the fuel consumption of HDVs operating under eco-driving mode, the method developed in this thesis combined four different techniques: data processing, feature engineering, geospatial analysis and regression analysis. The combination of these four techniques resulted in a more robust method, easy to implement when addressing similar issues.

Field (raw) data from operation of the vehicle and from the road path taken by the same vehicle must first be aggregated (from 75 Hz to 1 Hz) and cleaned. The processed vehicle data may need to be feature engineered to derive certain factors like instantaneous accelerations, speeds, time-related fuel demand, etc., in case these were not directly measured during data collection campaign. Cleaned and processed data from the two considered streams must then be geo-processed to map the instantaneous vehicle positions to their corresponding locations on the taken road path, excluding vehicle data points situated at a Euclidian distance of above 97.5 percentile of the nearest road element. The result is one unique compiled database ready to be analyzed. The analytics stage involves first grouping data points based on vehicle operating mode (i.e. acceleration, deceleration, constant speed), then splitting them in gradients bins of 0.5% length and applying average on the independent variables contained in each bin, before combining the result together and regressing the energy demand on the road gradients. To define the correct order of the model and find a fit that better explain the observed pattern, the regression analysis is reinforced by a residual analysis. The performance of the resulting models was evaluated by means of adjusted R-squared and the root mean square error. A workflow summarizing this method is shown in Figure 3.1.

It should be noted that the adoption of regression analysis as the key technique for pattern finding was motivated by its capabilities to accurately scrutinize the connection between two or more variables of interest (Chatterjee & Hadi, 2015; Ezekiel & Fox, 1959). This multi-task technique is widely employed in quantitative pattern finding to answer questions related to significant factors, the degree of certainty for the retained and neglected factors or the interaction between the factors (Bates & Watts, 1988; DeFries & Fulker, 1985). Using regression in this case proved to be a rational choice.

3.1.2 Silhouette enhancement

To find the configuration of the vertical alignment that returns the best environmental profile during use phase, the developed method combined road (or route) data with speed-gradient vehicle performances into one unique model and used optimization techniques to search through a very large number of possible alternatives. The main idea remains to capture the effects of the vertical alignment on the vehicle performance into a mathematical model which is then used to poise these performances acting on the alignment, using simple optimization techniques. This idea led to the development of two concepts which are described below:

3.1.2.1 The single layer approach (SLA)

The single level approach (SLA) consists in combining two types of inputs: the performances of one unique heavy-duty vehicle (here termed as the test vehicle), and data of the chosen road path.

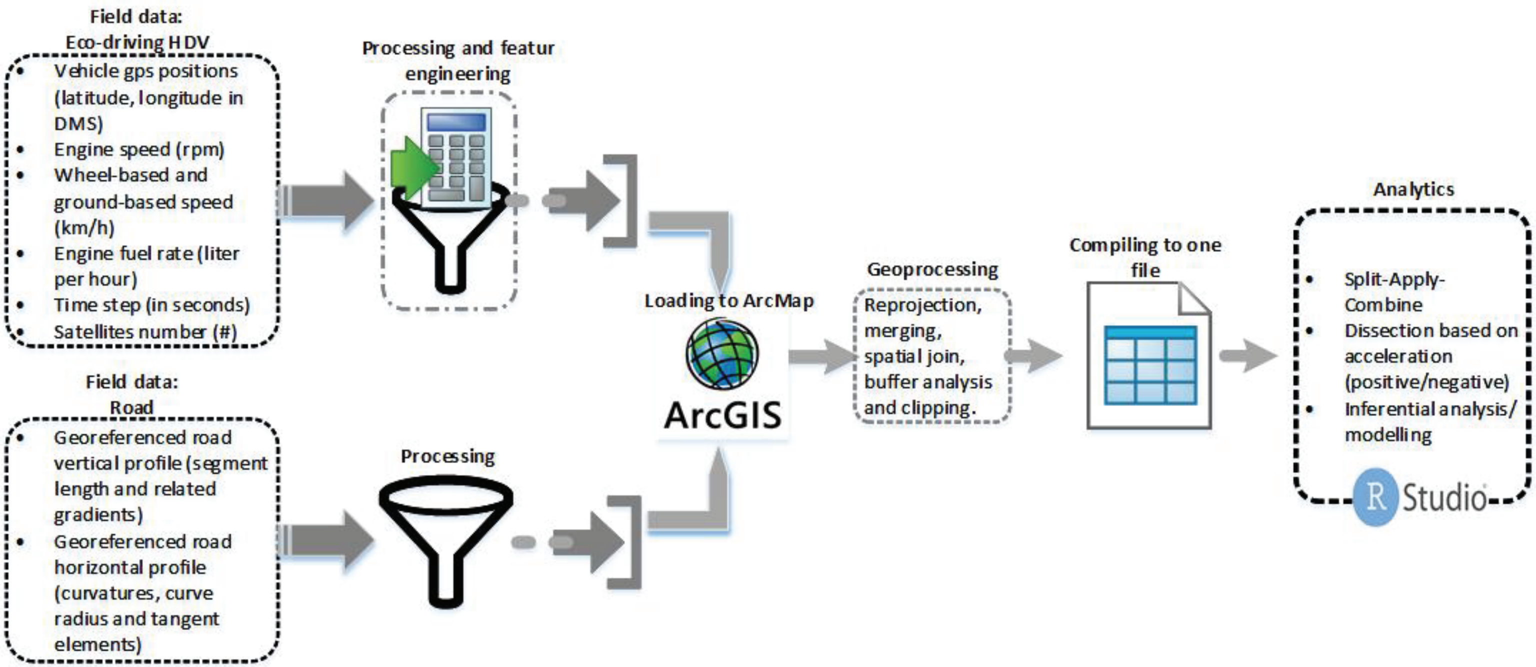

Figure 3.1 Proof of concept's workflow.

The test vehicle performances include fuel consumption and hot emissions from the exhaust of the vehicle, whose profiles are tightly linked to the vehicle speed, its payload, and the gradient of the road. Road path data may be of two types. One type entails information on distances and gradients of each road segment (this is the case where the studied alignment is from an existing road), whereas the other type comprises continuous elevation information from the initial terrain that is intended to host the projected road.

The presence of these two types of data related to the road path led to two different formulations of the problem and consequently to two different types of modelling approaches. In one case – where the road already exists, the problem is formulated as a "***vertical alignment modification***" conundrum, whereas in the other case – where no road exists – the challenge is framed as an "***optimal vertical alignment generation***" question. Both formulations encompass optimization models, where specific techniques are employed for solving them.

This concept is termed single level approach because only one performance indicator – here the fuel consumption – of one specific vehicle type of a specified technology is used in combination to road path data to formulate the optimization problem. The vehicle is assumed to operate under constant speed and load for the entire trip. The diagrammatic summary of the SLA concept is portrayed in figure 3.2. The developed optimization schemes are given below:

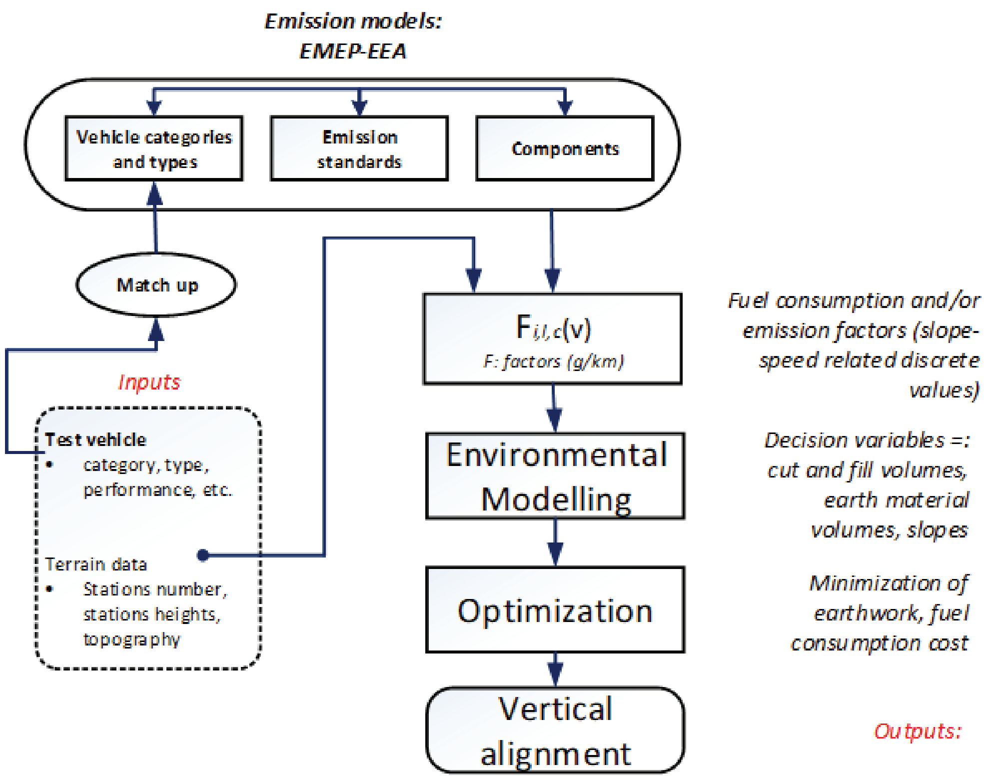

Figure 3.2 Diagrammatic summary of the single level approach concept.

The alignment already exists

To adjust the vertical alignment of an existing road the developed model introduces three different objectives termed here as "***reduction levels***". The retained reduction levels include the following:

- ***minimum total fuel consumption (TotFC minimum)***: modifies the existing vertical alignment so that it allows the test vehicle to consume the lowest fuel amount possible, during its operation for a specified speed and load,
- ***minimum slope variation (delta slope minimum)***: transforms the existing vertical alignment to obtain the lowest possible elevation difference between the initial and the resulting alignments, and
- ***percentage-target reduction***: adjusts the existing vertical alignment so that it permits the test vehicle to achieve a specified percentage of reduction in its fuel consumption during its operation at a constant speed and load.

The *percentage-target reduction* level is an intermediate level because any reduction in fuel consumption achieved will be comprised between the ones resulting from the *minimum total fuel consumption* and *the minimum slope variation* levels, also designated here as "*practical*" levels. Hence the two values of fuel consumption returned by these practical levels constitute the limit of the feasible region of the percentage-target reduction. The term practical is used to differentiate them with the preexisting reduction levels – two extreme alignments – that are obtained considering the existing alignment without any modification and the flat road (i.e. with one unique gradient equal to zero). These two extreme alignments correspond to what is termed here as "*nominal*" levels. The adopted formulation of the problem is presented in Table 3.2. Other model components and related description are provided in paper III and corresponding appendices which are annexed to this thesis.

Table 3.2 Formulation of objectives, target functions and constraints

Target	Function to be minimized	Constraints
(#1) Minimum Fuel Consumption	$F(X) = \sum E[X]_{l,fuel\,(d,r)}(v) \cdot L_i$	$h_1(X):\ x_{I,1} \cdot L_1 - x_1 \cdot L_1 = 0$ $h_2(X): \sum X_I \cdot L_i - \sum X \cdot L_i = 0$ $h_3(X): -0.06 \leq X \leq 0.06$ $h_4(X)$[1]$: \sum E[X]_{l,fuel\,(d,r)}(v) \cdot L_i -$ $-(1-\beta) \times \sum E[X_I]_{l,fuel\,(d,r)}(v) \cdot L_i = 0$
(#2) Minimum Slope Variation	$\Delta S(X) = \sum_i (X_I - X)^2$	
(#3) Percentage-target Reductions[2]		

[1] *Valid only for target case #3*
[2] *Achievable reduction levels whose values are bounded by that of the lower and upper practical levels bound.*

X_I and X refer to segments' gradients in the initial and generated alignment respectively. The difference between the optimal values of ΔS(X) and F(X) resulting from target cases #2 and #3 determines the range of reduction that can be achieved for the intended alignment.

Overall, there are two objective functions, three equality constraints and two bounds in the formulated model. F(X) represents the vector of segments' gradients that guarantees the minimum quantity of fuel to be consumed by the selected test vehicle, at fixed speed and load, for a roundtrip travel on the alignment under study. ΔS(X) (or delta slope) aims at introducing the lowest difference possible between the initial and the optimized (i.e. generated) alignments. It helps control the impact of the optimization process on the overall estimated cost of the road project by keeping the generated alignments as close as possible to the alternative proposed by the designer, i.e. the existing vertical alignment.

The alignment does not exist

When the vertical alignment does not exist, two types of inputs must be available: a test vehicle (here an HDV) and the topology of the terrain whereby the intended road is planned to pass. The topology data comprises the elevations of the initial terrain, punctuated at constant distance, specified by the designer. The problem is solved towards the minimum cost. The developed model integrates several cost functions including the earthwork cost and the actualized fuel consumption cost, to decide on the shape of the returned alignment.

$$\begin{aligned}
&\sum_{i\in S} V_i^c \cdot C_{exc} + \sum_{i\in S} V_i^f \cdot C_{emb} + \sum_{i\in S}\sum_{\substack{j\in S\\ i\neq j}} C_{i,j}\cdot X_{i,j}\\
&\qquad + \sum_{i\in S}\sum_{d\in D} C_{i,d}\cdot X_{i,d}\\
&\qquad + \sum_{b\in B}\sum_{i\in S} C_{b,i}\cdot X_{b,i}\\
&\qquad + \sum_{t\in T}\left[\frac{\left(\sum_{i,j\in G}[\Phi^v(S_{i,j}) + \Phi^v(S_{j,i})]\cdot D_{i,j}\right)\cdot(\rho_{fuel})^{-1}\cdot \Pi_{fuel}\cdot\theta\cdot\tau}{(1+r)^t}\right]
\end{aligned} \tag{3.1}$$

$\mathbf{\Phi^v}$ is the piecewise linear function used to calculate the fuel factor at uniform speed ($\mathbf{v}$) for the segment gradient$(\mathbf{S_{i,j}})$; $\mathbf{D_{i,j}}$ is the corresponding length of the considered segment gradient; $\boldsymbol{\rho_{fuel}}$ is the density of the operating fuel (used to convert fuel quantity from mass to volume unit i.e. from $\mathbf{g}$ to litter); $\boldsymbol{\theta}$ is the considered cycle factor (to check for test vehicle performance); $\boldsymbol{\tau}$ is an adjusting factor (to account for the number of cycle within an operating year); and $\boldsymbol{r}$ is the actualization rate. Details and descriptions regarding other components in the above model and other parts of the proposed approach are provided in paper IV and associated appendices annexed to this thesis.

3.1.2.2 The multi-level multi-layered approach (MLMLA or ML2A)

The multi-level multi-layered approach is identical to the single level approach developed in (Gaylord K., 2019) with the difference that the model developed here allows to account for several test vehicles (here designated as levels) and several powertrains, load profiles and standard technologies (here termed as layers). Vehicles are considered to operate under constant speed. The developed concept is schematized in Figure 3.3. The optimization model is formulated to tackle the conundrum of "***optimal vertical alignment generation***".

The selection of the levels and layers to integrate in the model is made by the decision-maker. Such decision can be informed by several factors including the structure of vehicle fleet – both actual and future fleet size, fleet composition, etc. (for a reasonable time perspective) – and the equivalent traffic (where the dominant vehicles could be retained as potential candidates), the legislation in force in the zone under study, the type of policy retained within the climate toolsets and /or the adopted pathways for implementing deep decarbonization strategies in the studied zone or region or country.

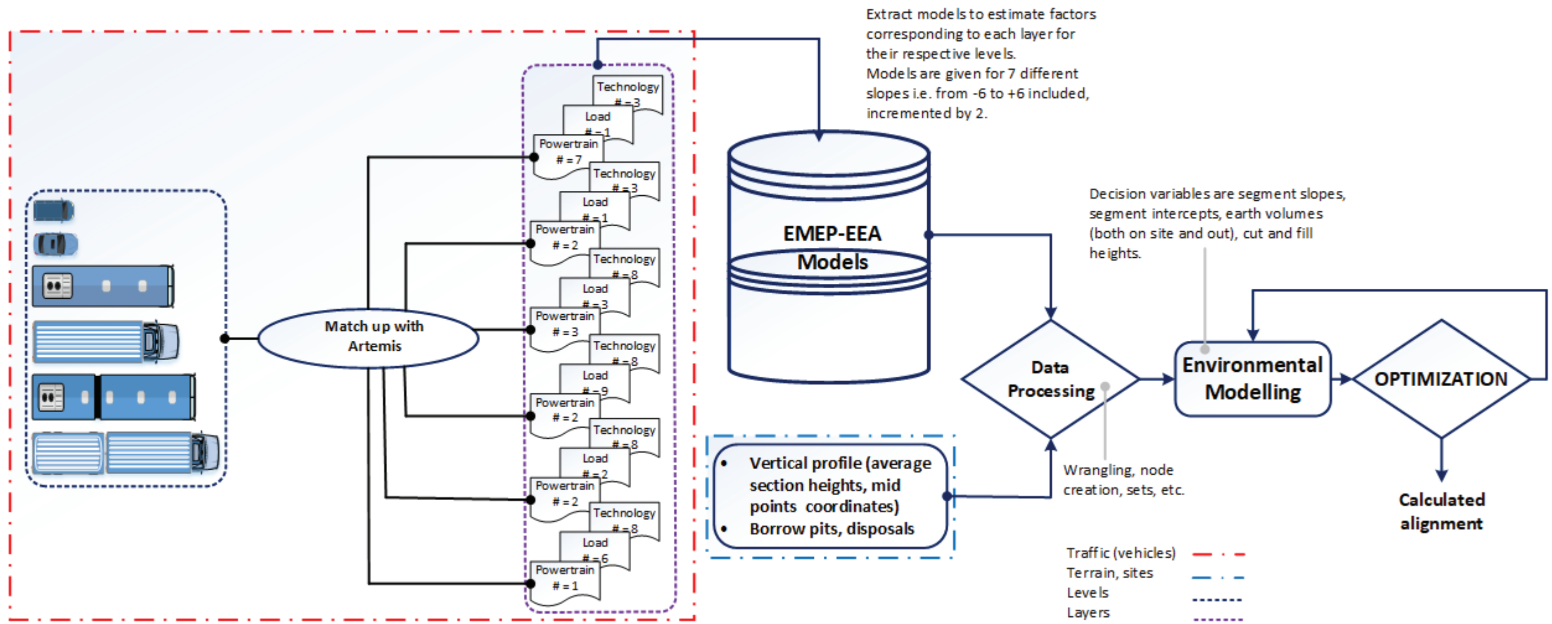

Figure 3.3 Workflow of the Multi-Level Multi-Layered Approach (ML2A)

The problem is a minimization one, solved for the lowest total cost. The cost functions embedded in the model includes the driver cost (DRV), the energy or consumed fuel cost (NRG), the fixed cost of vehicles (FIX), the maintenance cost (MRT), the toll cost (TOL), the climate change cost (CLC), the air pollution cost (AIP), the noise cost (NOI), the accident cost (ACC), and the earthwork cost (EAW). The equation 3.2 presents just the objective function of the problem as formulated in this thesis. Other components of the model are given in paper V in great details.

$$\boldsymbol{min\ C_{tot}} = (\boldsymbol{EAW} + \boldsymbol{AIP} + \boldsymbol{CLC} + \boldsymbol{NRG}) + \ (\boldsymbol{DRV} + \boldsymbol{FIX} + \boldsymbol{MRT} + \boldsymbol{TOL} + \boldsymbol{NOI} + \boldsymbol{ACC}) \tag{3.2}$$

The cost functions included in the model presented above are split in two groups: the relevant costs, encompassing the NRG, CLC, AIP and EAW and the other costs. The designation “relevant costs” refers to the fact that they are directly related to the vertical alignment i.e. to the decision variables. Other costs are not directly connected to the alignment profile but still constitute an important part of the model, as they can help in understanding the project in greater details, for better planning, design, and execution. Nonetheless, it is possible to relate some of those costs with the road alignment, although not an easy task. Vehicle wears, for example, can be due, in part, to the way geometrical elements are arranged along a given road – used more frequently – since the driving profile is partially dictated by the alignment. This field just needs more research to come up with clear models connecting such cost with road gradients.

3.1.3 Silhouette appraisal

The various alignments resulting from the different optimization models discussed in the previous section need to be evaluated to facilitate the decision-making process. Such assessment can be performed in different ways, based on data in hands and expected results. In this thesis, it was adopted to gauge the alignments indirectly i.e. through the analysis of the performances of the retained test vehicles and other vehicles intended to use them. The following metrics were developed in this thesis to appraise the vertical alignments based on the environmental and technical performance indicators:

3.1.3.1 The indicator’s overall value

The first evaluation metric considered in this work is the overall value of a given performance indicator $O_c(v)$ in mass unit (g), calculated in both direct and reverse traffic directions for a specified speed and load.

$$O_c(v) = \sum E[X]_{l,c(d,r)}(v) \cdot L_i \tag{3.3}$$

where:
X: Vector of the decision variables [x_1, x_2, x_3.........x_n] (the segment slopes).
l: Engine load.
c: Desired performance indicator (i.e. FC, NO_x, PM, VOCs, CO, or CO_2).
v: Operating speed.

3.1.3.2 The average emission rate (AER)

This metric represents the degree at which a given vertical alignment induces the release of pollutants from the exhaust of a given vehicle. It is calculated as follow:

First the value of a given performance indicator for each road segment is calculated, in unit of mass (g). Then The calculated values are summed up within their respective slope ranges to get a range subtotal.

$$ES_i(v) = E[X]_{l,c}(v) \cdot L_i \qquad i = 1, 2, 3, \dots, n \tag{3.4}$$

where:
ES_i: Estimated desired performance indicator for segment of slope i;
L_i: Corresponding segment length.

$$EE_n = \sum ES_i\,(v) \tag{3.5}$$

$$ER_n = {}^{EE_n}/_{D_n} \tag{3.6}$$

$$AER = \frac{1}{N}\sum_{n=1}^{N} ER_n \tag{3.7}$$

Those subtotals are further corrected by their corresponding range distances to give a rate (fuel consumption or emissions) in mass per unit distance (g/km) for each slope range. The rates are then averaged over the classes to give the Average Emission Rate (AER), also expressed in mass per unit distance (g/km). Appendix B in paper III gives more details regarding the notation and other parameters in the calculation of the AER.

3.1.3.3 The per-kilometer life cycle environmental impact performance (per-km LCEIP)

The per-km LCEIP is taken as the value of a given environmental impact indicator calculated for the entire life cycle of a given test vehicle when operating on a specific alignment. This metric captures mostly the use phase behavior which is the phase that makes the difference in the entire life cycle environmental impact of the considered system, as the alignment dictates the driving behavior, and thereby the induced impact profile.

The impacts are computed following an LCA approach, on a cradle-to-grave attributional perspective, according to the iso 14040, 2006 (Finkbeiner et al., 2006). In this thesis, the per-km LCEIP is calculated only for the three trucks that were designed for the purpose of this study. The LCA is conducted as follow:

Goal and scope (study-related)

LCA is conducted here with the aim of comparing, on an attributional prospect, the ecological performances of the three heavy duty vehicles designed for the purpose of this study, where each is considered to operate on the generated alignments. In this way, it is possible to also assess the performances of the optimized alignments, in terms of what they imply as environmental loads, from a complete life cycle perspective. The retained vehicles are separated into three types of powertrains shown in Figure 3.4**.** Powertrains' configurations are designated as follow:

- conventional truck (CT): a fossil-fueled internal combustion engine truck, powered with diesel,
- battery electric truck (BET): a full electric truck powered with electricity,
- fuel cell electric truck (FCET): a full fuel cell truck powered only with hydrogen.

The vehicles scrutinized in the present work are designed from scratch. This is done to guarantee that they all are comparable and exhibit same technical capabilities (gross vehicle weight, drivability, gradeability, achievable speeds, acceleration, power, etc.). The only difference among those vehicles remains their powertrain configurations which, for each vehicle, was adapted based on design specifications employing related technologies.

Functional unit (FU)

For this study, the functional unit is defined as driving 1 km on a given optimized alignment. The FU consider the entire life cycle of a truck assuming it operates at full load and constant speed of 80 km/h, covering 160934 kilometers each year for 12 operating years.

System boundaries

All the LCA models developed in this thesis include the entire value chain of a truck (i.e. from raw materials extraction to end-of-life). In the use phase, several fuels (or energy types) are considered. The vehicles' end-of-life is limited to material recycling and recovery, and related energy flows. In addition, the developed models encompass other components based on specificities in truck's technology. For example, for the FCET, the entire hydrogen value chain (i.e. production and distribution of the hydrogen fuel including the refueling station) is also included, while for the BET, recharging stations are not accounted in the analysis. The end-of-life, as modelled in the present work, does not incorporate management of the BET battery pack. Changing the system boundaries will impact the obtained results.

Life cycle inventory (LCI)

The life cycle inventory (LCI) of the entire value chain of each modelled vehicle, is compiled by treating and merging data acquired from various sources. The LCI compilation is done following a streamlined approach combining feature engineering and mass and energy balance. The reason for adopting this approach is principally to overcome the lack of access to the appropriate industry-related data from truck manufacturers, given the fact that no EPDs could provide the bill of the materials (BOM) of trucks or detailed information of the different parts of the trucks (e.g. related materials composition, their origin, structures, employed treatment processes, and so on). The LCI compilation is based on the BOM of a twelve tons conventional truck. Information related to the breakdown of weight for the constitutive vehicle systems and subsystems as well as the composition by material and weight of this vehicle can be found in (Skinner, 2015). The workflow adopted for conducting the LCA of the three trucks is summarized in Figure 3.5. Detailed information can be found in paper V. Apart from the trucks, LCAs of possible energy sources required for powering each

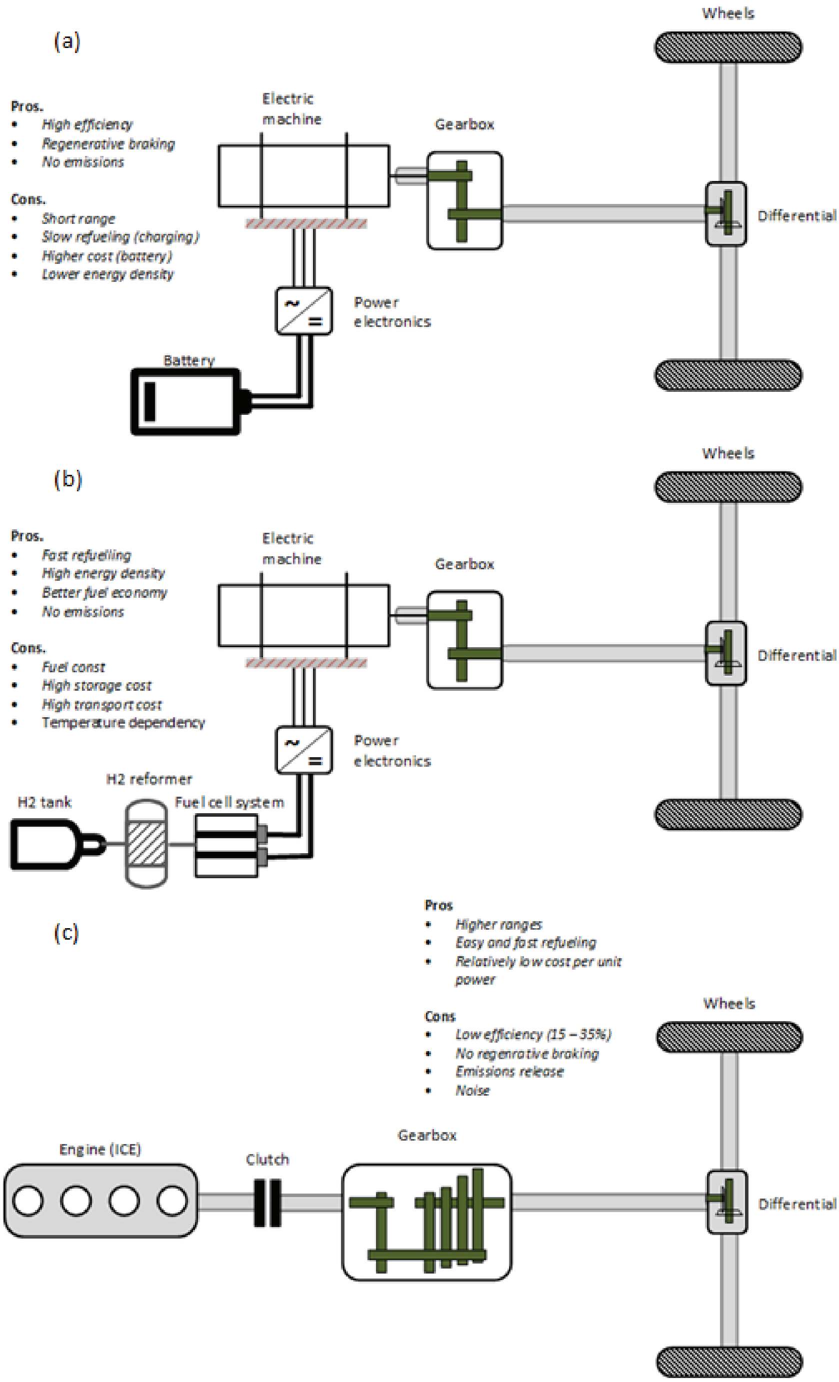

Figure 3.4 High-level configurations of the studied powertrains

powertrain are also conducted. They are labelled as fuel production – distribution. Three types of energy careers (or fuels) are considered in this thesis: diesel fuel, electricity, and pure hydrogen (H_2). For diesel, it is the marketed low-sulfur type that is considered here, while for both electricity and hydrogen several alternatives are considered. Seven electricity sources are considered including hard coal, hydroelectricity, European mix, Norwegian mix, natural gas, solar photovoltaic and wind. For hydrogen, two production pathways are considered i.e. water electrolysis and steam methane reforming (SMR), each supported by electricity from the same seven sources mentioned above. So, in total, about 22 fuel alternatives are analyzed in this study (i.e. one with diesel, seven with electricity and fourteen with hydrogen).

After merging all LCA results, a complete LCA model comprised the following life cycle stages: material processing, vehicle assembly and production, battery pack (BEV), fuel production and distribution, fuel tank (FCEV), fuel use (or electricity use), maintenance, fuel cell stack, and end-of-life (EOL). The battery pack (BEV) is modelled as in Ellingsen et al. (2014); the fuel tank, the fuel cell stack and the production-distribution of hydrogen fuel are modelled following the work of Cox and Mutel (2018). The shipping distances from manufacturing and or assembling stations are considered analogously, to account for related environmental loads. All data used for the LCI compilation phase are checked to verify their representativity, consistency, completeness, recentness. Priority is given in data fitting into the Norwegian context, with a high representativity (in average) of the local industrial and technological construct.

Life cycle impact assessment (LCIA)

According to the Joint Research Center – Institute for Environment and Sustainability, the four impacts categories that are thought to be of most concern for the automotive industry – especially for the truck manufacturing sector – include the global warming potential (GWP), abiotic resource depletion potential (ADP), acidification potential (AP), and human toxicity potential (HTP) (Handbook, 2010). In this thesis the assessment is extended to include a few more impact categories in the above list, adding the eutrophication potential (ET), photochemical oxidation potential (POP), and ozone layer depletion potential (ODP). By screening the above indicators it is believed that the decision-making process can be informed in much more sound way (Bicer & Dincer, 2018; de Souza et al., 2018). The impact assessment method retained in this analysis is the CML 2001 characterization method, following a midpoint approach.

3.1.3.4 The efficacy performance

This metric tells how far a specific vehicle can go when operating on a given alignment, with fixed energy autonomy. The calculation of this metric does not involve any LCA. Hence, it can be used to compare several vehicle segments if appropriate data are available. For the analysis presented in this thesis, an equivalent of 100 kWh autonomy was used.

3.1.3.5 Clean technologies' operational phase GWP behavior

This is a metric to analyze the effects of penetration of clean technologies (i.e. BET and FCET) on GWP of the considered system, during vehicles' operation. It expresses the gain – positive or negative – of clean technologies over the fossil technology (CT), when operating on a given (optimized) alignment. This gain is expressed in percentage and concerns the operation phase (i.e. fuel production – distribution, and fuel use). The gain is derived as follow:

$$GWP_{gain,i} = \left(\frac{GWP_{fossil,i} - GWP_{clean,i}}{GWP_{fossil,i}}\right) \times 100 \tag{3.8}$$

Where i designates the concerned subphase (i.e. either fuel production – distribution or fuel use).

With this metric it is possible to capture the induced phase-related GWP trend per unit distance, when replacing a fossil vehicle by an equivalent (in technology and size) clean technology, operating under same conditions (same road alignment, same speed and same load profiles). The overall gain is obtained by summing up the gains from the two subphases. $GWP_{clean,use}$ is set to be equal to zero, as no greenhouse gases are expected from clean technologies during use phase.

3.2 Materials

To efficiently tackle the questions investigated in this thesis, a few materials were used to support the developed methods. These materials include data sources, databases, software and other tools. Concise details of those materials are provided in the subsections that follow.

3.2.1 Vehicles

The vehicles used in this thesis can be grouped in two classes: fossil vehicles and clean vehicles. However, all used vehicles belong to the categories of Heavy-Duty Vehicles. For the fossil vehicles, all operational data are from the spreadsheet model developed by the European Monitoring and Evaluation Programme – European Environment Agency (EMEP-EEA) which is widely employed for accurate computation of road transport emissions in Europe (L Ntziachristos & Samaras, 2014; Leonidas Ntziachristos et al., 2009; L Ntziachristos et al., 2010; Rexeis, Hausberger, Kühlwein, & Luz, 2013). It is the EMEP-EEA Tier-3 datasheet that was considered for the purpose of this research work. The clean vehicles are designed from scratch based on the specifications provided in the previous chapter.

The fossil vehicles considered in this thesis comprise seven different segments from four technology standards, adding up to a total of 28 heavy-duty vehicles. The segments include the followings:

- Articulated truck of 14 tons
- Articulated truck of 28 tons
- Articulated truck of 40 tons
- Articulated truck of 50 tons
- Rigid truck of 12 tons
- Rigid truck of 28 tons
- Urban biodiesel bus

For each of the above vehicles four technology standards were considered i.e. Euro IV, Euro V-SCR, Euro V-EGR and Euro VI. The above four technology standards are retained to comply with the Norwegian HDV fleets' age which is largely dominated by Euro V technologies and with a consistent share of Euro VI technologies.

3.2.2 LCA databases

The databases used for conducting the environmental life cycle analysis in this thesis are the commercial database *Ecoinvent versions 2.2 and 3.4, and the freely available ELCD database developed by the European Platform on Life Cycle Assessment.*

3.2.3 Software and other tools

This thesis made use of **ArcMap (ArcGIS)** product for handling of geographical data and related analytics, **R** and **R-Studio** for data analytics and visualization, **MATLAB** for optimization modelling, solving and visualization, **Simulink** for modelling and design of the trucks (with the **QSS Library**), **Pyomo** for optimization modelling and solving, and the python ecosystem for data analytics, modelling and visualization.

For optimization tasks conducted in the MATLAB environment, the *FMINCOM* optimization routine was employed with the sequential quadratic programming (*SQP*) algorithm for simulation of optimized alignments. The maximum function evaluation was set to its highest value (i.e. INF). For each run, a maximum of 5000 iterations was required. Optimization tasks conducted in Pyomo used the *Gurobi* optimizer (version 7.5.2), which is a state-of-the-art mathematical programming solver accessible at no charge for academic use.

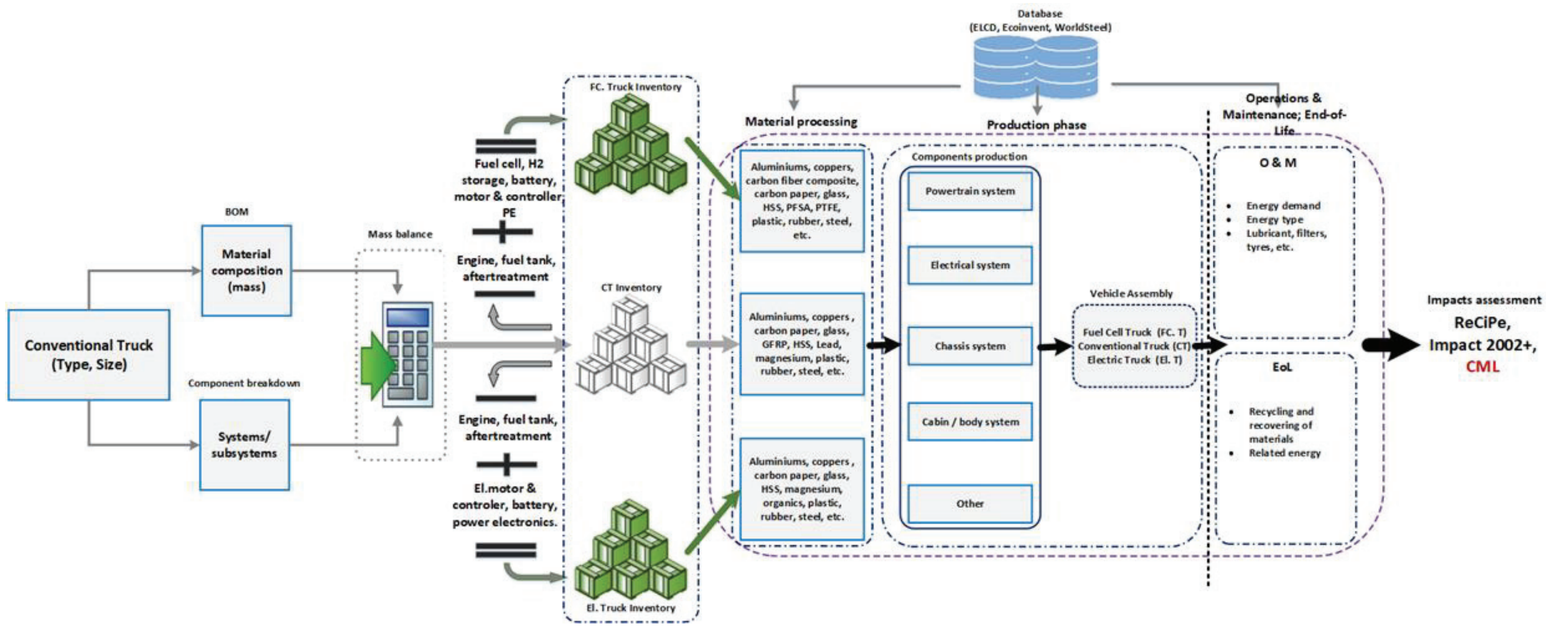

Figure 3.5 Workflow of the streamlined LCA model of the designed trucks.

Chapter 4

Case Studies

To gain tangible, appropriate, far-reaching knowledge about the performance of vertical alignments of linear infrastructures, the methods developed in the present thesis were exemplified through cases studies. The instances retained in this thesis used two different datasets both representing real world situations (either an existing road alignment or an existing road route terrain). This chapter provides few information related to the study cases used in this research work.

4.1 Studied cases

A total of four different study cases were conducted in this thesis. A brief overview of each of them is given below:

4.1.1 Modelling the effects of highway vertical alignment for an eco-driving HDV

This case study is conducted to proof the concept of the verified influence of the vertical alignment on the vehicles' energy demand. The difference is that this time the vehicle is a heavy-duty vehicle which adopted to operate under an eco-friendly regime. All data are from a real-world situation. The test platform is a highway section in the southern Norway i.e. the Norwegian ferry-free costal highway E39. The analysis performed followed a quantitative approach, combining statistical modelling and data analytics techniques to formally answer the deriving questions.

4.1.2 Optimizing vertical alignment to reduce fuel consumption and emissions

In this studied case, the main goal was to develop and test an optimization model capable of modifying the shape of an existing vertical alignment to return a better environmental profile during use phase. The approach retained here is purely quantitative, combining environmental modelling and several non-linear optimization (NLP) techniques, as well as metrics development for environmental performance assessment. The test platform is the same as in the previous case study, i.e. the same section of the existing E39 road. Only one test vehicle was considered.

4.1.3 Balancing between earthwork cost, fuel cost and emissions in the design phase of an alignment

This study case starts from an initial terrain profile, where a road project is expected to take place, to generate several optimized vertical alignment silhouettes that poises between earthwork, tank-to-well emissions, and vehicle energy demand. The adopted approach is again a purely quantitative one, involving environmental modelling and spline linear programming (SLP) techniques as well as indicator-based reasoning to evaluate the performance of generated optimized alignments. The test platform is a 1 km-long route terrain from Valentin R Koch and Yves Lucet (2010). One test vehicle was considered here.

4.1.4 Optimizing vertical alignment to reduce fuel consumption and emissions

The last study case builds on the previous one and uses the same test platform as well. The main purpose is to spawn optimized vertical alignment silhouettes that minimize the life cycle environmental profile of a defined vehicle-alignment system. The proposed logic is purely quantitative and encompasses an integrated modelling approach, spline linear optimization (SLP) techniques and life cycle assessment (LCA) method as well as metrics development for appraising the resulting vertical shapes. The formulation implied the use of several vehicles and different pollutants.

4.2 Case data

The Case-related data used in this thesis are essentially of two types: an existing alignment and terrain profile. The existing alignment is a chunk of the existing Norwegian E39 highway whereas the terrain profile is a 1 km-long road route collected from the literature. Both are real-world locations.

4.2.1 The Norwegian ferry-free costal highway E39

The Norwegian Ferry-free Coastal Route E39 is a 1100 km European corridor, extending from Kristiansand (southern) to Trondheim (upper mid), on the western coast of the country (Figure 4.1). It

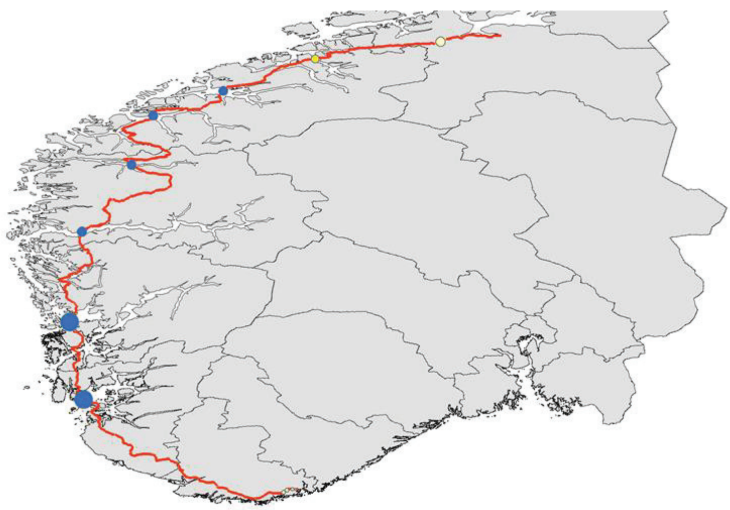

Figure 4.1 Layout of the Norwegian costal highway E39.

is a large highway construction project currently being administrated by the Norwegian National Public Road Administration (NPRA) and the Norwegian Ministry of Transport and Communications. The main objective of this highway project is to reduce the travel time by up to 10 hours through elimination of the many ferries currently interfacing with the existing route and expanding the capacity of the route by widening the roadway.

In the present work, a relatively short portion of the E39 route was considered as a case for testing the constructed models. The selected area is a 58 km section of homogeneous two-way and two-lane road with no physical median. It is comprised between ***Søgne*** and ***Lyngdal*** in the southern part of Norway (Figure 4.2). Geometric elements' information for this selected section of the road were extracted automatically from the online geoportal ***vegkart*** developed by the Norwegian Road Authority. The vertical profile of the selected road section encloses georeferenced data of road

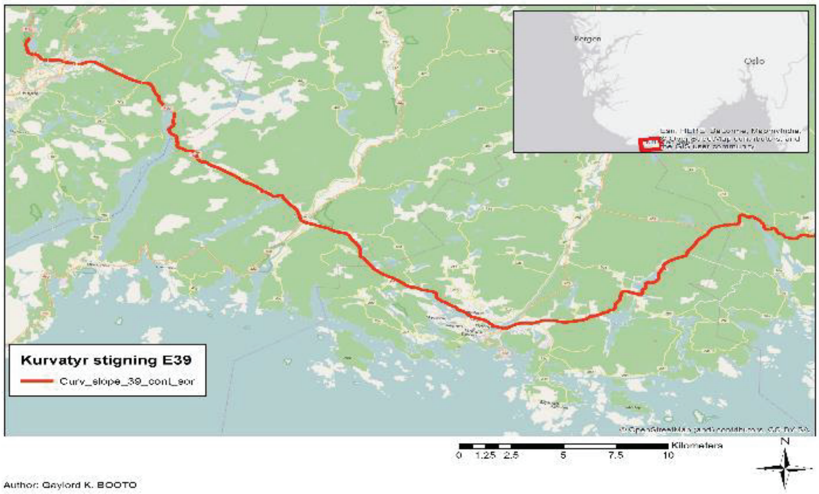

Figure 4.2 Layout of the retained portion of the Norwegian costal highway E39.

gradients arranged in segment per each gradient value. Gradients are provided in percent and segment lengths are given in meters. Some statistics related to this section can be found in table 4.1. In figure 4.3, the profile of the vertical alignment of this selected section is portrayed.

Table 4.1 Descriptive statistics of road data layers

	VG	L_S	R	L_C	L_T
	%	m	m	m	m
Avg.	0.16	151.30	606.50	77.65	147.00
Max.	10.50	1195.00	9626.00	351.00	1069.00
Median	0.30	66.00	303.00	62.00	111.00
Min.	-11.00	3.00	51.00	8.00	41.00
SD.	2.95	184.27	1035.98	59.38	134.33

VG is vertical gradient, L_S is slope length, R is curve radius, L_C is curve length, and L_T is tangent length.

4.2.2 The 1 km-long road route terrain

This terrain profile was taken from Valentin R Koch and Yves Lucet (2010) who argued that it is from a real location and was obtained from industrial partners. The terrain profile is illustrated in Figure 4.4, where elevation is shown with the initial point set to zero meters (0 m).

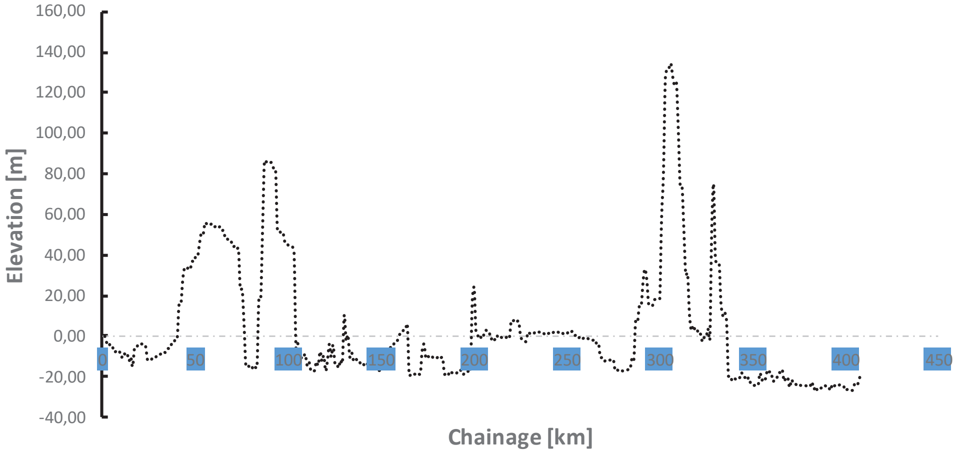

Figure 4.3 Profile of the vertical alignment of the retained portion of the Norwegian costal highway E39.

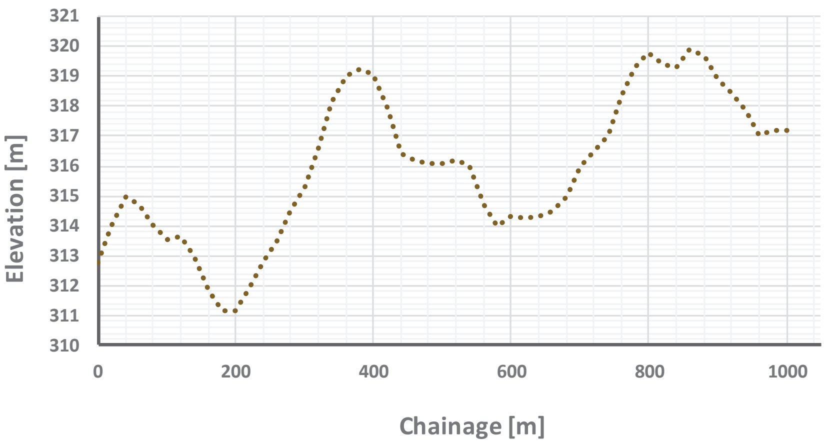

Figure 4.4 Vertical profile of the retained terrain (road route).

Chapter 5

Main Results

This chapter presents the key findings from the combined research activities conducted throughout this thesis. Results are only portrayed and explained but not discussed. More results can be found in the appended papers where they are also largely discussed. The outcomes shown in this chapter are slightly discussed further, in the next chapter. The reason for focusing on the main findings in this part of the compendium is that, it appeared to be an essential step both for clarifying the accomplished work, considering the formulated objectives, and to avoid repeating the discoveries contained in the appended research papers. So, here, only insights pointing directly to the formulated research questions are highlighted, in a systematical way.

5.1 Factors influencing a road project

The research work conducted in G. K. Booto, O'Born, et al. (2019) revealed that a road project is subjected to several factors which also dictate its overall shape. Those factors are of different types and can be grouped in five main categories including preliminary actions, construction, operations and maintenance, user, and environmental and socio-economic groups. For each group, employing a semi-qualitative-quantitative approach, G. K. Booto, O'Born, et al. (2019) studied their influence on a given road project and provided their weights (mostly from a financial perspective) and their direct effects on the alignment shape (from purely engineering standpoint). Their findings are summarized below:

5.1.1 Key factors

Considering the Norwegian practices for linear infrastructure projects, the factors of most interests are found in the group user, which also weigh heavier economically. As it can be seen in Table 5.1, the category "User" weighs up between 65 – 75% of the total investment, if converted to financial means.

Table 5.1 Breakdown of weight for the most influential factors under the Norwegian context

Category	Included items	Dimension			Metrics/Analysis	Weight
		Eco.	Soc.	Env.		
Construction	Earthwork and subgrade formation, pavement, and structures			X	NO_x, CO_2 and Energy use / Life Cycle approach (LCa)	**< 10%**
Maintenance	Reparation, reinforcement	X		X	Price, NO_x, CO_2 and Energy use / CBA, LFA	**< 10%**
User	Traffic fuel, accidents, Duration, road tolls		X	X	Non-priced, NO_x, CO_2 and Energy use / CBA, LCa	**65 – 75%**
Environmental and socio-economic	Local landscape, green space, natural areas, resources, cultural heritage, noise		X	X	Non-priced / CBA	**15 – 25%**

This higher weight is mostly due to energy cost – often the biggest component of the total cost of ownership of the vehicle and dictated by the alignment profile and the adopted driving style. Accident cost, principal reason for vehicle insurance, also make a significant contribution to that category. Environmental and socio-economic factors come in second position, in terms of their contribution to the overall weight, ranging between 15 – 25%. The reason is that, once priced, land acquisition, environmental protection actions and enforcing social acceptability will induce significant financial charges when materializing linear infrastructure projects. The factors grouped in the remaining categories come right after the environmental and socio-economic factors, each representing 10% of the total weight.

5.1.2 Effects on the alignment

Each of the factors within the categories mentioned in the previous section, influences the infrastructure design or realization in a specific way One practical element of the project to refer on is the vertical alignment, whose shape is directly impacted but the decision made on the key factors (dimensions, position, location, design, etc.), see Table 5.2.

Table 5.2 Effects of related cost items on optimized alignment

Item	Action(s) on the alignment
Preliminary survey, consulting, supervision, contractor selection, etc.	Fixed (constant) non-technical effect
Earthwork and subgrade formation, site preparation	Reduces deviation from initial terrain topography; favours introduction of structures (bridges, tunnels)
Pavement, super and substructures	Reduces alignment's length
right-of-way	Induces more circuitous alignment; favours introduction of intersections, overpassing, ...
Structures,	Induces circuitous alignment; reduces alignment's length
Miscellaneous, etc.	-
Reparation, reinforcement, and rehabilitation	Reduces alignment's length ;
Direct and indirect consumables (including fuels, tires, spare parts, etc.), vehicle depreciation	Reduces alignment's length; reduces curves and irregularities (i.e. induces more direct and flat alignment)
Vehicle hours (daily exploitation time duration)	Straightening and flattening
Accident rate, accident occurrence and their related weights	Straightening and flattening
Environmentally sensitive areas and cultural heritage	More circuitous alignment (or high socio-environmental cost if violated)
Land use change	More circuitous alignment (or high socio-environmental cost if violated)
Air pollution and noise	Various actions depending on pollutant types, power trains and project phases.

When forcing an alignment towards the desired extremums, construction factors such as minimizing earthwork costs and related site preparation activities, will tend to favor actions like keeping the design as close as possible to the initial terrain or introducing some (hyper)structures (bridges, tunnels) to keep the overall cost lower, while providing a service of acceptable, yet consistent quality. Higher right-of-way cost will force a more circuitous (winding) alignment, favor the implementation of intersections and overpassing where the best option would be a straighter path.

Lower fuel consumption will induce fewer rolling alignments, more direct paths, and less constraining surfaces to allow making fuel economy and consequently decrease the rate of environmental stressors' release. Same effects may be observed when designing an alignment for minimized accident events and land use, which may compromise some of the retained design parameters and the overall project cost. A more circuitous and highly rolling alignment will be hard to drive on, increasing both the occurrence of accident as a result of the driver being tired, and surplus energy demand to develop more force to overcome the rolling resistance and other forces opposed to the vehicle motion. Preservation the cultural heritages, avoid disturbing sensitive natural areas, repairing and maintaining or operation the infrastructure, keeping direct and indirect costs lower, will all constrain the formed alignment to unfold in a well different shape than the one retained initially, in the preliminary design, as presented in Table 5.2. The most weighting factors i.e. the ones belonging to the “User” category will act mainly on the vertical alignment, forcing it the be kept flat and straight (G. K. Booto, O'Born, et al., 2019).

5.2 Influence of the vertical alignment on energy demand of an eco-driven HDV

In G. Booto et al. (2017), the influence of the vertical alignment on the energy demand of an heavy-duty vehicle, operated under environmentally-friendly mode was clearly evidenced. G. Booto et al. (2017) demonstrated, using a quantitative approach, that although an eco-driving mode returns sound environmental benefits during the use phase of road vehicles, the vehicle energy demand (i.e. vehicle fuel consumption) is still affected by the arrangement of the road on the vertical plan (i.e. road gradients). Several regression models were developed to visualize the captured effects of vertical alignment on the fuel consumption of an HDV under eco-driving mode (see Figures 5.1 – 5.3). The regressions considered the road gradient (in percentage) as the explanatory variable and the engine fuel rate (i.e. the energy demand or fuel consumption of the vehicle, in liter per hour) as the explained variable. For all developed models, the explanatory variable was significant at 5% significant level (95% confidence level), i.e. P-value <0.05. The developed models described quite well, the relationship between the two variables with coefficients of determination (i.e. adjusted R-squared) ranging from 0.55 to 0.71.

When no distinction was made between the driving modes (i.e., acceleration, deceleration and constant speed), the alignment effect on the observed engine fuel rate was well captured using a second order model (Figure 5.2), explaining up to 71% of variabilities, in average engine fuel rate. The linear model captured about 63% of variabilities in both modes (Figure 5.1). Splitting the analysis on each driving mode (Figure 5.3), it appeared clearly that more energy was demanded in higher positive slope (acceleration mode) and less energy was required in lower negative gradients (deceleration mode). A residual analysis was done for the first two models to complement the performed regression analysis (see paper II in the appendix).

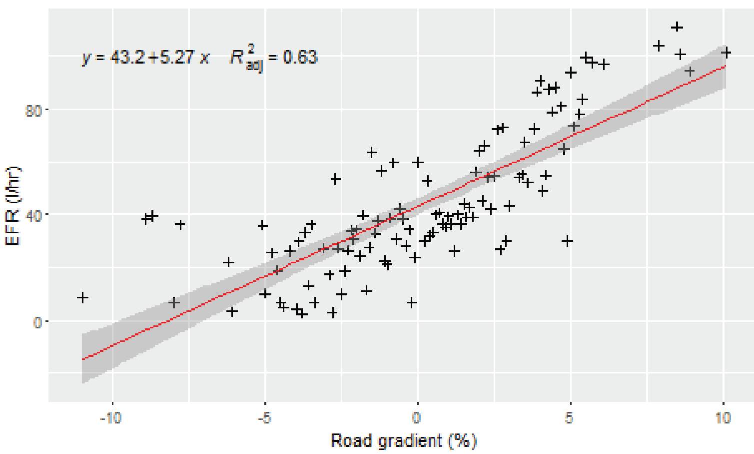

Figure 5.1 eco-driven HDV Engine fuel rate (EFR) vs road gradient. This is a first order (linear) model

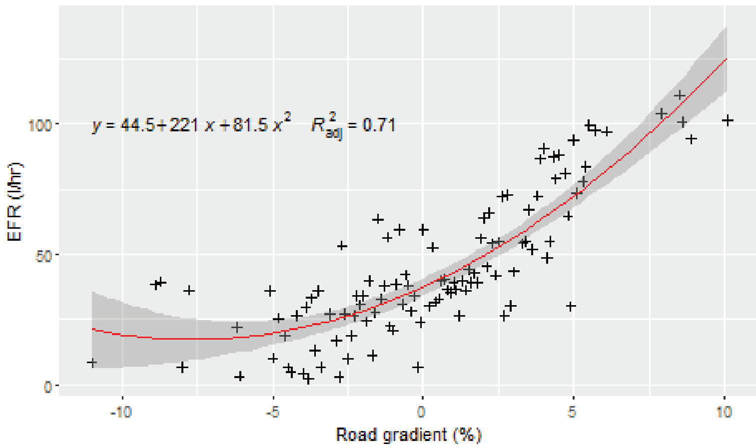

Figure 5.2 eco-driven HDV Engine fuel rate (EFR) vs road gradient. This is a second order (polynomial) model

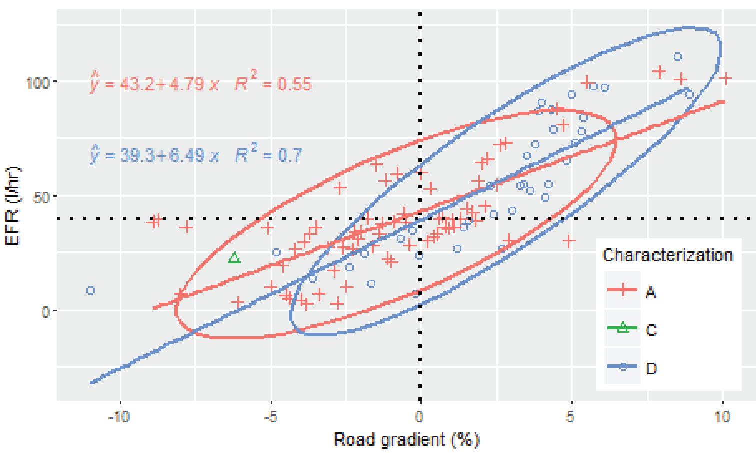

Figure 5.3 eco-driven HDV, multi-mode Engine fuel rate (EFR) vs road gradient. First order (linear) models. Blue: acceleration, Green: constant speed, Red: deceleration.

For models developed based on the driving mode, behavior of the engine fuel rate on acceleration mode was explained by 70 % variabilities against 55% in the deceleration mode.

5.3 Methodological approaches for environmental modelling and optimization of vertical alignment

Modelling and optimizing a vertical alignment can be achieved in several ways. In this thesis, the adopted modelling approach privileged simplicity against complexity, while consistency and the quality of the outcomes from the model had to be guaranteed. Hence, the retained approach consisted in combining both the earthwork (in the construction stage) and the emission release during vehicle pavement interactions (VPI, in the use phase). Both these components needed to be related to the road geometrical elements in the vertical plan. In that way it was possible to then apply optimization techniques towards minimization of the earthwork cost and/or environmental costs. The employed approach is described in greater detail in the related sections in the methods' chapter, and is further discussed in the next chapter, with emphasis on its weaknesses and strengths. More information can be found in G. K. Booto, Marinelli, Brattebø, and Bohne (2019), Kabongo Booto, Run Vignisdottir, Marinelli, Brattebø, and Bohne (2020), and Kabongo Booto, Marinelli, Brattebø, and Bohne (2020), all appended to this thesis.

By implementing the adopted approach, it was possible to optimize the vertical alignment of a highway towards minimum fuel consumption (Figure 5.4), minimum emissions (Figures 5.5 and 5.9) or minimum earthwork cost (Figure 5.8). Further, it allowed to perceive the pertinence and the

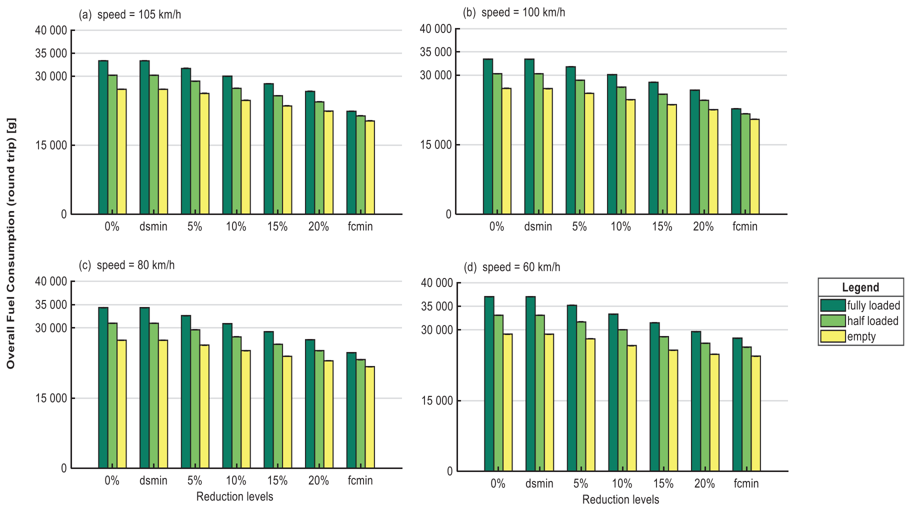

Figure 5.4 Fuel consumption performance of generated alignments with respect to operating speed and engine loads

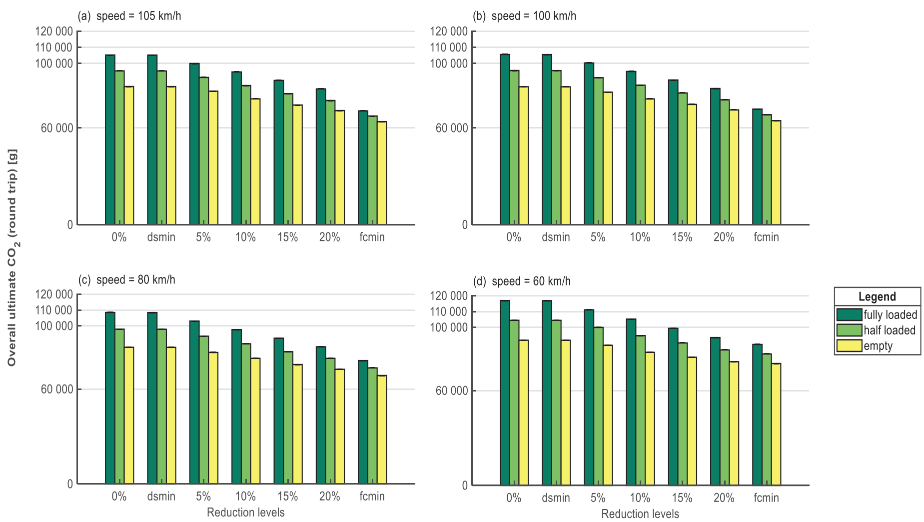

Figure 5.5 CO_2 performance of generated alignments with respect to operating speed and engine loads

physical meaning of the parameters embedded in the models.

As shown in the Figures 5.4 and 5.5, the reduction levels that were introduced in the single level approach (SLA), using the goal programming technique, proved to be of great significance for optimizing the vertical alignment of a highway. This parameter acts as a control factor and can be used to generate several design alternatives, based on the desired achievable limits – in fuel consumption or emissions – set as a target. The higher the reduction level the more the achievable cutback in both energy demand (i.e. fuel consumption) and CO_2 emissions. The load scheme of the truck also played a significant role, as higher load correlated with higher overall emissions or fuel consumption. Another important factor is the operating speed, which correlated negatively with the emissions and fuel consumption i.e. faster motions demanded less energy and induced less emissions, while the exact reverse profile was observed at lower speeds.

The reduction targets and operating speeds rendered a particularly difficult pattern when analyzing the overall slope difference that was achieved between the initial alignment and the generated alignment for each target (Figure 5.6). The returned pattern was difficult to interpret, especially when higher ΔS(X) values were observed for intermediate reduction targets (10%, 15%), and lower values for higher targets (20%, 25% and fcmin). Also, lower speeds tended to return lower ΔS(X) values for the same target, while in some cases, the solver failed to converge to an optimum. No further actions were taken, in this research, to try to uncover the rendered patterns and understand the reason for observing such behavior. However, it is believed that this could be due to the employed optimization techniques, as it was observed that the goal programming (GP) generated different tessellations as compared to the genetic algorithm (GA).

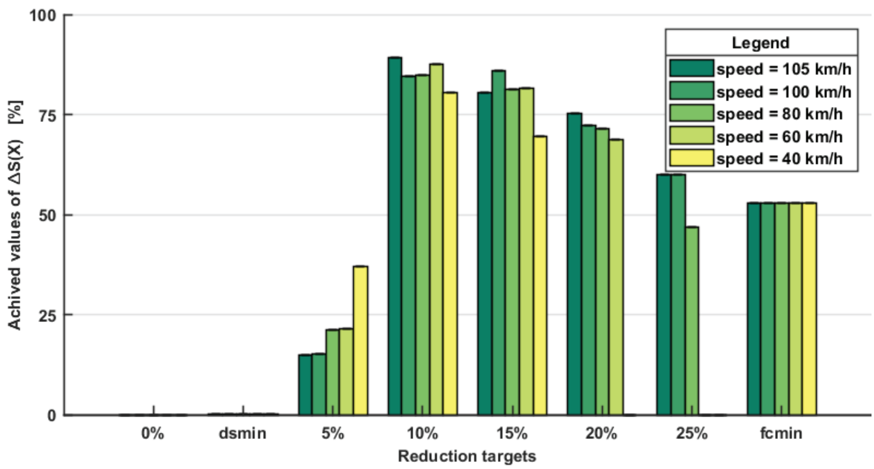

Figure 5.6 Achieved overall slope difference ΔS(X) [%] with **respect to reduction targets**

A hypothetical driving (i.e. simulation) on the optimized alignments proved to enable significant savings in both fuel (up to 4000 liters) and emissions (up to 750 kg) per cycle (Figure 5.7). For the vertical alignment, the best optimization scenario was found to be the one targeting both the earthwork cost and the energy cost. As it can be seen in Figure 5.8, when the goal is set to minimize the earthwork cost only, the cost of fuel for operating the vehicle was remarkably higher, and vice versa, the earthwork cost was higher if only the fuel consumption was retained as the goal. These two costs were kept at acceptable level – and relatively low – when both were set as the goal in the model.

Same kind of effects were observed for air quality. The driving on the alignment generated with the best optimization scenario (i.e. the alignment resulting from optimizing both the earthwork cost and the fuel consumption) induced significant reduction in particulate matters, and the difference with the best performing alignment (i.e. the alignment obtained minimizing the total fuel consumption) was insignificant – to less than 0.5% (Figure 5.9).

Other variants of the developed model, using the same retained approach, embedded components linked to specific pollutants. Employing those variants substantiated the possibility to shape the vertical alignment such that its guarantees lower release of a specific pollutants i.e. in a goal-oriented fashion. Figure 5.10 portrays the optimized alignments arranged in four groups. Returned alignments' shapes provide information on the effect of the various items embedded in the model and which were targeted in the optimization process. Alignments with least undulations are obtained by optimizing the initial terrain profile for minimum cost of pollutants (a). Higher waves are observed in minimum earthwork costs' alignments (d), while fewer ripples are encountered in the alignments obtained by minimizing the sum of earthwork and pollutants costs (b), and (c).

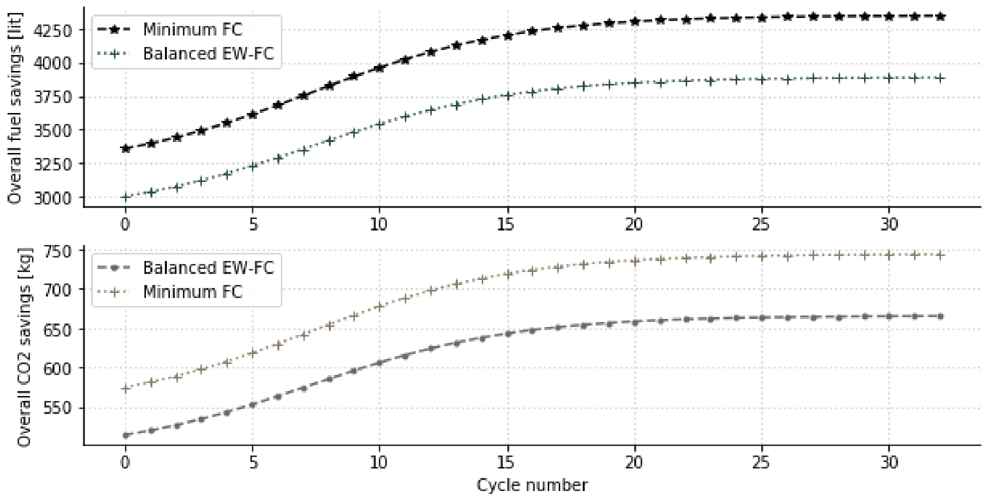

Figure 5.7 Achieved savings in fuel and GHG (CO2-eq) after each cycle on the alignment of minimum fuel consumption.

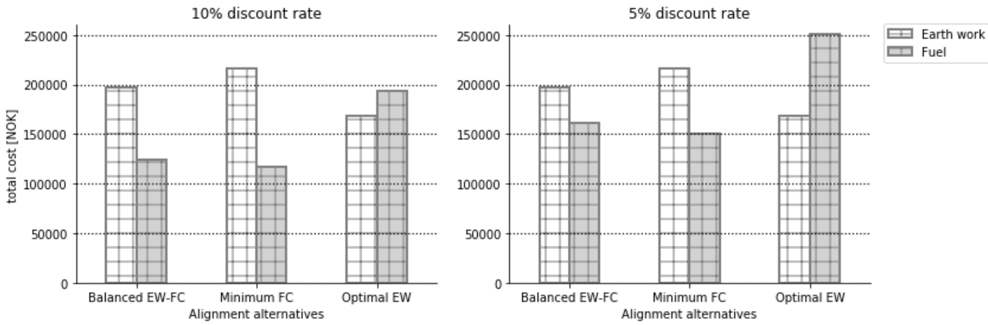

Figure 5.8 Earthwork cost and Fuel cost for selected optimized alignments for two discount scenarios.

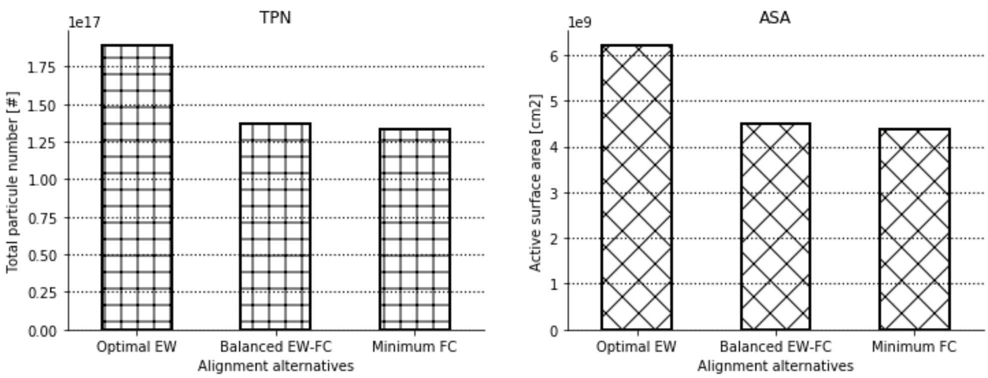

Figure 5.9 Total number of particles (TPN) emitted during operation on optimized alignments and corresponding active surface area (ASA)

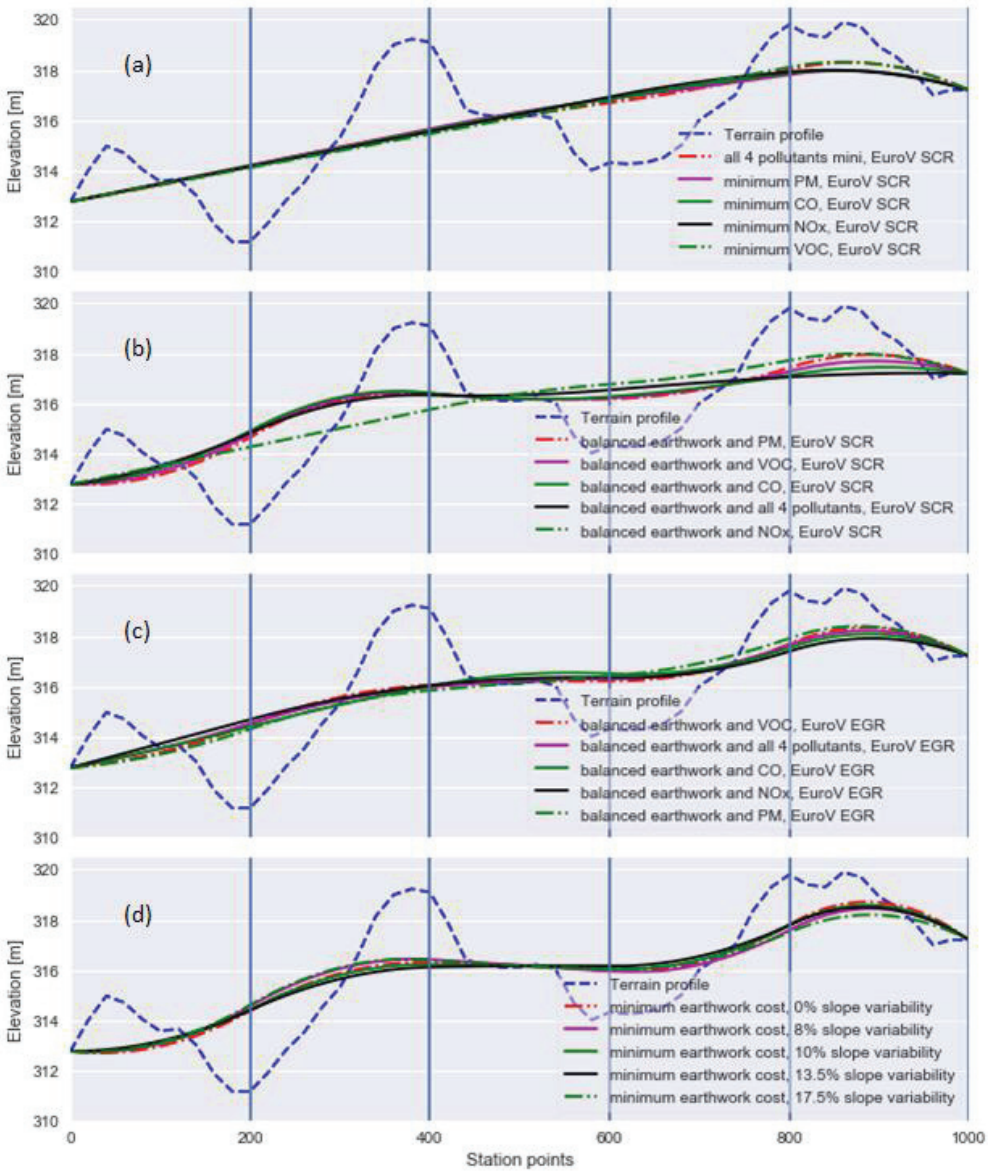

Figure 5.10 Trend of optimized alignments for a few retained scenarios. (a): minimum pollutant costs; (b): combined earthwork and pollutant costs using 12-tons diesel Euro V, SCR truck; (c): combined earthwork and pollutant costs using 12-tons diesel Euro V, EGR truck; (d): minimum earthwork cost

5.4 Technology-related impact profiles on optimized alignments

Kabongo Booto, Marinelli, et al. (2020) analyzed the environmental profiles of three different heavy-duty vehicles' powertrains (i.e. a battery electric truck (BET), a conventional truck (CT) and a fuel hydrogen fuel cell electric truck (FCET)) throughout their entire life cycles. The performed analysis considered either all the optimized alignments or the alignment returning the lowest fuel consumption possible, i.e. the best-case alignment. The results revealed the followings:

5.4.1 LCA of three trucks technologies

LCA results are based on 1 km driving on the best performing alignment (i.e. best-case of all generated optimized alignments – in terms of fuel consumption). he results are given for each life cycle stage considered in the model. Only few impact categories are reported in this section.

Figure 5.10 shows that, for 1 km driving on the best-case alignment, the best environmental scores for the GWP is performed by the battery electric truck (0.107 kg CO_2 – eq./km), followed by the fuel cell electric truck (0.425 kg CO_2 – eq./km). The conventional truck exhibits the highest GWP score (0.959 kg CO_2 – eq./km) – the worst performance of all three vehicles – and is largely due to the contributions of the fuel production-distribution phase (23.39%) and the fuel use phase (64.78%). The relatively higher score observed in the FCET comes from the contribution of fuel production-distribution (73.99%) and the assembly – production phase (13.29%). Dominant life cycle stages for the BET are the assembly-production (50.81%) and the battery pack production (19.56%). In Figure 5.11, the conventional truck remains the one exhibiting the worst grade when it comes to abiotic depletion potential, with about 0.0106 kg Sb – eq./km. About 92% of impacts, for the CT, are observed to occur during fuel production-distribution stage. Both the fuel cell electric and the battery electric trucks unveil relatively lower scores (0.0022 kg Sb – eq./km and 0.0008 kg Sb – eq./km, respectively). H_2 production-distribution accounts for about 60% of the total impact, while for the BET, the most impactful phase is the vehicle assembly-production, with up to 64% of the share.

When it comes to photochemical oxidation potential (aka summer smog), the finest performance is registered for the battery electric truck (3.37E-05 kg C_2H_4 – eq./km), followed by the conventional truck (1.69E-03 kg C_2H_4 – eq./km) (see Figure 5.12). The fuel cell electric truck displays poor performance (2.68E-03 kg C_2H_4 – eq./km), most of which occurring during fuel production-distribution stage (85%) (Figure 5.12). Largest amounts of ODP are generated during fuel use stage (for the CT, ~ 96%), fuel production-distribution stage (for the FCET, ~ 90%) and material processing (for the BET, ~ 80%) (Figure 5.13). The battery electric truck displayed the best environmental profile, for ODP as well, for 1 km driving.

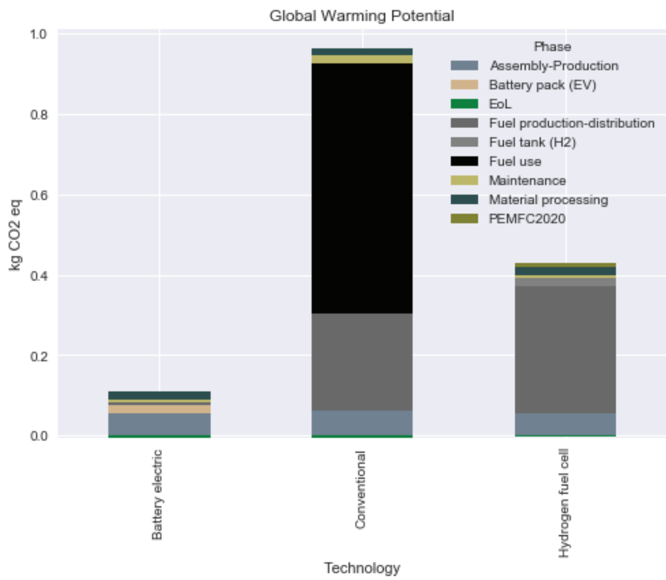

Figure 5.10 Global warming potential of the three trucks on best-case alignment

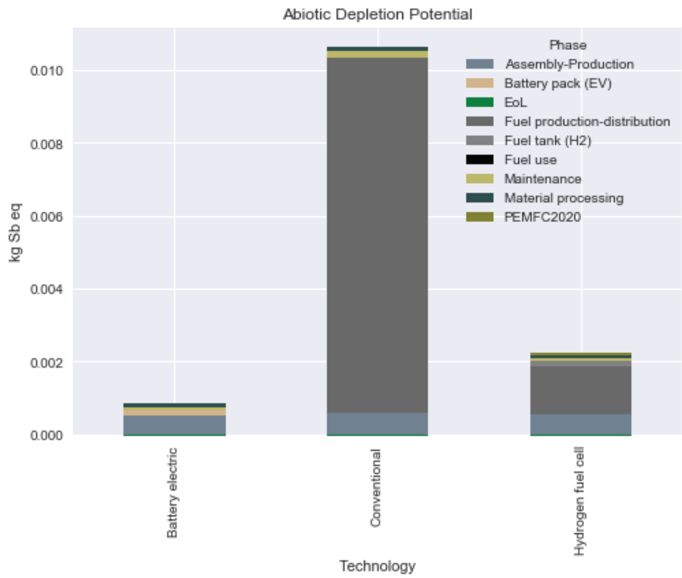

Figure 5.11 Abiotic depletion potential of the three trucks on best-case alignment

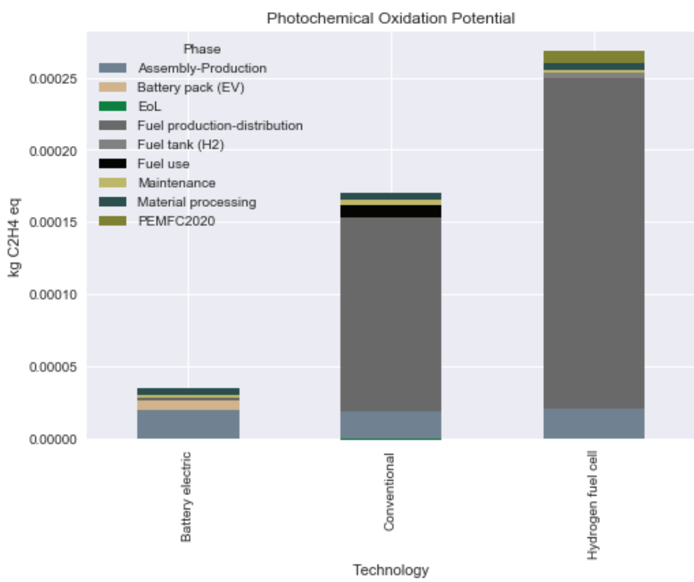

Figure 5.12 Photochemical oxidation potential of the three trucks on best-case alignment

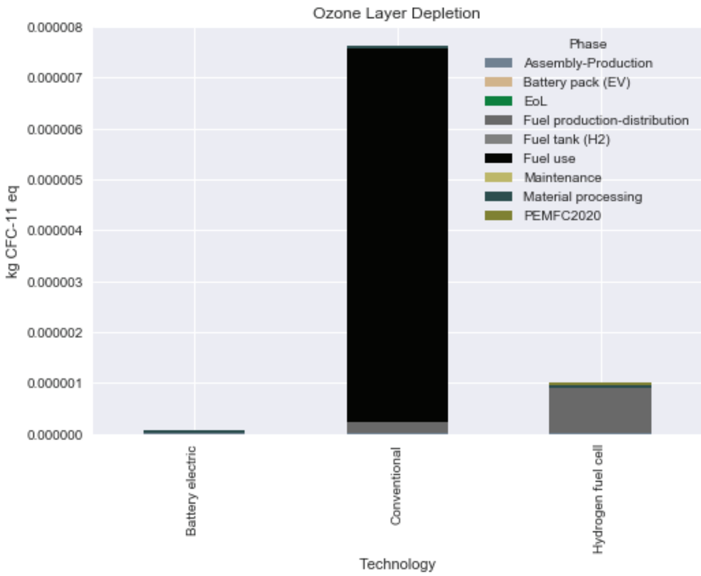

Figure 5.13 Ozone layer depletion potential of the three trucks on best-case alignment

5.4.2 Performance of optimized alignments

Kabongo Booto, Marinelli, et al. (2020) examined around 20 alignments alternatives which were generated from the optimization process. Each of these alignments was obtained considering specific targets in the optimization model. Two indicators were developed (see detail in the corresponding section of the method chapter) and used to assess the performance of the generated alignments. The following verdicts hold:

Per kilometer life cycle environmental impacts performance (Per-km LCEIP)

Examining the results for this indicator, it was first pointed out that the same pattern as in LCA was observed with the alignments. The battery electric vehicle seems to hold the best performance while driving on all optimized alignments, for all impact categories (see y-axis in Figures 5.14 – 5.17). Second, the trend of the dots follows a remarkably different arrangement, for the conventional truck, regarding the performance on depletion of the ozone layer and photochemical oxidation potential (Figures 5.16 and 5.17). This observation concerns mostly alignments obtained by optimizing both earthwork and pollutant cost (for the SCR technology) as well as those of minimum pollutant costs (Figures 5.16 and 5.17). Last, the configuration of the vertical alignments seems not to influence on the life cycle ADP when the conventional truck is retained as the reference vehicle (Figure 5.15).

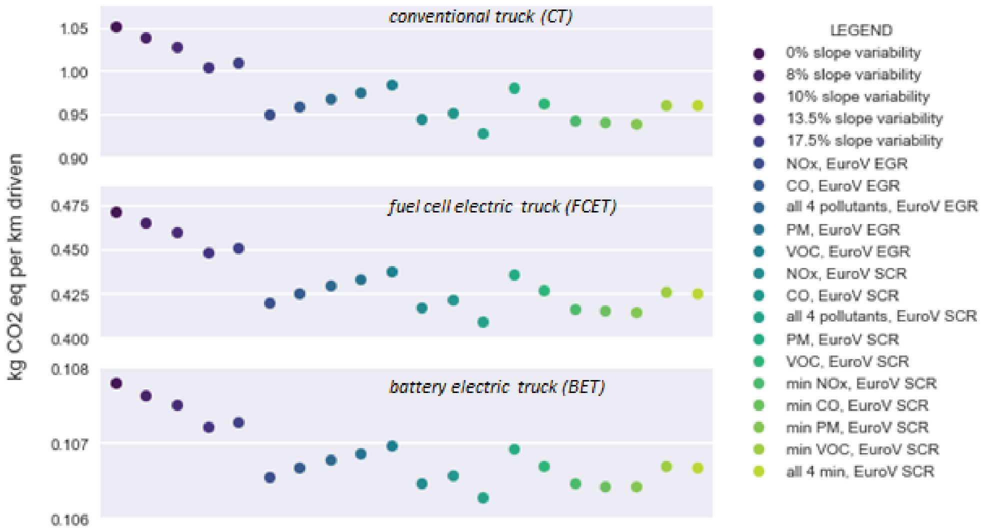

Figure 5.14 The per-km global warming potential of each alignment

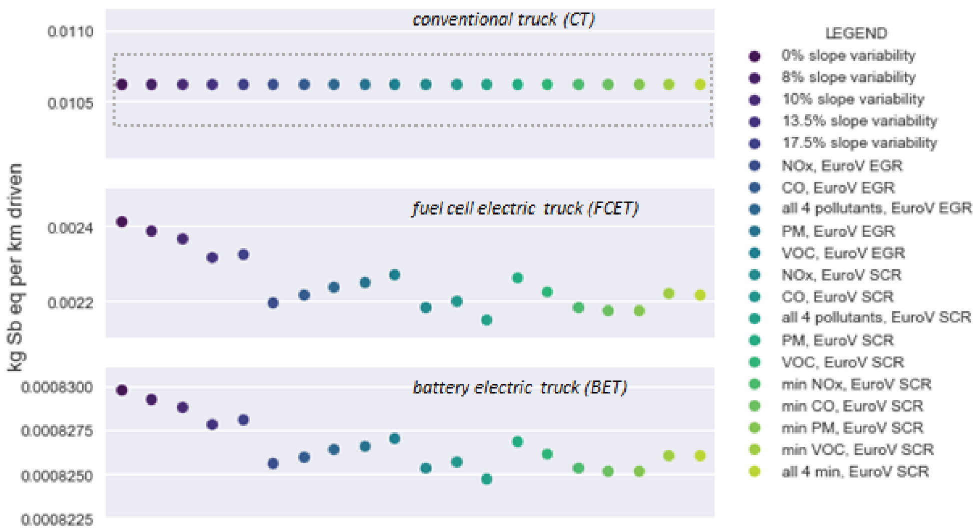

Figure 5.15 The per-km abiotic depletion potential of each alignment

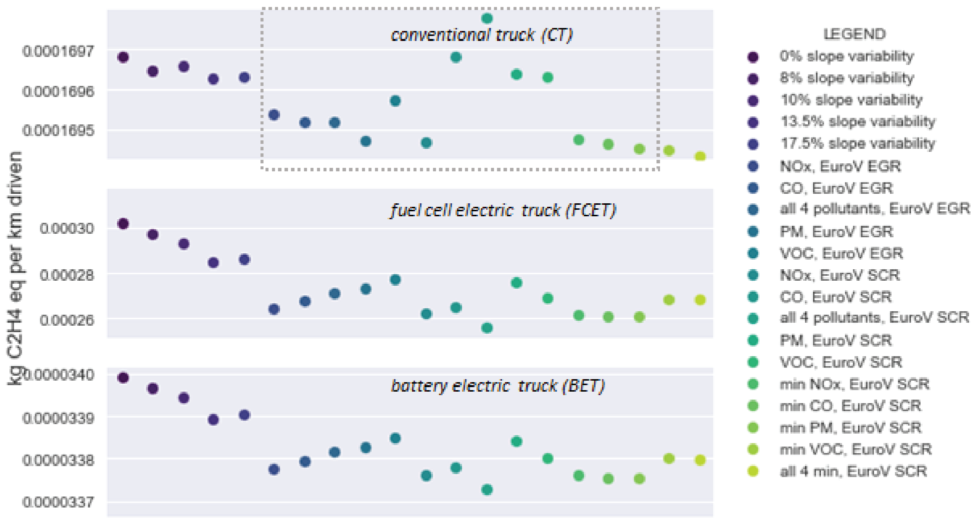

Figure 5.16 The per-km photochemical oxidation potential of each alignment

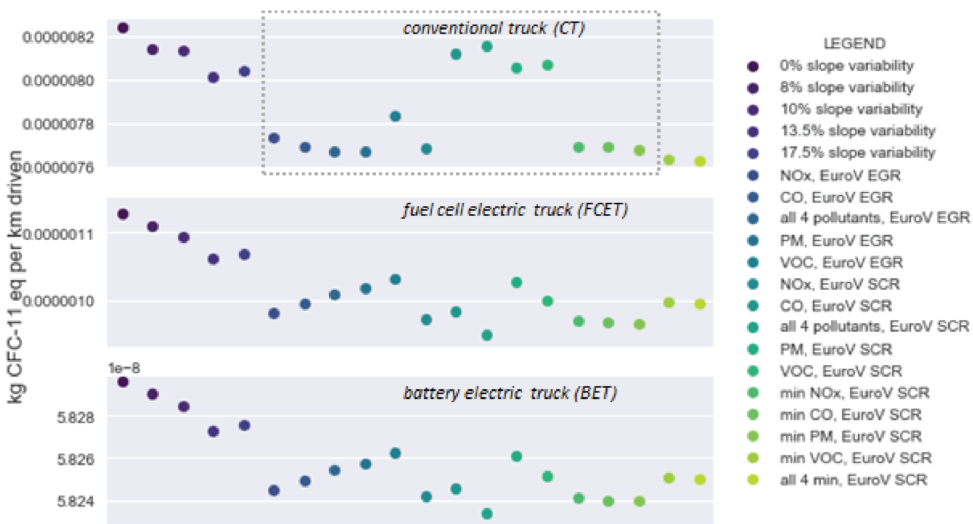

Figure 5.17 The per-km ozone layer depletion potential of each alignment

Efficacy performance

Analyzing how far a given vehicle can go with a fixed energy autonomy, on each of the generated optimized alignment was termed as the efficacy performance, in this study. Investigating this indicator, for the designed powertrains, Kabongo Booto, Marinelli, et al. (2020) found the found the followings:

In view of the results (Figures 5.18 – 5.20), it appears that the alignments with higher undulations constrain the tested vehicles to drive shorter distances, for the same fixed autonomy, while alignments with least waves enable larger driving ranges. The best performance is registered for the alignment obtained by minimizing all four pollutants simultaneously, for the Euro-V SCR technology. The worst performance is registered for the alignment generated by minimizing the earthwork cost without any limitation to the variability of the resulting gradients. Driving on the alignment of best performance helps achieve higher driving ranges compared to the alignment of least performance. Detailed explanations on the alignments and related optimization targets are found in Kabongo Booto, Marinelli, et al. (2020). A gain in driven distance of about 3.15 km can be achieved when the conventional truck is used on the best-case alignment compared to the worst-case alignment (Figure 5.18). This gain is increased to about 4.08 km if the hydrogen fuel cell truck is used on the two extreme alignments (Figure 5.19). This performance is much higher, to about 23.6 km, with the battery electric truck as the operating vehicle (Figure 5.20). The efficacy performance is studied for 100 kWh fixed autonomy on each powertrain.

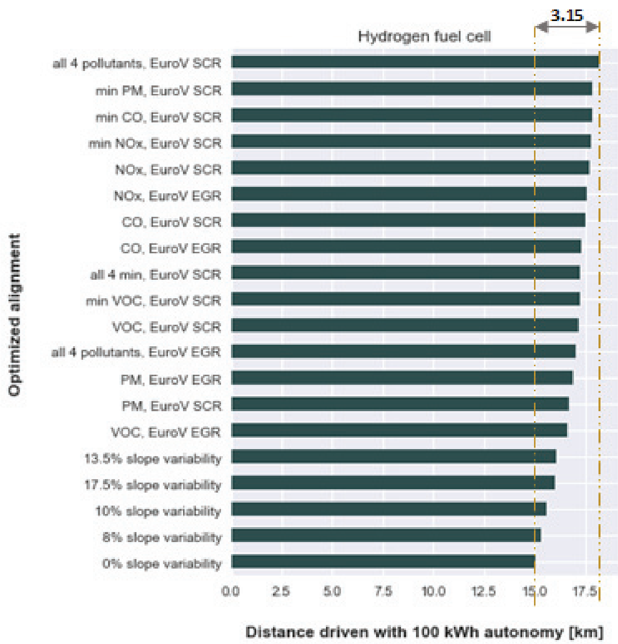

Figure 5.18 Efficacy of a 12-tons hydrogen fuel cell electric truck

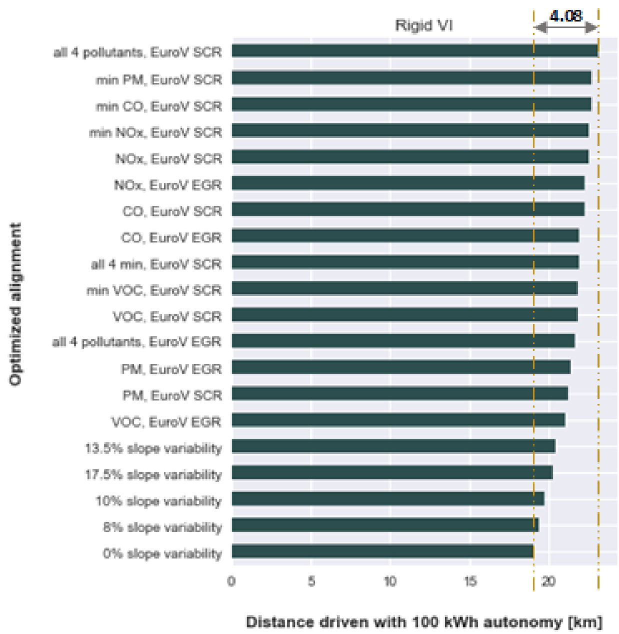

Figure 5.19 Efficacy of a 12-tons Euro VI diesel rigid truck

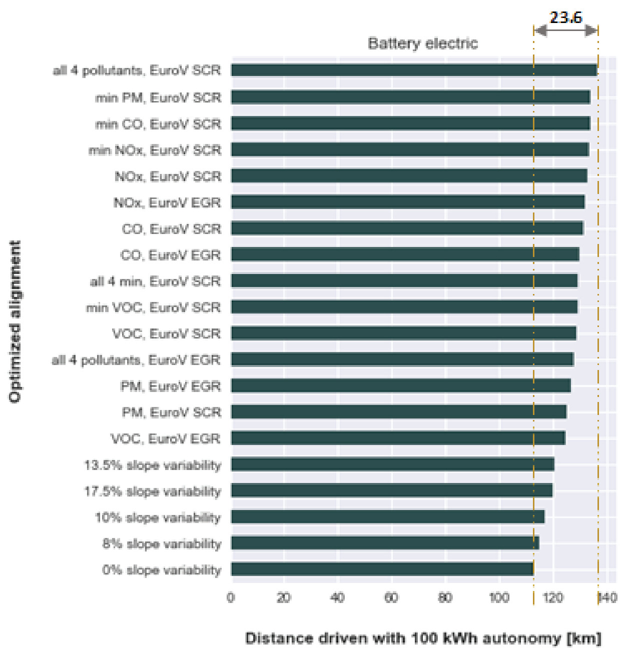

Figure 5.20 Efficacy of a 12-tons battery electric truck

5.4.3 Effects of clean vehicles' penetration on GWP

The effect of the penetration of clean vehicles on operating-phase GWP (i.e. GWP from both production-distribution and use phases). The overall gain (i.e. for both phases combined) for each clean vehicle, over a selected number of fossil and alternative HDVs are portrayed below (electricity is from hydro dams):

The battery electric truck displays significantly higher overall gains over the selected fossil trucks, with average values approaching 99.5% (Figure 5.21). The hydrogen fuel cell electric truck displays good scores, about 78% gain, on average, over the selected fossil and alternative trucks (Figure 5.22). Operating the fuel cell electric truck with hydrogen produced through SMR happens to yield strictly negative GWP gains, over the fossil technologies. The average figure is about -76.40% (Figure 5.22). Gains are presented for both worst and best-case alignments, and in both use and production-distribution stages.

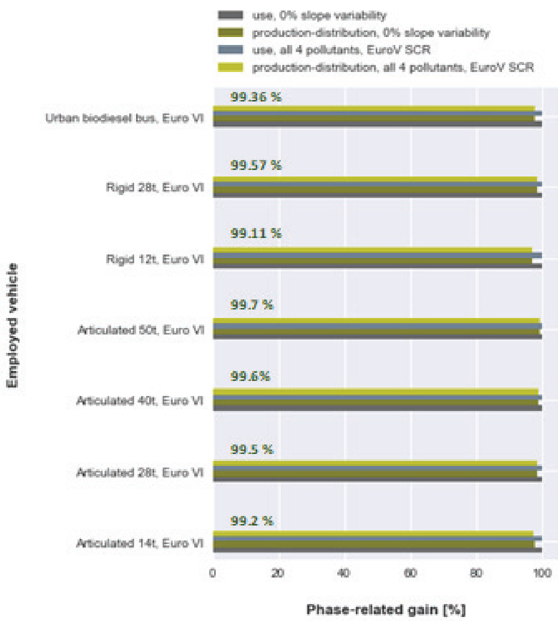

Figure 5.21 Gain, in GWP, of the BET over diesel and biodiesel trucks (electricity from hydro, Norway)

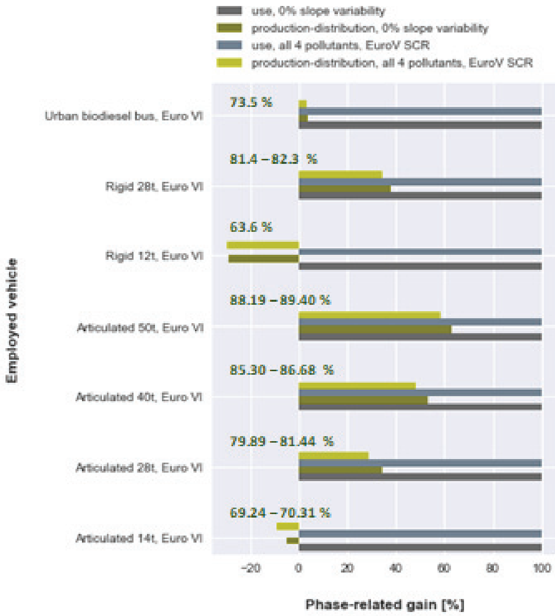

Figure 5.22 Gain, in GWP, of the H_2 FCET over diesel and biodiesel trucks (H_2 from electrolysis; electricity from hydro, Norway)

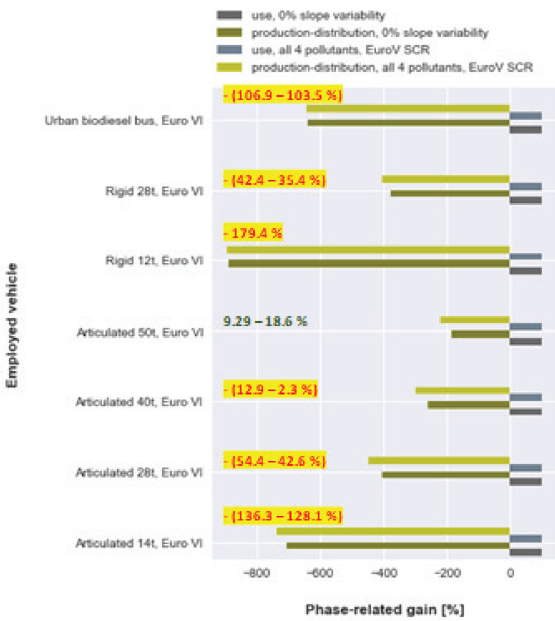

Figure 5.23 Gain, in GWP, of the H_2 FCET over diesel and biodiesel trucks (H_2 from SMR; electricity from hydro, Norway)

5.4.4 Effects of driven distance (sensitivity analysis) on GWP

The behavior of the life cycle GWP against variation in yearly driven distance was also studied. Results from Kabongo Booto, Marinelli, et al. (2020), for the three trucks under study, is compacted in Figure 5.24. The battery electric truck (BET) achieved the best scores, for all examined driven distances, with a maximum of 227.13 tons CO_2 – eq. Depending on the adopted H2 production path, the fuel cell electric trucks achieved maximum scores of 7512.98 tons CO_2 – eq for SMR, and 1692.16 tons CO_2 – eq for electrolysis. The Conventional truck returned a maximum score of 4250.74 tons CO_2 – eq, for the total driven distance of 125000 miles per year.

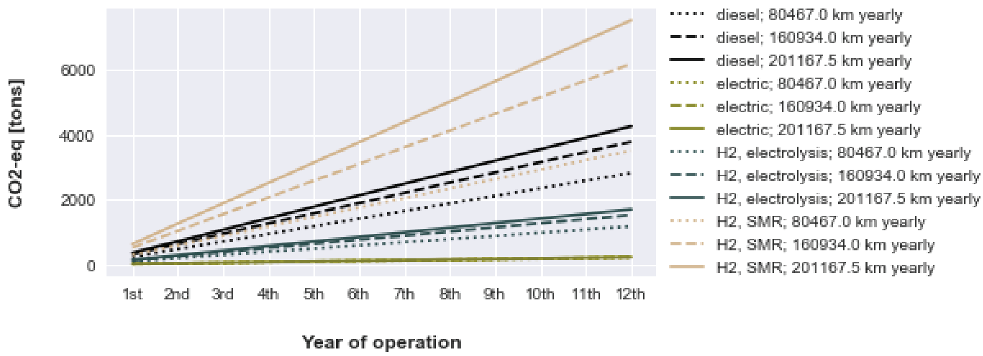

Figure 5.24 Driven distance effects on cumulated GWP over 12 years operation of trucks (electricity from hydro, Norway)

Chapter 6

Analysis and Discussion

This chapter can be grouped in two main parts. The first part (6.1) discusses the main findings that are presented in the previous chapter (Chapter 5.). The core findings are commented and debated at high level, to keep things simple, short, and concise. The second part (6.2 – 6.4) discusses the adherences, considerations, assumptions, remarks and reflections made in the course of this research work, including the lessons learned and the understanding gotten from blending the content of the five papers appended to this thesis. It is deliberately chosen in this second part, to put efforts on discoursing issues of the research work that were not deeply surveyed in the affixed papers. The goal is to avoid being repetitive by reproducing what is already presented in the attached papers, and rather reinforce the pertinence of the conducted works by supplementing their discussion and conclusions with some new and relevant insights. Topics commented in this second part are linked to the different models that were developed, the assumptions made, choices of certain parameters, data collection, procedure of LCI compilation as well as the developed indicators.

6.1 Key findings

As stated above, this section is dedicated to the main findings of the project. It does not discuss all the findings in the appended papers but points to the main ones at a very high level.

6.1.1 Criticality weight of vertical alignment in road planning project

Each road project is unique and always complex. Depending on the characteristics of the region intended to receive the road, several factors will need to be carefully regarded to poise between serviceability, cost, and environmental benefits. Paper I identified four key factors as the most influential ones, in mountainous regions (Norway used as a representative case). These factors are seen to directly affect not only the project cost, but also the quality of the deliverables. The factors are grouped in the following categories (also termed as costs): construction, maintenance, user, and environmental and socio-economic. Among them, the user compartment appeared to be the most important one, representing about three-fourth of the total weight (i.e. 65 – 75%). One of the most critical components in the user cost is the energy bill, accounting for not less than 65% of the total charge. This finding is not new. In fact, many research works came to the same conclusion of the user cost being the most critical one (J.-C. Jong & Schonfeld, 1999; Kang et al., 2012).

The energy bill however is related to the energy demand of the vehicle which for HDVs is demonstrated to be influenced to a very large extent by the profile of the vertical alignment of the used road. Results from this research project have shown that the high fuel cost can be reduced by up to 40% if driven at acceptable speed on an optimized alignment (Papers III & IV). The vertical alignment is indeed one of the critical factors to hold under control in the early planning and design stage of any highway project (Jha & Schonfeld, 2004; J.-C. Jong & Schonfeld, 1999; Kang et al., 2012; Shafahi & Bagherian, 2013; Yang, Kang, Schonfeld, & Jha, 2014).

6.1.2 Influence of vertical alignment on eco-friendly operating mode of HDVs

Findings from paper II attested that the vertical alignment of a highway does influence the consumption of fuel of an HDV even if this is exploited in a scheme which integrates only environmentally benign practices. Results showed that the effects of the gradient on energy demand of an HDV operating eco-friendly will be more pronounced on acceleration mode than in deceleration mode. Negative gradients will tend to retardate the vehicle, imposing more idling events and stops-and-go. This can also be accounted for tire and road wear, contributing to toxification of natural ecosystems.

For each unit positive gradient, it was estimated by the developed models that the considered vehicle demanded 5.3 unit more fuel. Numbers provided in this study compared quite well with those found in the literature (Barth & Boriboonsomsin, 2009; Christo J Bester, 1984; Hussein, Johansson, Karlsson, & Hansson, 2008; Svenson & Fjeld, 2016). This amount was relatively lower in the negative gradients where more frequent decelerations were recorded.

The influence of the vertical alignment of a road on the energy demand of an HDV was found to not to be influenced by the selected operating mode of the vehicle.

6.1.3 Environmental modelling and optimization of vertical alignment

Works performed in papers III to V demonstrated that it was possible to integrate the environmental dimension directly in the vertical alignment optimization models. The proposed models were able to include more than one environmental factor for one than one vehicle type, category, and technology standards. The task is quite challenging especially with finding the correct way to integrate those components. However, if well performed it is seen to be as one potential way to contribute in curbing the earth's warming through reduction of GHGs. The achieved results, will depend of course, in the optimization techniques, the syntaxes of the proposed models (how it is built, what is embedded in it, quality of the factors and related data), the nature of the terrain (initial topology or initial alignment), as well as the supporting approach behind the model's mind. In any case, it is possible to save both energy and emissions, and consequently, also save money.

The key for succeeding in constructing such models is the availability of information on environmental performance of HDVs. This information needs to be somehow linked to one or more geometric elements of the vertical alignment. This work selected to go for speed-gradient based environmental performances, as it was found to be reliable for successfully implementing the selected tasks. This is not the only option, but one option to go. Other options do exist, and finer methods can be developed. However, the choice made revealed to be very useful in the implementation phase when the only option to retain was to be able to make use of linear optimization techniques for optimizing the model. It was profitable to model the alignment in the proposed way to be able to conserve the linearity required for using this optimization technique. This guaranteed the existence of optimal points solution for each alternative. Keeping the model linear was also very important for decreasing the computational cost while solving the model.

Situating this work and comparing the results with other previously conducted work, for the tasks in this section was not possible. The main reason was the unavailability of comparable studies to be used for benchmarking. Although many researchers address the problem of intelligent road design and optimization of the vertical alignment of highways (Jha & Schonfeld, 2004; J.-C. Jong & Schonfeld, 1999; Kang et al., 2012; Shafahi & Bagherian, 2013; Yang et al., 2014), almost no previous study attempted to link the alignment design to environmental improvement and especially to emissions. This thesis poses the fundament to upon which to continue building for including more environmental and emission parameters into the modelling of highway alignment, on a science-based and goal-oriented approach.

6.1.4 The effects of powertrain type, technology, and vehicle category

Capturing the influence of vehicle powertrains, categories and related technology standards was the main motivation for the work presented in paper V. The revelation is that the designation “clean vehicle” can be mistaking if the focus is put only on the type of energy used. Also, categories of HDVs can also be misleading if only the weight is thought of. Finally, the technology standards may reveal complicated patterns if load factors and speeds are discarded. Few details about the assertions made above are provided below.

Regarding “clean vehicles”, results from the performed works showed that when the entire value chain is considered, the fuel cell electric truck could also depict poorer performances than the conventional fossil truck. This postulate holds true as the same trend is also observed by other researchers in the field (Al-Thawadi & Al-Ghamdi, 2019; Chan, Miranda-Moreno, Alam, & Hatzopoulou, 2013; Cooney et al., 2013; Nordelöf, Romare, et al., 2019). The fact that the fuel cell truck is powered with hydrogen which is a clean and renewable fuel does exonerate it from pollution only during use phase. Also, it really depends on the production pathway of the hydrogen fuel. For the entire life cycle, components like hydrogen tank, and the entire value chain of hydrogen fuel itself can weigh heavier for some indicators returning highly negative credits to the performance of this clean technology for a given alignment, compared to the conventional technology (Nordelöf, Romare, et al., 2019).

It was also found that for hydrogen, the best option would be to always use it complimentarily with batteries and always add CCS in the process if the production is based on non-renewable energy sources. The battery electric truck proved to be more environmentally friendly for all tested alternatives and returned positive credit in almost all cases. This could mean that it is the way to go, if it is wished to efficiently address deep transport decarbonization issues (Chan et al., 2013; Nordelöf, Romare, et al., 2019).

For the vehicle categories, one possible mistake to commit would be to think that the heavier the vehicle, the more polluting it will be. This sounds like a trivial statement but in fact can really be mistaking. The revelation was that some heavier vehicles returned far better performance scores than lighter vehicles. This can be explained from the fact that heavier vehicles will often have powerful engines, but also adapted aftertreatment devices which in some events, may perform relatively well due to environmental conditions. Categorizing vehicle only based on weight and relating environmental indexation must be avoided.

As of the technology standards of the conventional HDVs, what needs to be stated is that some vehicle of higher standards may end up polluting the same way as some others of lower standards under specific loads and for specified speeds. For example, it is not uncommon, in the EMEP-EEA database, to notice that a Euro IV HDV moving at 80 km/h and fully loaded releases much less NO_x than a Euro V HDV running at 65 km/h and empty. This is to say that higher or better technology standards do not guarantee that the bet is won. The operating conditions (combination of speed, load, and alignment profiles) remains determinant.

6.2 Developing models to generate environmentally optimal highway’s vertical alignment

From the works reported in the papers I and II, flawless evidences were gotten that the vertical alignment is among the determinant factors to consider in the selection and planning of a road and that it exerts a clear influence on the energy demand profile of a heavy-duty vehicle (HDV) – during its operation – independently of the selected driving mode. This knowledge cemented the motivation – already existing – to consider designing alignment which will lead to reduced energy demand of HDVs, and consequently to a better environmental profile. This was the main drive for instigating the development of the three optimization models described in the papers III, IV and V. From the research gaps identified after reviewing the literature and, following a discussion with practitioners on the trail of a whirlwind tour of needed skills, it came up that it was realistic enough to tailor optimization models that would return optimized vertical alignment leading to lower emissions of vehicles during their operations.

The main idea for having this work done was to provide designers with a tool that assist them in the decision-making process – at early design phase of a given road project – providing them with the possibility to choose among several alternative greener solutions. The present research work should lay the first stones in the development of such tool, by setting up realistic models approaching the nature of the studied problems, and by providing means for solving those models. This goal was supplemented by a few additional goals encompassing the followings: the developed models need to be (1) simples, (2) build on existing ones, (3) solvable with simple but robust enough optimization techniques, (4) easy to replicate and, (5) most importantly must depict a clear link between the vertical alignment elements of a road and the pollutants released by the vehicles. Some details regarding the conducted process – from conceptualization to tiding-up the models – are briefly passed over below:

6.2.1 Unfolding the development of the models

The first task to perform was to review a few existing models and to quickly pinpoint some of their key characteristics. A few published works were reviewed, and efforts were made to understand their related underlining approaches. A particular interest was directed to the works of Hare et al. (2014), J.-C. Jong and Schonfeld (1999), Kang et al. (2012), C. Goh, E. Chew, and T. Fwa (1988), Said M. Easa (1988), J.-C. Jong and Schonfeld (2003), Moreb (1996), Liatsis and Tawfik (1999), Li, Pu, Schonfeld, Zhang, and Zheng (2016), Yang et al. (2014), Said M Easa and Wang (2010), Yamasaki, Hongo, Hiyane, Iio, and Yatabe (2002), Moreb and Aljohani (2004), Miao, Li, Yang, and Huo (2009), Ahmad A Moreb (2009), Valentin R Koch and Yves Lucet (2010) and Maji and Jha (2013). Applications from closely related fields – such as railroads – were also considered (Lai & Schonfeld, 2016; Li et al., 2016). The abovementioned screening review resulted in the following observations:

On the one hand, it was observed that most of the developed models were quite complex (i.e. involving many equations and integrating many aspects of the problem) and computationally expensive, and incorporated relatively heavy mathematical abstractions, making them difficult to replicate. On the other hand, it was remarked that most of the models were non-linear – except in few cases (Said M. Easa, 1988; Valentin R Koch & Yves Lucet, 2010; Moreb, 1996; Ahmad A Moreb, 2009; Moreb & Aljohani, 2004) – and necessitated the use of non-linear optimization techniques (also tools) for their solutions. The predominant use of low-level languages such as C, C++ and Fortran for implementing the algorithms can be perceived as a marker for both the level of complexity and the degree of difficulty in tiding up and resolving models.

The second step was to decide which modelling approach to choose in order to efficiently tackle the problem in hands, considering both the outcome from the screening review, and the pursued goals of the project. The choice converged to the method initially developed by Ahmad A. Moreb (Moreb, 1996; Ahmad A Moreb, 2009; Moreb & Aljohani, 2004) and further enhanced by Valentin R Koch and Yves Lucet (2010). The approach was found to be simple – as not so many decision variables were contained in the model, understandable and easy to reproduce (even in a standard spreadsheet). The optimization technique employed was linear programming (LP) either in a standalone mode or coupled with a spline (i.e. an approach to approximate dynamic programming through LP techniques (Farias & Roy, 2003)). At this stage, the supplemental goals (1), (3) and (4) were met, and the choice to build up on these models confirms the fulfillment of the supplemental goal (2).

The next stage was to think about possible strategies to model the release of emissions and the geometrical elements of the road in the vertical plan. This task was critical, since it was the heart of the approach, knowing that the resulting shape of the vertical alignment is tightly connected to the nature of the interactions between the vehicle and road elements. Based on the characteristics of the existing fuel consumption and emissions calculation's models (Corvalán, Osses, & Urrutia, 2002; Fontes, Pereira, Fernandes, Bandeira, & Coelho, 2015; Mak & Hung, 2008), this study retained an approach that consecrated the adoption of speed-gradient dependent models. These models were found to be the most appropriate ones because of their capability to include the effects of road grades and performances of the vehicles in the estimation of fuel consumption factors and emissions factors (FCF and EF).

The handbook of emission factors for road transport (HBEFA) is one such model and is very well adapted for capturing speed dependency variations of both fuel consumption factors and emitted pollutant factors, for several vehicle categories (Rexeis, Hausberger, Kühlwein, Luz, & Ligterink, 2013). HBEFA allows for considering both vehicles' nominal factors (i.e. vehicle type, technology, and emission type) and relevant context-specific factors (such as road gradients and vehicle loadings), all of which were considered in the developed models. In its full version, HBEFA (version v3.2) contains 7.8 million HDV (heavy-duty-vehicle) fuel consumption and emission factors. Those factors are documented for nineteen distinct categories of HDVs under three vehicle loadings (empty, half loaded and fully loaded), considering nine emission concepts, 272 traffic situations and seven road slopes (-6%, -4%, -2%, 0%, +2%, +4%, +6%). Numbers are provided for vehicles' fuel consumption and seven exhaust gas pollutants (CO_2, NO_X, NO_2, HC, CO, PM, PN).

For the purpose of this research project, it was decided to make use of the spreadsheet model of the HBEFA – freely available online – which is developed within a joint framework between the European Monitoring and Evaluation Programme (EMEP) and the European Environmental Agency (EEA). The selected spreadsheet model provides speed-based fuel consumption and emission factors for nineteen HDVs, considering three engine loads, seven road grades and several emission concepts (from conventional to Euro I to VI). Models developed in this work consider only hot-start emissions, as not many trips start directly on highways. This is a quite common practice when applying the EMEP-EEA spreadsheet model to estimate fuel consumption or emissions from HDVs (Ahn, Rakha, Trani, & Van Aerde, 2002; Cen, Lo, & Li, 2016; Csikós & Varga, 2012; El-Shawarby, Ahn, & Rakha, 2005).

The following stage dealt with how to get the speed-gradient related fuel consumption, and/or emission factors, implemented in the model, so to determine the sketch of the vertical profile after optimization. Specifically, this task was about answering the following question:

how to relate the information in the spreadsheet model to one or more decision variables in the developed optimization models*?*

Answering to this question led to the development of two concepts to support the proposed approach. The concepts termed as "Single Level Approach – SLA" and "Multi-level multi-layered Approach – ML2A" is described in the papers III & IV, and V respectively. The main idea behind these concepts is whether to optimize the alignment considering one performance from only one unique test vehicle or expand the process by including several performances from several test vehicles. The key feature here is the basis on which to proceed for selecting one or many test vehicles. This was defined in paper III (See Table 1 in paper III appended). The motivation for choosing one unique test vehicle or more than one such vehicles is that one peaks the candidates that are thought to be among the main actors – if not the only responsible – causing the environmental burden in the considered segment of the road transport. Then, if the alignment is optimized based on the worst candidate, its performances will be relatively better when used by other candidates composing the vehicle fleet. There is room for discussing this motivation. In fact, vehicles may behave differently due to the adopted driving style. This may lead to substantial differences in the resulting performances at the operating stage where a pointed worst candidate may end up performing better than a least worst candidate – for one or more indicators – due to the operated driving behavior (Barth & Boriboonsomsin, 2009; Daun, Braun, Frank, Haug, & Lienkamp, 2013; Díaz-Ramirez et al., 2017; Liimatainen, 2011; Llopis-Castelló et al., 2018; Rolim, Baptista, Duarte, Farias, & Shiftan, 2014; Xu, Li, Liu, Rodgers, & Guensler, 2017; Zhou, Jin, & Wang, 2016). The Multi-level multi-layer concept was meant to compensate for such issues by incorporating several performances from several vehicles and to observe their effects in the outcome.

The final phase was to decide the environment to host the development of the worked-out models and their optimization. Several tools or environments were tested and used, based on the orientation of the investigated problem (see section 4.1.2.1 in chapter 4). The excel spreadsheet was used to test the SLA, in the alignment modification version of the problem, employing the goal programming approach, while the MATLAB-Simulink environment was considered for modelling and solving the same version of the problem, making use of genetic algorithms (GA). For the optimal alignment generation version of the problem, the python ecosystem was adopted for modelling and solution of both SLA and ML2A models. Python was found to be the prioritized tool given it is open source, powerful, multi-task and just excellent for pre- and post-processing of data. A validation stage was also considered to attest that the modelling in python with PYOMO was consistent in regards of the studied problems. The benchmarking process consisted in remodeling and solving the problem in Moreb (1996) and (Valentin R Koch & Yves Lucet, 2010), and comparing the obtained results among them (see Table 6.1 – 6.3 and Figure 6.1).

6.2.2 Assumptions made in the models

The models developed in this research project were subjected to some assumptions, which all can be discussed.

Table 6.1 Earth moved from-to sections (yd^3)

In A.A. Moreb		In this work	
Sites (from - to)	*Qty*	*Sites (from - to)*	*Qty*
(1,d)	11256,23	(1,d)	0,00
(1,3)	0,00	(1,3)	11249,78
(2,3)	5229,58	(2,3)	5210,222
(6,3)	2007,64	(6,3)	21400,44
(6,4)	44454,84	(6,4)	25029,78
(7,3)	30592,3	(7,3)	0,00
(7,4)	0,00	(7,4)	19470,22
(7,5)	8704,62	(7,5)	8729,778
(7,8)	2822,44	(7,8)	2830,222
(7,d)	0,00	(7,d)	11069,78

Table 6.2 Thickness of cuts [ft.]

In A.A. Moreb		In this work	
Section	*Value*	*Section*	*Value*
1	25,3265	1	25,312
2	11,7666	2	11,723
3	0	3	0
4	0	4	0
5	0	5	0
6	104,5406	6	104,468
7	94,7686	7	94,725
8	0	8	0

Table 6.3 Thickness of fills [ft.]

In A.A. Moreb		In this work	
Section	*Value*	*Section*	*Value*
1	0,00	1	0,00
2	0,00	2	0,00
3	85,1164	3	85,186
4	100,0234	4	100,125
5	19,5854	5	19,642
6	0,00	6	0,00
7	0,00	7	0,00
8	6,35048	8	6,36799

First, the development of the models considered that the test vehicle (or vehicles, in the case of the ML2A) will be moving holding a constant speed, for the entire duration of the trip along the investigated alignment. This assumption poses some questions like how realistic it is for an HDV to keep a constant speed during the whole trip, on a given highway.

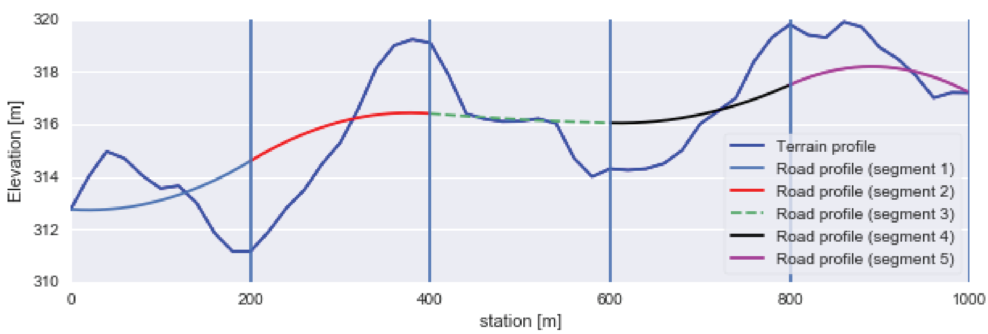

Figure 6.1 Optimized alignment (by section) and terrain profile (dark blue). Attempting to recover results from Hare, Lucet, and Rahman (2015)

The argument in support to this assumption is the fact that there is usually less traffic (free flow conditions) on regional roads than within the city (Hansen & Huang, 1997; Peden et al., 2004; Reis et al., 2000). Also, regional transport duties often hold longer, necessitating long duration breaks in between, before reaching the destination. To minimize the driver cost, it is common for regional transporters HDVs to have a quite faster driving style, within the authorized speed limits (Gibreel, Easa, Hassan, & El-Dimeery, 1999). Further, highways are reputed to be used by vehicles in relatively higher speeds which often keep a constant tempo in the adopted driving scheme to avoid the occurrence of possible congestion events (Krammes, 2000; Mumford, Mumford, Mumford, & Mumford, 1964; Walters, 1961). Therefore, the constant speed assumption was found to be admissible, even though it may seem not realistic at first eye. However, it is to recognize here that the best approach would be to consider a real-life driving profile and adopt the related speed scheme for calculating the energy demand and emissions from HDVs.

Second, it was assumed that the alignment has a homogeneous and regular surface from start to end. The main reason behind the consideration of this clause was to reduce the level of complexity of the models. In fact, a homogeneous and regular surface simply means that the value of the friction coefficient of the road is one and unique for the entire length.

This assumption was found to be less questionable as in practice, the most observed trend is that many roads conserve the same type of surface, from start to end, as a unit project (HU, WANG, & Senthilmurugan, 2010; F. Thomas, 2004). However, the assumption can be violated for larger road projects, such as the Norwegian E39, as some cost considerations may lead to alternatives going mostly with climatic zones and/or soil types (the geology) within each bypassed location. Terrain topography is also one element that can favor one or another type of pavement, for stability and durability reasons. Nonetheless, the homogeneous surface postulate applies very well in the cases of most regional highways, in many regions of the globe.

Third, the models generate optimized alignments whose segments' gradients are comprised between negative and positive 6 percent. This is since the EMEP-EEA spreadsheet that constituted the main source of speed-gradient vehicles' performances considered in this project comprises data only within this spectrum of gradients (i.e. plus-minus 6 percent). This statement is questionable, especially in mountainous regions where the difficult topography often imposes the realization of hyper structures such as air bridges or complicated tunnels (e.g. underwater ones). Another obstacle can come from the fact that some locations (altitudes) may not be possible to be reached with a maximum gradient of 6 percent or a lower limit of minus 6 percent. There exist cases where higher values than 6 percent gradient (respectively lower values than minus 6 percent) may be needed to balance between economy, nature, and people. In such cases, the model may fail to deliver an alignment that will connect required locations. Yet, this supposition still holds, as many legislations are introducing the plus-minus 6% gradient as the edge limits for their highways (Colberg, Tona, Stahel, Meier, & Staehelin, 2005; Kühlwein & Friedrich, 2000; Osaki et al., 2010; Park, Kong, Jo, Park, & Lee, 2001).

Another assumption made while developing these models was to consider interpolating between the seven discrete gradients provided in the EMEP-EEA spreadsheet model for estimating values of fuel consumption and/or emissions of the test vehicle(s) at intermediate gradients (e.g. between 0 and +2%, or between -6% and -4%, etc.). The focus of the discussion here was to know whether the chosen interpolation techniques was appropriate to explain the pattern behind the data in use. One may think of different statistical modelling (inference) to end up with equations that could easily be used further in the main model. However, this was proved not to be feasible, especially with the goal of implementing the well-known and robust linear optimization technique (LP) to solve the models.

It is to underline that the above assumptions were made either to facilitate the modelling process or the solution one, while remaining as close as possible to the representation of the reality. The assumptions made contributed also to the robustness of the models, amplifying the results (i.e.

the generated alignments) from nonsmoothed (paper III) to smoothed and well adapted profiles (papers IV & V).

6.2.3 Some pertinent lessons learned

Running this research project was rich in learnings and discoveries. It was fascinating to come across new features that one might not have thought of otherwise.

The first thing to point out is the importance of choosing the appropriate interpolation method. While all methods strive to guess missing values given the existing ones, they may result in different profile of the curve when trying to connect the dots. Worst, the difference between the results from a given method with those of a reference method (say e.g. the linear interpolation) may be surprisingly huge for several speed levels and for certain load profiles. Figure 6.2 depicts the outline obtained using three different methods of interpolation in MATLAB (including the pchip or cubic, the spline and the linear interpolation) in the first row, and in the second row, the difference between these methods are shown. It is easy to observe that the methods perform extremely well for gradients comprised between -2% and +6%, where they return almost same values. From -2% and below, significant differences are noticed, depending on speeds and loads. These differences affect the performance of the models in different ways which are not detailed in this work.

The second discovery is related to the optimization techniques employed to solve the models. As stated in section 6.1.1, several modelling and solution tests were run in excel spreadsheet, and the excel solver was employed to decipher the optimization problem modelled in the same environment. A goal programming approach was adopted, using the fuel consumption as the target to minimize (paper III), in the alignment modification conundrum. The results were eye-catching due to the observed trend of the alignments varying in a certain fashion according to the percentage-target that was used. Higher targets in fuel consumption reduction were parented to offsetting downward and flattening the initial (i.e. existing) alignment (see Figure 6.3 & 6.4). The same problem ran with the GA in the MATLAB environment resulted in totally different shapes of the alignments, given the character

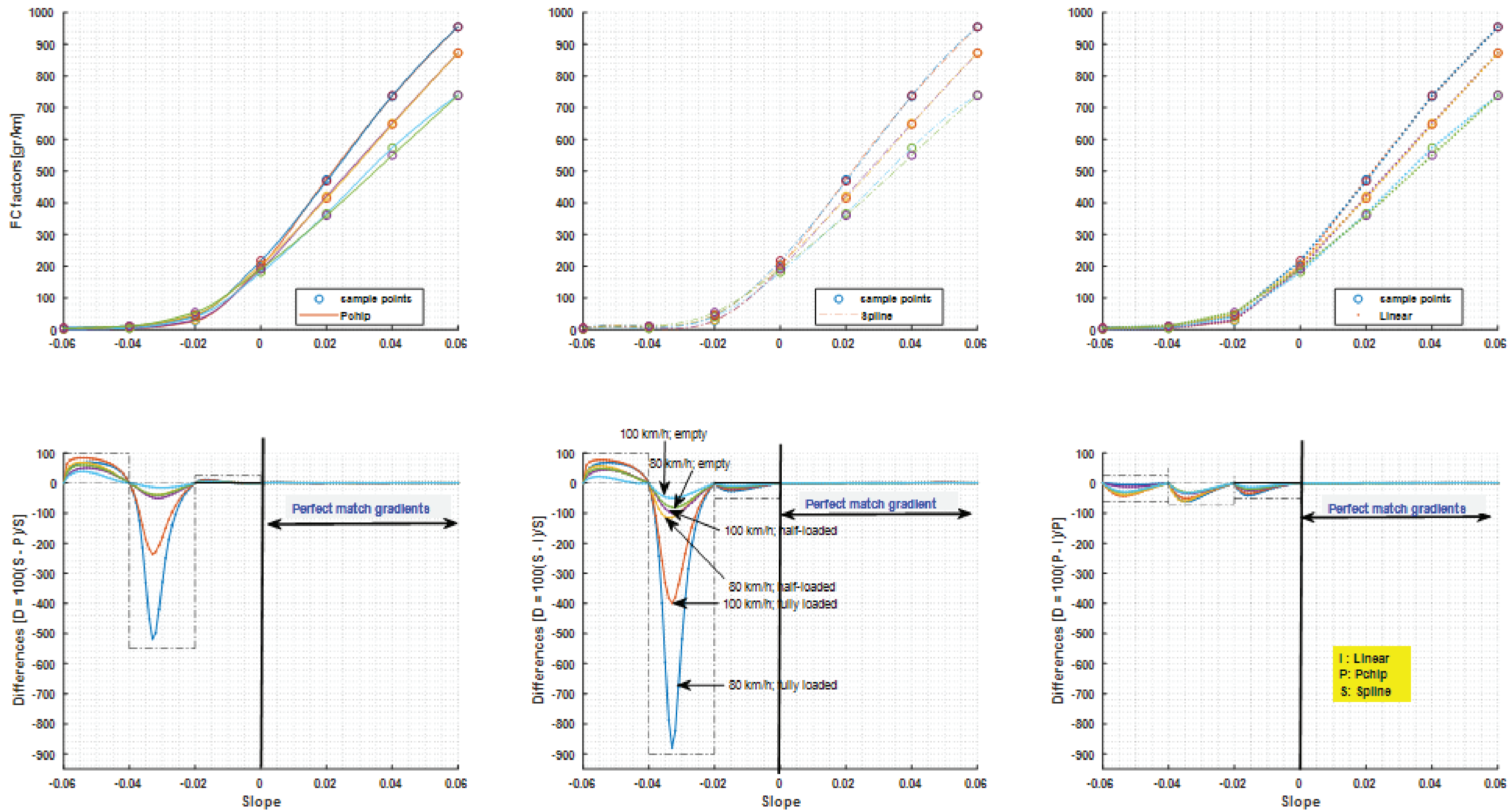

Figure 6.2 Trend of the selected interpolation methods (row1) and the difference [%] between the methods over the spline (row 2). The test vehicle is an articulated coach of 18 tons (SCR, Euro V).

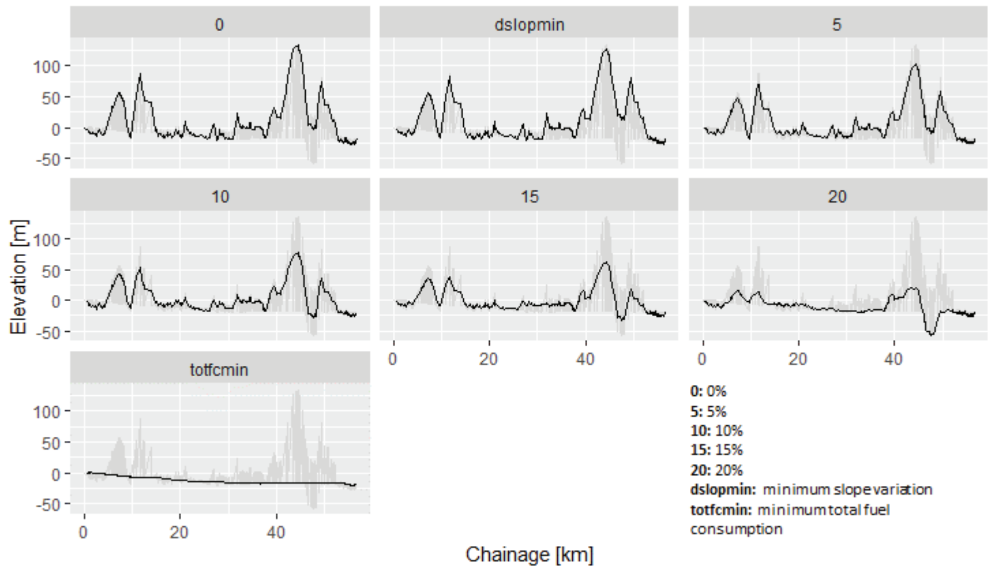

Figure 6.3 Trend of the alignments for different optimization target, using goal programming (0 is the existing one). The model acts in downshifting and flattening the initial alignment to end up almost even. The test vehicle is an articulated coach of mass 18 tons (SCR, Euro V).

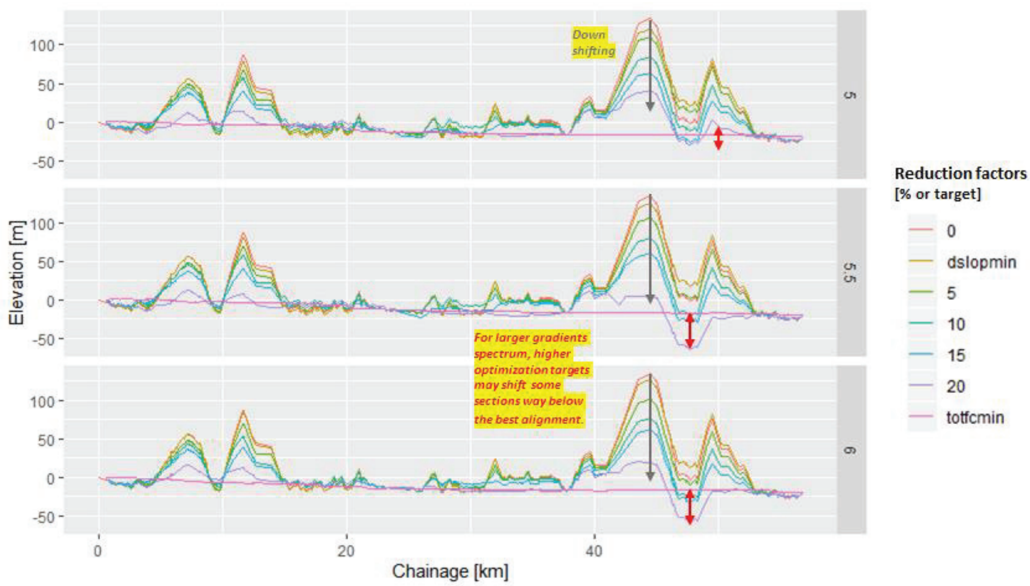

Figure 6.4 Trend of the alignments for different optimization target, with different upper and lower gradient limits, using goal programming (0 is the existing one). The test vehicle is an articulated coach of mass 18 tons (SCR, Euro V).

imprecise of the employed technique (See Figure 6.5). However, the two techniques returned the same shape of the minimum fuel consumption alignment, with a practical physical meaning.

The third unearthing has to do with the limitation of the lower and the upper gradient values. As many legislations are experiencing the plus-minus 5% gradient limits in modern highways (Christo J. Bester, 2000; Brilon & Weiser, 2006), it was decided to test the effects of such policy on the resulting alignment, in the case of the modification of an existing vertical alignment.

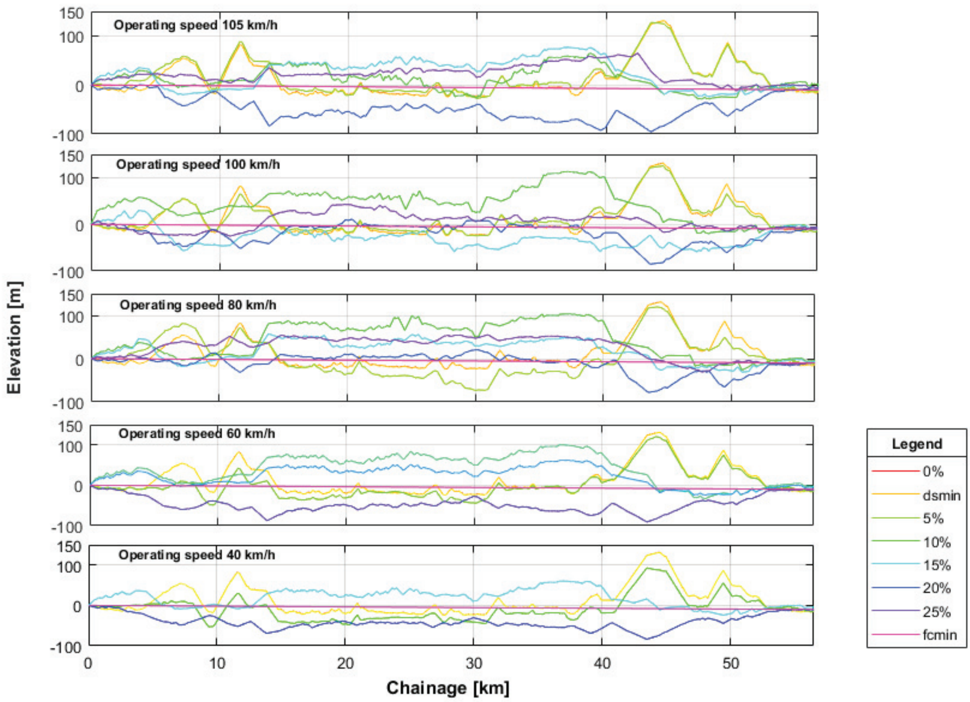

Figure 6.5 Trends of generated alignments for each reduction target and specified operating speed, using genetic algorithms (GA). The test vehicle is an articulated coach of mass 18 tons (SCR, Euro V).

The tests were run in Excel, using the same affixes detailed above. Results showed a quasi-inexistent influence of the gradient, in the retained range, on the generated alignments. The outlook of the alignments' profile did not change since the distribution of gradients in the alignments generated with restricted upper and lower limits looked almost the same as for the plus-minus 6% case (see Figure 6.6). This trend, however, did not compose with the percentage of the road that was entitled to be changed – in terms of total length – after optimization. In fact, numbers indicated that the higher the target in reducing fuel consumption, the higher the portion of the road to undergo substantial changes (see Figure 6.7). The tests were not conducted further to assess even lower limits, given it was assumed nonrealistic to go behind plus-minus 5% gradient limits, both in mountainous regions and other locations.

Another encounter to bring up is linked to the behavior of the other pollutants when an existing vertical alignment is optimized based on fuel consumption only. It was discerned that the optimum for fuel consumption – and consequently for direct CO_2 – did not correspond always to optimum for other pollutants. This can be clearly stated as follow: going from the initial alignment to the alignment of minimum total fuel consumption, the resulting amount of total fuel consumption – and thus that of direct CO_2 as well – was decreasing, as a logical repercussion. However, for other pollutants (CO, NO_x, PM) the trend was not so explicit. In the contrary, for each of the other pollutants, variable patterns were noticed. Figures 6.8 – 6.10 show the trend of CO, NO_x, and PM, normalized per kilometer of the entire studied road, considering a grouped approach detailed in paper III (normalization happens in each gradient bin). For each pollutant, numbers are provided for all considered optimization targets and under three loads for an articulated coach of mass 18 tons +. Normalized PM values increases for adjusted (i.e. optimized) alignments for empty truck and reaches a higher value for a flat terrain. Physically, it looks like it is easy to drain particles when driving on a flat road then when the road is rolling. CO gets somehow higher for adjusted road, except when the truck is empty. NO_x goes up for the adjusted alignment in all the intermediate optimization targets and goes down for the optimum fuel consumption when the truck is fully loaded. When the truck is half-loaded, nitrogen oxides pattern is quite irregular and hard to characterize. Its trend reverses to lower, in all optimization targets for an empty truck. These behaviors are not easy to explain, and a lot of features are to be accounted for getting a clear insight of the reasons for observing them. Nevertheless, it is worth an attempt to mark here that what is observed after employing these models is a clear result of the engine behavior, dictated by the vertical alignment of the used road. More advanced investigation needs to be conducted for getting deeper and clearer insights with a better understanding of the involved processes.

One last sighting to refer on is the correspondence between some of the alignment obtained with the objective function that combined both the earthwork cost and fuel consumption cost and the ones obtained through optimization based on environmental performances only (i.e. emissions). A few similarities are observed among these two groups of results which are obtained using different approaches (see results sections in papers IV and V). It may be worth considering eliminating the earthwork cost in the model, as the resulting shape can also be obtained, only by considering one of the pollutants in the model, seen to act in a similar way as the earthwork cost component of the model. More tests are required to ascertain this affirmation. However, if validated, such knowledge will contribute in decomplexifying the models, reducing the number of constituting equations.

6.2.4 Strengths and weaknesses of the models

No model is perfect, and all models tend to represent the reality, the best way possible. So, models developed in this research project are not an exception at all. There are indeed a few points to reveal as pitfalls in the constructed formalisms, and some of them can be found below.

First, as stated also in the lines above, the HDVs driving profiles are different from constant speed scheme. In real life, HDVs can keep constant speed for quite a long period in the regional duty operating scheme, but not for the entire duration of the trip. Stops, idling, accelerations and decelerations are always parts of the driving portfolio of all road vehicles, independently of the type of the journey. So, the constant speed assumption may in a sense be a weakness for the developed models.

Second comes the limitation in gradient values. The data source used limits the application of the model to a selected range of gradients – literally within plus-minus 6 percent, incremented by 2, each time. This fact limits the use of the model in situations where higher or lower gradient values are necessary to apply. Extrapolation techniques, although not advised, may be considered to overcome such pitfalls. However, that practice would cost a lot in terms of accuracy and precision, hence affect the applicability of the gathered results.

Third, the models being based on previous models and existing databases will inherit all the imperfections of those models and datasets. The uncertainty level – not discussed in this work – may also be higher. This rises the attention of the users when making decisions after running the developed models. Research is still going on in this field and the topic is increasingly getting higher interest,

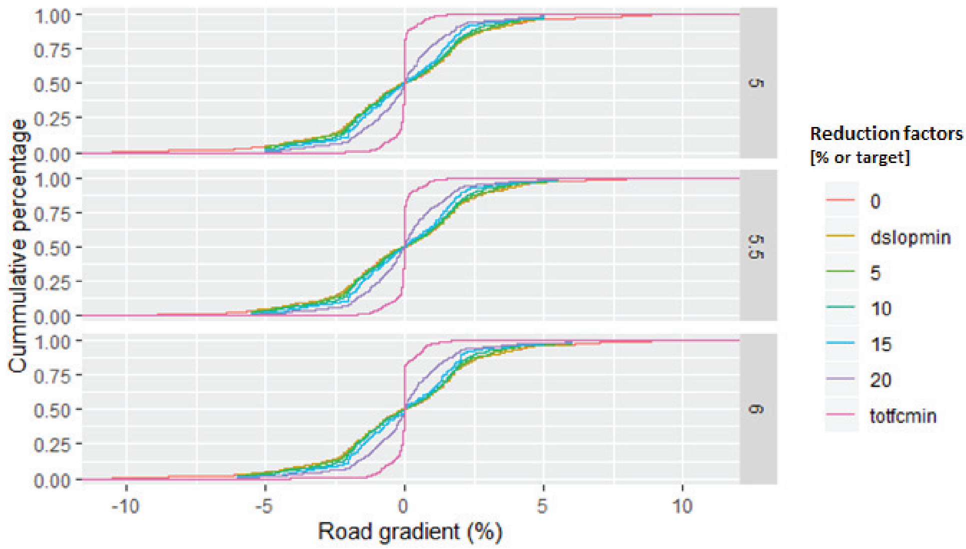

Figure 6.6 Cumulative distribution of gradients for several optimization target (using goal programming) and three different upper and lower gradient limits (the gradient limits seem to have no effect on the shape of optimized alignments). The test vehicle is an articulated coach of mass 18 tons (SCR, Euro V).

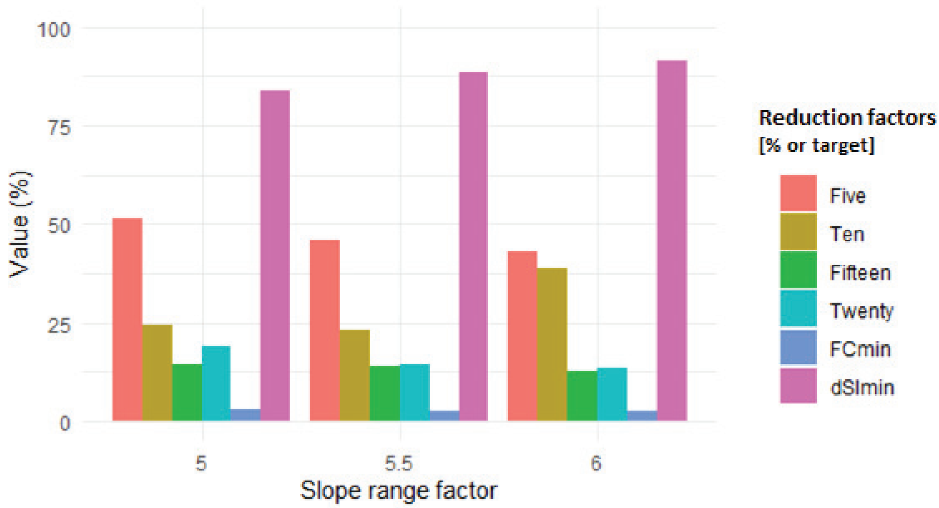

Figure 6.7 Percentage of the road not to undergo changes after optimization (employing goal programming) for different targets (80 km/h). The test vehicle is an articulated coach of mass 18 tons (SCR, Euro V).

bringing the level of perfection of the models to higher standards than it previously was (Beiranvand, Hare, Lucet, & Hossain, 2017; Casal, Santamarina, & Vázquez-Méndez, 2017; Said M Easa & Mehmood, 2008; Jha et al., 2006; Pushak, Hare, & Lucet, 2016).

Other elements to mention include the lack of incorporating several other pertinent factors in the models, embracing the blocs and side-slopes, some specific dimensions of the road (lane width, super elevation, length, etc.) , several pavement types (gravel, bitumen, concrete, etc.), soil types, emissions during earthwork and related machinery types, technological changes in the construction phases, etc. This clearly demonstrates that the field is still vast to explore, and there are still steps to be taken towards this direction in future attempts.

6.3 Data collection

Collection of appropriate data for conducting this research project was not easy. Definition of the type and amount of data needed to accomplish this work was done during the research design stage, where the necessary skills for approaching the problems were also evaluated.

To support the first method (i.e. the proof of concept), it was indispensable to acquire real-life GPS data of an HDV operating on a real highway, under eco-driving mode. The acquisition of this data was facilitated by the Norwegian Public Road Authority (NPRA or SVV) which conducted field works on several Norwegian highways using a Volvo FH16 truck, combined with a trailer. During this field work, NPRA employed a professional eco-driving coach with the instructions to drive strictly as if he was only trained on driving eco-friendly. The vehicle was equipped with several electronic sensors that measured more than one parameter (including the vehicle ground speed, engine temperature, vehicle micro-position, engine fuel rate, separations with other target in the surroundings, etc.). To each registered data point, coordinates determining the related GPS position were attached. Registration was done in 75 Hz frequency. To approach the problem as planned, this dataset was matched with existing roads in the Norwegian network. Road data were gathered from the Norwegian Veg Data Bank (NVDB), in a georeferenced format. The main challenge at this stage was to process this data to end up with one unique database for use in support to the proposed methodology. There are several types of georeferenced information of Norwegian roads in the NVDB platform. Choosing the appropriate one was also challenging. The selected road section (about 55 km long) had to be uniform (with no round about and cut from interchanges), homogenous in pavement type and lane dimensions, dedicated to highway operations with a considerable volume of trucks (relatively high AADT), and representing the reality of counties in terms of geology and topography. Figure 5.11 shows the distribution of gradient along the selected road section. The section has segments with gradients ranging from -11% to +12%, with most of the alignment being between -6% and +6%.

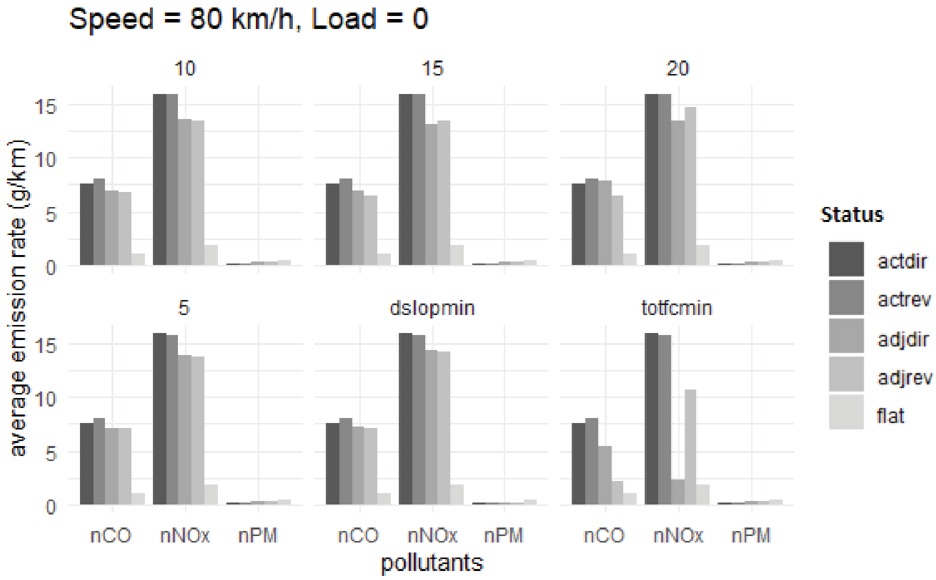

Figure 6.8 Normalized pollutants of an articulated coach (Euro V, SCR) @80 km/h and 0% load, in adjusted alignments

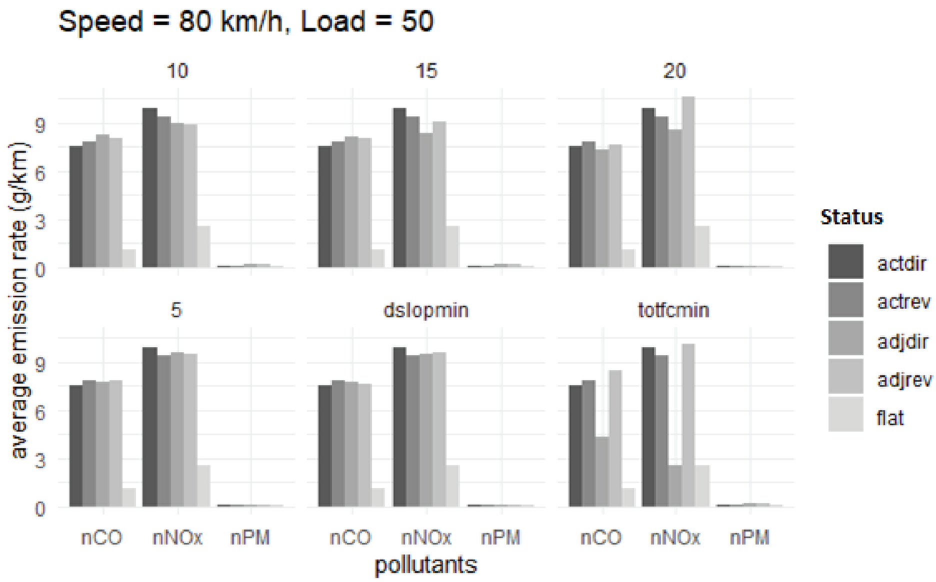

Figure 6.9 Normalized pollutants of an articulated coach (Euro V, SCR) @80 km/h and 50% load, in adjusted alignments

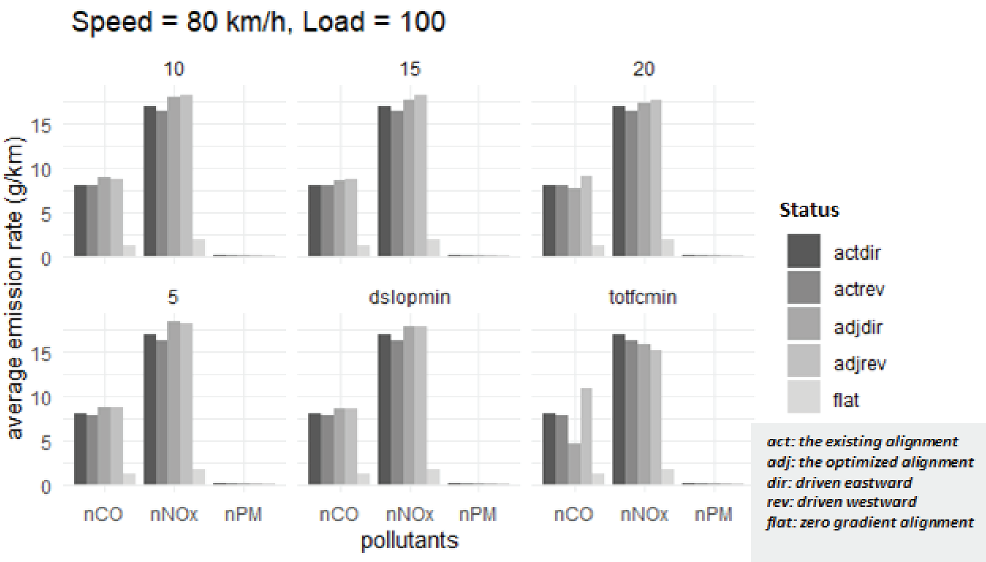

Figure 6.10 Normalized pollutants of an articulated coach (Euro V, SCR) @80 km/h and 100% load, in adjusted alignments

To support the silhouette enhancement method, data of an existing alignment or an existing terrain need to be available. Added to that, data for the performance of vehicles retained as test vehicles must be obtainable. The challenge here was to acquire the terrain data for the case of non-

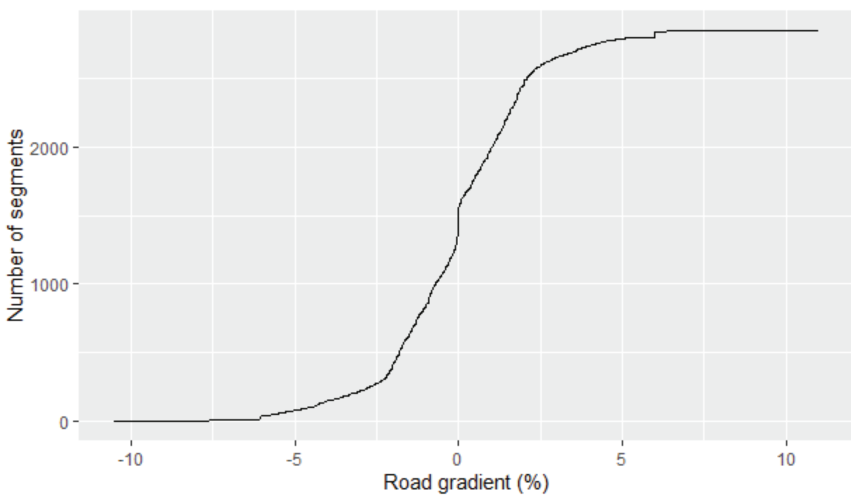

Figure 6.11 Distribution of gradient with segment number for the selected road section of E39, Norway.

existing alignment, and the data for the vehicle performance, whose consistency with the local situation must be verified. For verification and validation reasons, it was decided to adopt terrain data from the literature. This solution made it possible to benchmark between results obtained from the different studies, and hence, helped in positioning the results from this research project.

As of the silhouette appraisal approach, it was essential to collect much more data for performing this task. The data portfolio consisted of information related to the alignment, the vehicles, the materials, and related processing techniques for the compilation of the life cycle inventory necessary for conducting the life cycle assessment (LCA). What was problematic here remains the access to industry data for the entire value chain of the studied trucks and their corresponding propelling energies. The prominent difficulty in accessing industry data for production of heavy vehicles and/or some renewable fuels (e.g. hydrogen, biofuels) made it even harder to perform this task. As first option, the appraisal focused on the use phase, basing all calculations on the sole fuel consumption and emission factors provided in the EMEP-EEA excel sheet (papers III and IV). This was to avoid getting into the endless loop of trying to acquire related industry data.

The lack of access to industry related data led to the development of a new approach, involving feature engineering and deeper modelling, sizing, and design of some of the components of the trucks, to constitute the inventory. The idea was favored by the availability of a bill of the material (BOM) of a rigid fossil truck, which was featured to develop a quite complete inventory and to derive data for different powertrains and technologies, of acceptable quality. This approach led to the development of stand-a-lone LCA model for assessing the alignments and comparing a selected number of powertrains and technologies of HDVs (paper V).

Having access to pertinent data is very determining for conducting research projects or projects in general. The criticality in the data availability is often reflected on the quality of the achievements in a project and, can be very compromising. Data collection is therefore a key stage in research and access to industry data needs to be guaranteed, not only for easing the process of conducting research but mainly for achieving meaningful results.

6.4 Developing indicators for evaluating the resulting alignments

The main motivation behind the development of the metrics used in this research project remains the ability of assessing the performances of the alignments. The idea is to be able to compare and rank several alignment alternatives, after being generated through optimization. For that to be done, indicators were important. Hence their development. The fundament for tailoring these performance indicators was simple: "An alignment is efficient compared to another one, for the same route, if relatively less energy is demanded for covering the same length". This postulate implies that the released emissions will also be relatively lower.

The challenge with developing the indicators for assessing the optimized alignments was to comply with conformity and consistency, i.e. make sure that the developed pointers really perform well and respond to their definition (Dale & Beyeler, 2001; W. A. Thomas, 1972). Developing environmental indicators is a meticulous and quite complex task. They need to capture the complexities of the system they are destinated to, while remaining simple and easily measurable, sensitive and integrative (Dale & Beyeler, 2001; Hák, Moldan, & Dahl, 2012; McKenzie, Hyatt, & McDonald, 2012; Müller-Langer, Majer, & O'keeffe, 2014; Rees et al., 2008; Tam, 2002; W. A. Thomas, 1972; Vandermeulen, 1998).

For the indicators developed in this work, the focus was heavily put in the function of the alignment, which is to allow vehicles to safely travel and connect different points. Indicators were developed based on the above postulate. The method is simple but very practical. The alignment is assessed from start to end, with key elements being the segment lengths and related slopes. The gauges quantify the total amount of pollutants released or the total amount of energy (fuel) demanded by a specific vehicle, after driving back and forth along the entire alignment with a constant speed. The alignment is than stated to be better if the calculated amounts of fuel and pollutants are the lowest among all the considered alternatives. It is to note here that most indicators were developed considering the vehicle in the use phase (i.e. when it uses the road) and did not include emissions from roads and those from the tires (papers III&IV). However, the range of the indicators were enlarged to consider the entire life cycle of the vehicles including the entire life cycle of their corresponding fuels. This approach is presented in paper V. From their definitions, the employed indicators are simple, easy to measure, practical, integrative, and easy to monitor. Their level of complexity is acceptable and moderate. They are said to be practical as they easily indicate what they measure and can be used to amplify the situation towards a better performing scheme, providing a strong support for improving the alignment system under study.

Chapter 7

Conclusions and Contributions

This chapter concludes this thesis work and presents the contribution and the key windups of the performed research work vis-à-vis the identified research gaps. The content reflects mainly on the conclusions in the appended papers and the discussion and analysis conducted in chapter five, while avoiding textual reproduction. The chapter is organized in three sections including the scientific contributions, the recommendations to the road authorities and the topics to be considered for possible future investigations.

7.1 Contributions of the thesis

The overarching goal of this thesis was to figure out ways in which a vertical alignment affects the inclusive environmental profile of heavy road transport activities, and how to enhance that profile using a life cycle thinking approach. A preliminary evaluation of the question evidenced the necessity of developing specific techniques and tools to successfully tackle the problem. This project devoted a significant amount of resources on theoretical work to conceptualize, develop, test, and implement methods and tools to support decision makers and practitioners when evaluating the environmental benefits of linear infrastructure projects throughout their entire life cycles. The developed methods, models and tools made available to the general public, constitute the generous contributions of this research project.

7.1.1 Detailed, comprehensive, easily scalable, and updateable models

In total, one data pipeline, three alignment optimization models and three life cycle assessment models were developed in the course of this project.

The data pipeline was developed for cleaning, munging, examining and patterning the influence of vertical alignment of a highway on the energy demand of an HDV operating under eco-friendly regime and it includes clear indications regarding steps to take for replicating the process using real-life data. The approach is simple but robust enough and can be applied using open source tools such QGIS and R. Concise details on this approach are given in paper II with further clarifications provided in chapter three of this thesis. The user is provided with the freedom to choose between considering the vehicle in acceleration (respectively deceleration mode) or ignore these modes and focus on the overall activity. While the models developed here relate to one specific HDV, the approach is yet to apply easily to all HDVs and may serve to estimate the direct emissions already at early design phase of the road for eco-driving related activities.

The optimization models were developed to adjust an existing alignment or to generate a new one in case it does not exist yet. Practitioners have the luxurious ability to select the approach and the concept that corresponds the most to the case they are examining. For example, users may decide to modify one part or the alignment or the entire alignment or even several chunks of the same alignment to balance between the environmental, financial, and social costs. In case of a new alignment, they may have to select to approach the problem balancing between the earthwork cost and the emissions or focusing only on the environmental cost. In addition, they can choose to work with one or several test vehicles, considering the composition of their fleet and the trend in traffic within the studied region. The methods can be replicated using freely available tools online, at relatively low computation cost, as the underlining techniques were carefully studied to meet such requirements. They are very well documented in the papers III, IV & V, where detailed procedures are also provided. The methods are flexibles, which is among the most researched quality in decision-making tools, as it allows for picking among several alternatives. The user has the freedom to modify the parameters of the models and adapt them to his/her conditions to end up with case-related conclusions regarding alignment performances.

The LCA models were developed to fairly compare the performance of the so-called best alignment for three HDV powertrains (including one fossil, one full electric and one fully driven by hydrogen). The development of these three models is by itself a great achievement, knowing that access to industry data for such applications is often not possible. Clear models for sizing the equipment and components of the studied powertrains are provided in the appendices of this thesis. The sized components helped to put in place full cradle-to-grave manufacturing inventories, making use of information found in existing databases. It is possible to adapt the models – following the same approach as detailed in paper V – using other bills of the materials (BOMs). The powertrain will need to be designed using the provided archetypes, while other component data will simply need to be adjusted accordingly. The full LCA models took into consideration the expected vehicle autonomy, the energy type, the driving cycle, the corresponding battery size, size of the hydrogen tanks and the related fuel cells, and many others.

All the above models were of great importance for completing this research project. They contributed to address the following gaps:

- Integrating the environmental dimension in vertical alignment optimization models
- Developing process based LCI for conducting LCA of heavy-duty vehicles other than busses

These research gaps are filled in a very consistent way, in this thesis.

7.1.2 Alignments assessment metrics

Several metrics were developed to assist in the evaluation of the vertical alignments. The idea was to allow a sort of ranking of the alternative solutions in a quantitative way. Some metrics were related only to the use phase, while others encompassed a life cycle perspective of the studied system. The vehicles (i.e. the HDVs) and the energy type constituted the main items in the life cycle thinking approach. The developed metrics inform on how pollution-inducing an alignment is, how energy demanding it is and how constraining it may be for a specific HDV. Comparison of alignments among them taking indicators normalized on distance and adjustment of a profile for specific performance target (i.e. proscriptive approach), are also among the functions of the developed metrics. It must be stated here that in general, the use of metrics depends on its applications. However, same metric can be used in more than one application if well thought and if consistency is not questioned. Development of these needles contributed to bridging the lack of techniques and dials to assess the vertical alignment.

7.2 Recommendation for road authorities

In the light of all that is developed in this research work, the following pieces of advice are directed to policymakers:

- Every project being unique, it is necessary to do a preliminary environmental screening of the entire work, to identify critical cost items and the related key components. The focus may be on those items, as found in this research work, which exert a considerable influence in the overall weight of the project (the user category and the environmental and socioeconomic one).
- Orientate the design so to include the environmental dimensions (namely emissions) already at earlier stages of the project
- Optimize the alignment for the most influencing factors and generate as many alternatives as possible among which to chose
- Apply the Life Cycle Thinking approach as it is found to be the most appropriate way to conduct analysis of vertical alignment performances if it is meant to enhance the environmental sustainability.
- Include as many indicators as possible and consider the entire life cycle of the vehicles and fuels as this revealed that use phase considerations may be misleading. Environmental performances of vertical alignments and their optimization will give more insights if seen from a life cycle perspective with clear and well define goals, scope, and time horizon.
- Include external environmental costs when balancing for financial means to choose among options
- Use expert (field-related) knowledge to choose the most suitable alternative – environmental wise – to be taken further in the decision-making process.

The tools and methods developed in this thesis will assist in conducting informed decision processes. They can be combined with other expert tools to complete the project appraisal from other standpoints.

7.3 Future research needs

At this stage of the end of this research project, it was surprising to observe that a lot more remains to do in this field. Several directions will need deeper investigations, including model perfecting, industry data availability, appropriate end-of-life managements, carbon capture and storage integration and light materials in vehicle design.

First, new sophisticated models need to be developed and will need to include a lot more features for getting much closer to the real life. The nature and type of the road pavement, the existence of side-slopes, the interchanges, the bridges, the lane width, the effects of super elevation, the effect of the horizontal alignment, a representative driving profile, and many more emission factors reflecting on the real situation. These steps will need to be carried out smartly and not all at once. Most efforts must be put on developing the models since the computation power available nowadays is more than enough to cover the needs. Clean vehicle hybridization level will also need to be accounted, especially if prospective analysis is considered.

Second, there is a necessity for developing more truck LCA to overcome the permanent lack of such studies in the literature. This supposes that policy is reinforced to allow availability of industrial data for qualified experts when needed. Clear protection measures will need to be put in place to prevent fraudulent practices from between industrial actors. Transparency must be prioritized, and clarity needs to be accentuated. Evaluation of road infrastructure must include several life cycles (pavement, vehicles, fuels, machinery in earthwork stages, etc.), to get much deeper insight and clearer picture of the whole system. Assessment methods also will need to be discussed to come up with acceptable framework to support such applications.

Third, it appears essential to associate the convenient end-of-life management in the analysis. For a country or a municipality or a region where recycling, reuse or remanufacturing are not practiced, they must not choose to include such End-of-Life (EoL) in its analysis, or if included, it should be specified where such services are available and in which way those services are provided to them. The LCA will include end of life analysis even though such management does not apply to the location it is conducted for. But it will need to perform a lot of scenarios and identify possible providers of such services in the regions and adapt the analysis including all the environmental burdens related to the purchase of such services. In that way, the evaluation of the performances of the alignment of linear infrastructures will be very representative and useful. Therefore, many end-of-life managements of new and clean technologies need to be researched in the future.

Fourth, the production of certain careers or fuels follows several paths and a variety of raw materials are used to fulfill that goal. Getting cleaner fuels out of unclean products rises several questions when it comes to how green those obtained products are. Transiting to greener economy will necessitate some more time and the combined use of both fossil and non-fossil sources will remain evident. However, it will be encouraging to implement decarbonization techniques in the existing carbonized systems. Implementation of negative emissions technologies and techniques such CCS or direct air capture (DAC) will contribute to positive effects in the carbon budget within societies. Fossil-based hydrogen production makes a good candidate for implementing CCS at the tail edge of the production pipe. Research is needed to push the boundary towards that direction.

Finally, lighter vehicles will certainly have some implications in their entire life cycle environmental profile. Questions are more open about the material types, their related processing techniques, and the appropriate assembling methods. Will the material be abundant and harmless to the environment? Will their processing and assembling be energy intensive or not? Will it be possible for future generation to have access to same materials given the economic growth, urbanization trend and population increase? More research is needed to examine these questions in several perspectives.

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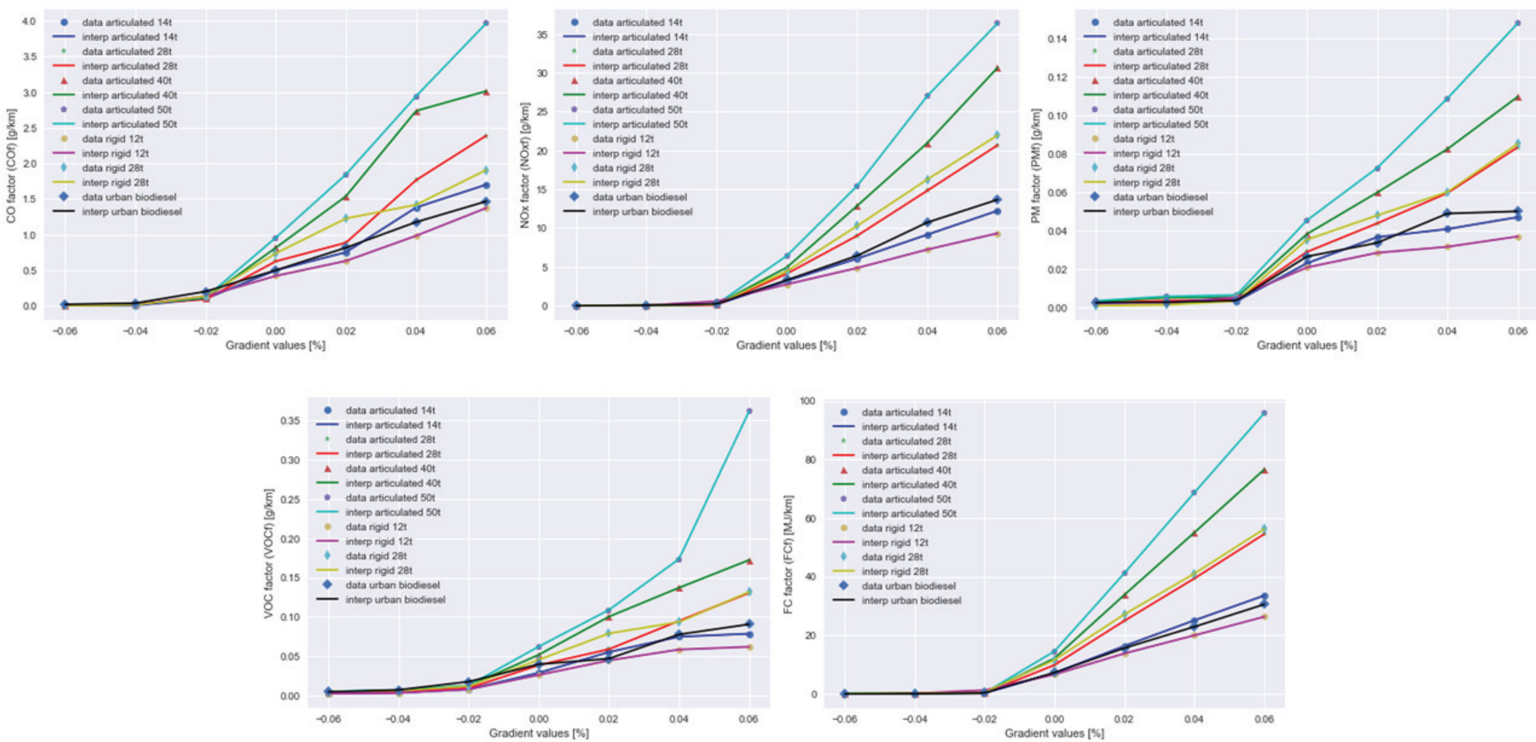
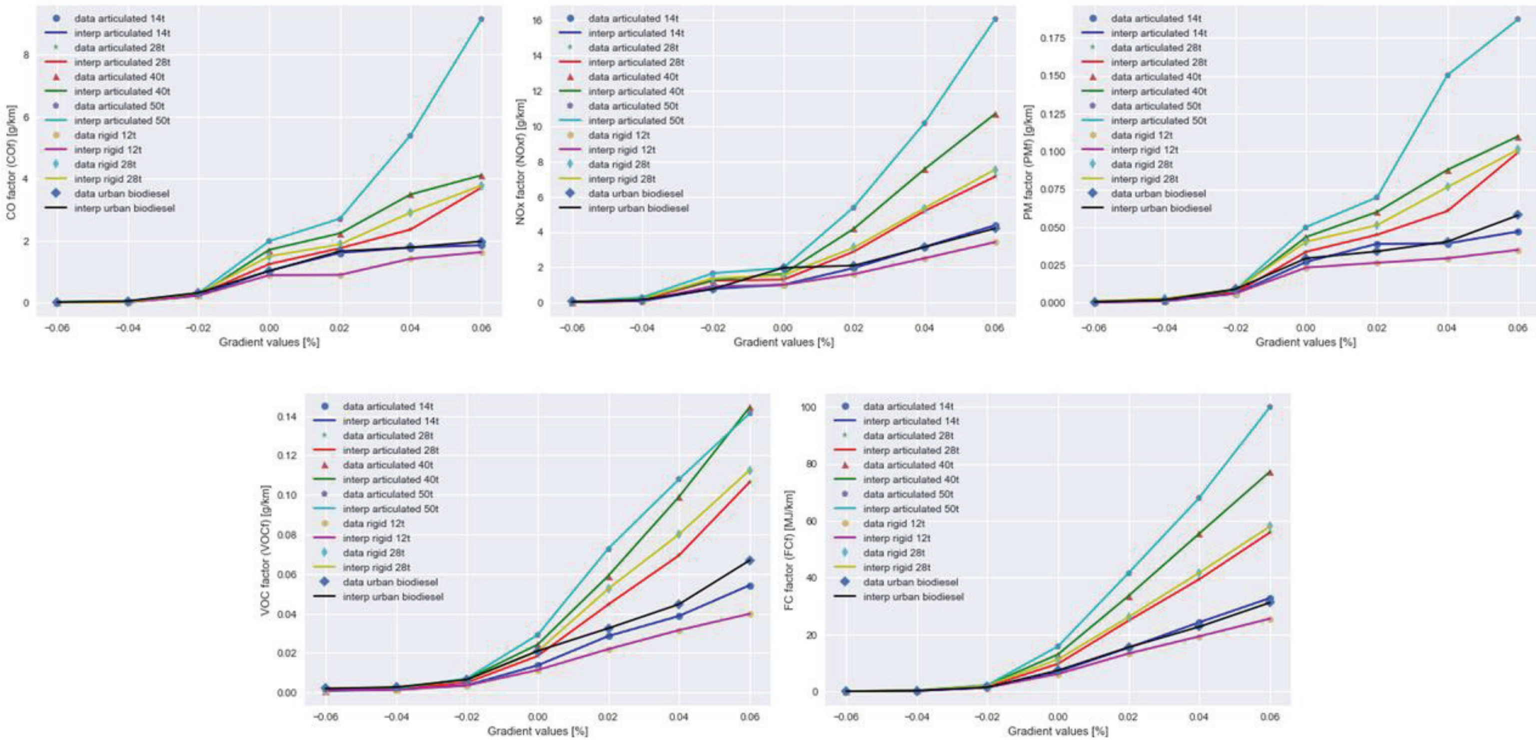
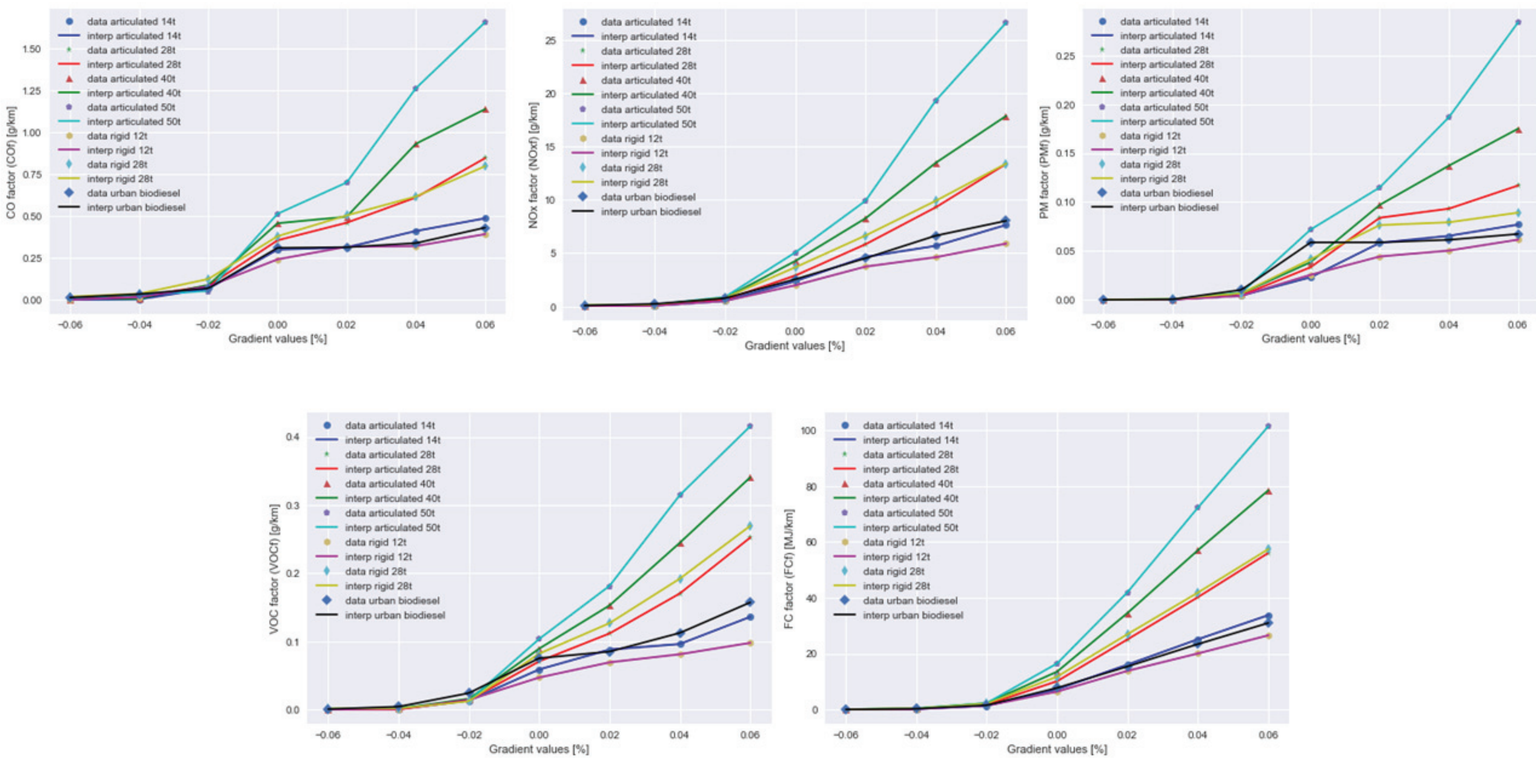
Appendices



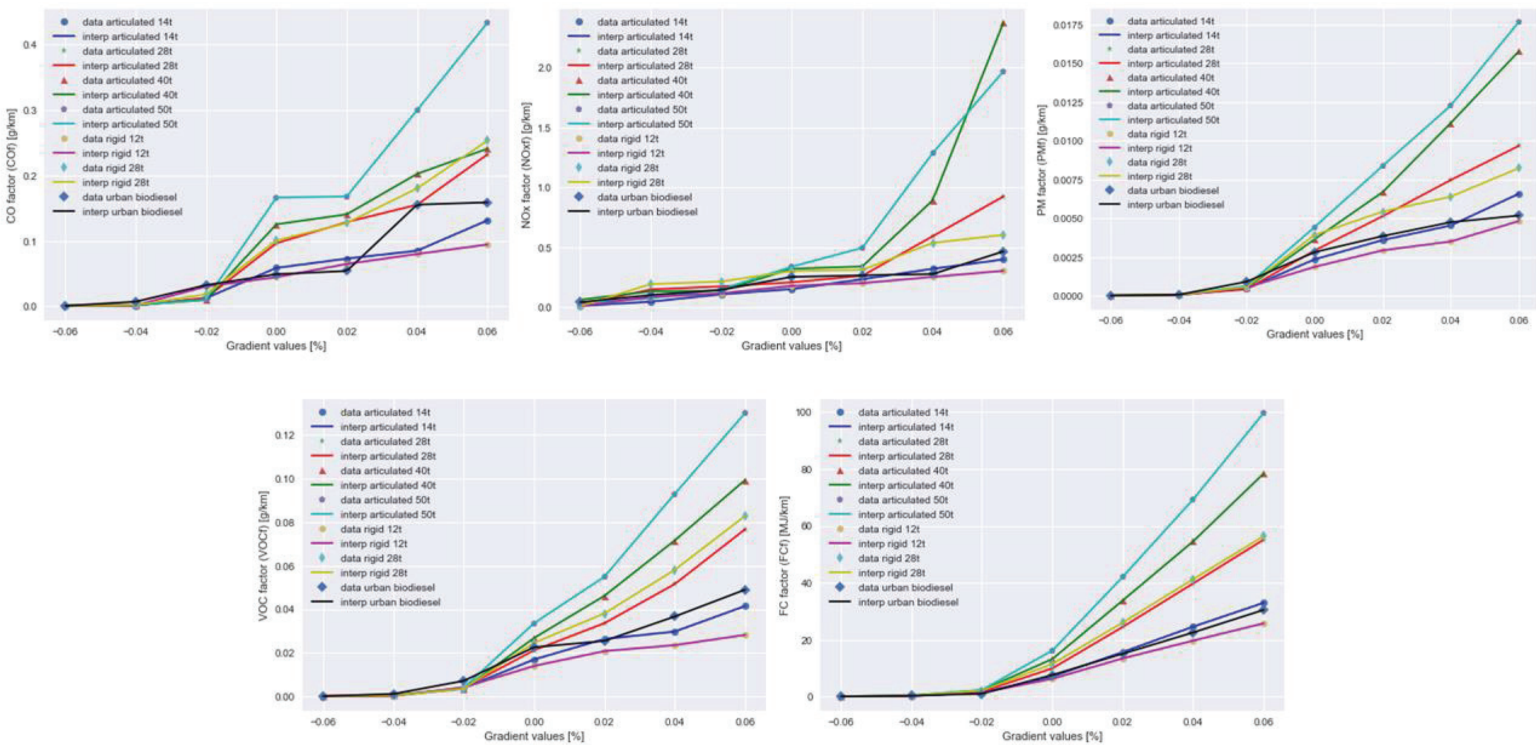
Appendix 1. Emission and fuel consumption factors for technology standard Euro IV (SCR &EGR are same).



Appendix 2. Emission and fuel consumption factors for technology standard Euro V-SCR.



Appendix 3. Emission and fuel consumption factors for technology standard Euro V-EGR.



Appendix 4. Emission and fuel consumption factors for technology standard Euro VI.

Design of Heavy-duty powertrains: methodological approach

Design of the studied vehicles

The performances of road vertical alignments analyzed in this study are captured indirectly by examining the behavior of the vehicles operating on those platforms. These behaviors (i.e. vehicles' environmental performances) are studied for the entire life cycle of the considered vehicles to get a holistic view of both their impacts and related magnitudes. To achieve a required level of consistency when assessing several alignment alternatives while considering different vehicle technologies and powertrain configurations, it is indispensable that the vehicles have same technical characteristics and capabilities. Hence, for the purpose of this work, three heavy-duty vehicles were designed including one conventional diesel truck (CT), one battery electric truck (BET, fully electric) and one hydrogen fuel cell electric truck (FCET, fully powered by hydrogen). This chapter unfold the steps retained for designing those vehicles. Version four (4) of the quasi static simulation toolbox (QSS_TB_2018 ver4) – a MATLAB-SIMULINK model for simulating vehicle design processes – was used to facilitate some steps in the vehicle design procedure. While this tool was fully employed in the design of the conventional truck (Figure 1), its use for the other two powertrains was limited to the vehicle model stage (Figure 2). The design of the clean heavy-duty trucks was performed programmatically in the MATLAB ecosystem.

1. Generic design parameters

1.1. Vehicles' characteristics

The vehicles designed for the purpose of this work belong to the category "heavy-duty trucks" and fit to the segment "rigid trucks" (Carpatorea, Nowaczyk, Rögnvaldsson, & Lodin, 2017; Park, Rakha, Farzaneh, Zietsman, & Lee, 2010). Some details on the characteristics of these designed vehicles are given in Table 1 below. The choice of this specific segment was dictated mainly by the

Table 1. Retained design requirements of the studied vehicles

#	Vehicle speed, Vveh [km/h]	Vehicle acceleration, aVeh [m/s2]	Gradient, G [%]	ta [s]	Description
I	5	1	10 %		*Accelerate at low speed uphill*
II	100	0	0 %		*Maintain constant speed flat road (high speed driving on a flat road)*
III	40	0	10 %		*Maintain constant speed uphill*
IV	40	0	-10 %		*Maintain constant speed downhil*
V	100	1,85	0 %	15	*Transcient acceleration on flat road, from stand still to higher speed*
VI	50	0,93	10 %	15	*Transcient acceleration on gradient, from stand still to moderate speed*

***ta**: acceleration time*

availability of necessary information (life cycle inventory – LCI) for conducting a scientifically sound environmental appraisal using the Life Cycle Assessment (LCA) method.

1.2 Forces acting on a vehicle during driving operations

A force is a push (or pull) applied upon an object when interacting with another body. A vehicle in motion is submitted to actions of certain forces. These forces, depending on the direction of their application will exert certain influences on specified parts of the vehicle. For example, forces acting in the longitudinal direction mainly impact the vehicle powertrain while pushes acting on other directions principally affect vehicle steering and suspension (MacKenzie & Walsh, 1990; Nakano, Okayama, Kinugawa, & Kosuge, 2014; Seneviratne et al., 2009; Vantsevich, Vysotski, & Doubovik, 2002). Two forces are always present during vehicle gesticulation, i.e., the ***rolling resistance*** and the ***aerodynamic resistance*** (Gobbi, Mastinu, & Giorgetta, 2005; Juhala, 2014; Lim et al., 2011; Petrushov, 1998). Figure 3 portrays a simplified illustration of forces acting on a vehicle.

The rolling resistance is a force resulting from the interaction between the tires of the vehicle, in motion, and the pavement of the road. Its magnitude is equal to zero, at standstill. At non-zero speed, the magnitude of the rolling resistance becomes different from zero and can be calculated as the product of the rolling resistance coefficient by the normal force between the vehicle and the road, as given in the formula below (Happian-Smith, 2001):

$$F_{Roll}(\propto) = \pm C_r \cdot m_{veh} \cdot g \cdot \cos(\alpha) \tag{1}$$

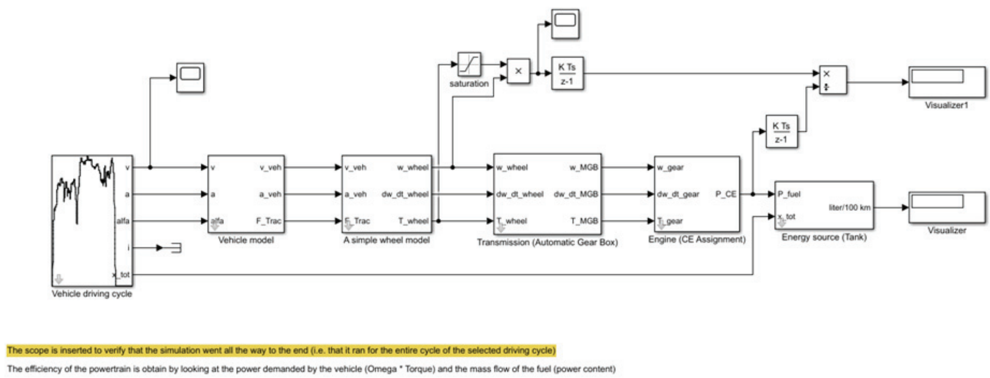


Figure 1. QSS model of the conventional truck (12 tons GVW)

This force is directly proportional to vehicle mass (m_{veh}), the rolling resistance coefficient (C_r) and the gravity (g). It is independent of the vehicle speed, variates slightly with the road angle (alpha), and is always opposed to the driving direction of the vehicle. It occurs at each tire but can also be represented by one unique component for the entire vehicle as shown in Figure 3. The coefficient C_r is very critical, as it influences the energy demand of the vehicle. Therefore, it should be kept as small as possible to maintain the energy consumption lower (typically in the range of 0.01) (Happian-Smith, 2001; Juhala, 2014).

The aerodynamic resistance starts appearing when the vehicle gains motion in a somehow faster fashion and is mainly caused by the air mass, as the latter is forced to flow around the vehicle while it is progressing (Guzzella & Amstutz, 2005). Such forces occur around the vehicle but can also be identified as one unique force component for the entire vehicle. The main reason for having aerodynamic forces is the variation in the air pression between the front and rear of the vehicle (high in the front, low behind) (Happian-Smith, 2001; Kim, Rideout, Papalambros, & Stein, 2003; Rho, Ku, Lee, Kee, & Kim, 2009). So, higher vehicle hustle will translate to more air needs to pass around the vehicle per unit time, leading to higher drag force.

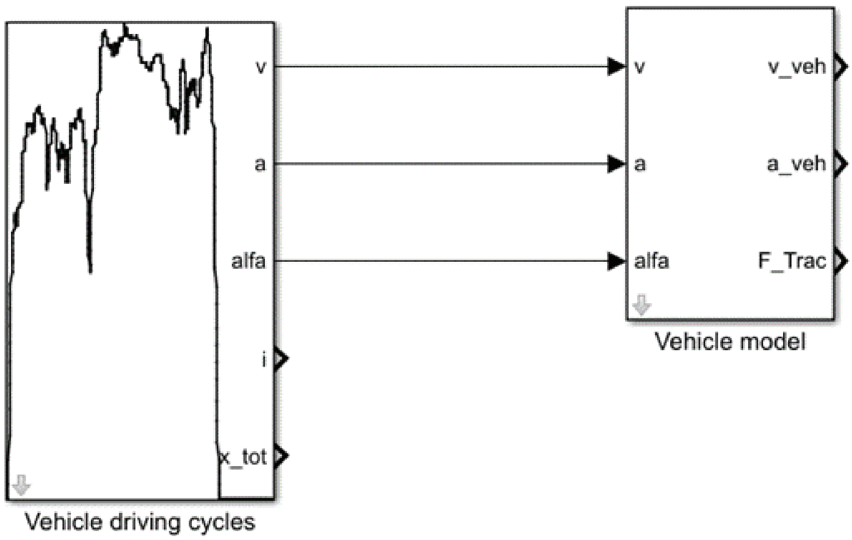


Figure 2. The two stage of QSS model used in the design of clean trucks (i.e. battery electric and fuel cell electric trucks, 12 tons GVW)

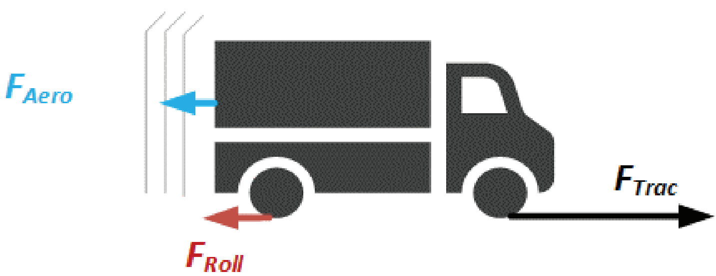


Figure 3. A simplified representation of vehicle forces.

At standstill, the aerodynamic resistance of the vehicle is equal to zero. At non-zero speed, this force can be calculated using the following expression:

$$F_{Aero}(v_{veh}) = c_d \cdot A_f \cdot \frac{\rho_{air} \cdot v_{veh}^2}{2} \quad (2)$$

The aerodynamic resistance is directly proportional to the vehicle's frontal area (A_f), the vehicle speed (V_{veh}), the air density (ρ_{air}) and the drag force (C_d). The aerodynamic force increases with squared vehicle speed, opposes the driving direction, and remains independent of the road angle (alpha) and vehicle mass. Best C_d values should be lower possible, in the range 0.25 – 0.35 for a typical car, and about 0.7 for busses and trucks (Juhala, 2014; Noguchi, Ando, & Kikuchi, 2015; Petrushov, 1998).

Looking at the above mathematical expressions, it is easy to deduce that rolling resistance and aerodynamic drag are two different forces driven by fairly different factors. While the first is not affected by the vehicle speed, the second increases with the square of the vehicle speed. Therefore, different speed levels will favor one force and not the other (the rolling resistance is bigger than aerodynamic drag at lower speeds while the aerodynamic drag becomes bigger). The sum of the above two forces is termed ***running resistance*** and can be calculated using the following expression (Happian-Smith, 2001):

$$F_{run} = F_{Aero} + F_{Roll} \tag{3}$$

By analyzing forces acting on a vehicle during driving operations, it is possible to determine the amount of force a powertrain needs to produce in order to efficiently tract the vehicle. This force is termed ***traction force*** and is very useful to estimate the magnitude of the acceleration of the vehicle, using the second law of Newton. The traction force is produced by the powertrain and is applied to the vehicle. It can be positive in sense (i.e. acting in the driving direction) or negative (i.e. the opposed to the driving direction) or even equal to zero. The traction force is scattered on all driven wheels of the vehicle but can also be illustrated as one unique component as shown in Figure 3. Balancing all the above three forces results in the ***Net force*** (Happian-Smith, 2001).

$$F_{Net} = F_{Trac} - F_{Aero} - F_{Roll} \tag{4}$$

Applying Newton's second law to the expression of the Net force:

$$F_{Net} = m_{veh} \cdot a \tag{5}$$

$$a = {}^{F_{Net}}/_{m_{veh}} \tag{6}$$

$$F_{Trac} = F_{Roll} + F_{Aero} + m_{veh} \cdot a \tag{7}$$

From the equation (7) above, it appears clearly that the vehicle speed can be controlled only indirectly by maneuvering the traction force, action which thereby influences the vehicle acceleration. So, to obtain the desired vehicle acceleration one needs to control the traction force produced by the vehicle's powertrain.

A net force of zero means the traction force equates the driving resistance (running resistance) which corresponds to a vehicle moving at constant speed, which is the hypothesis made in this study, when modelling environmental performances of the vertical alignment of linear infrastructures. Further details will be given in the chapter that follows. Positive traction forces imply acceleration of the vehicle, whereas negative traction forces lead to vehicle deceleration. So, the three vehicle operating modes (i.e. acceleration, deceleration, and constant speed) are dictated by the traction force.

When driving uphill or downhill, the mass of the vehicle will enable another type of force acting in the longitudinal direction of the vehicle. This force is called ***gradient force*** and can be estimated using equation (8) below:

$$F_{Grad}(\propto) = m_{veh} \cdot g \cdot \sin(\alpha) \tag{8}$$

The gradient angle alpha can be found by relating the segment elevation to the segment length as follow:

$$G = \frac{\Delta h}{\Delta d} = \tan(\propto) \tag{9}$$

The gradient force changes with the road angle but is not linked to the vehicle speed. On pronounced downhill gradient road segment, the vehicle can be driven only by the gradient force as the running resistance will then become negative and act to accelerate the vehicle.

Often, the angle alpha is approximated (as in this work) rather than calculated using the exact method (equation (9)). Using the approximation method to estimate the angle alpha returns values quite close to the exact method (Figure 4). For small values of alpha, the following expressions will hold

$$\sin(\propto) = \alpha = \tan(\alpha) = G \tag{10}$$

$$F_{Grad}(G) = m_{veh} \cdot g \cdot \sin(\alpha) \tag{11}$$

So, combining equations (10) and (11) yields

$$F_{Grad}(G) \approx m_{veh} \cdot g \cdot G \tag{12}$$

From equation (3.12) it appears clearly that the gradient force has the same size as the that of the force required to accelerate the vehicle (equation (3.13)), if $a_{veh} = g \times G$.

$$F_{Accel}(a_{veh}) \approx m_{veh} \cdot a_{veh} \tag{13}$$

Understanding the relation between the vehicle acceleration and the road gradient is essential in the procedure of designing a vehicle. A force from a -10% gradient is enough to accelerate the vehicle to 1 m/s^2 or vice versa, a force which can accelerate a vehicle to 1 m/s^2 suffices to climb a 10% gradient at constant speed. Road gradients exert an important influence on Heavy vehicles, especially when driving uphill or braking downhill. Therefore, it is important not to have very steep gradients when arranging road geometrical elements at early design stage. This is the main reason for having winding roads (zigzagging) in mountainous region, as it helps keeping gradient values at reasonable levels.

So, in sum, several forces act on the vehicle during its operation. Models to analyze those forces exist. Vehicle speed and acceleration are controlled indirectly by acting on the traction force developed by the powertrain. It is possible to calculate the required traction force of a vehicle under specific driving situations. Driving situations are described by the vehicle speed, the vehicle acceleration, and the road angle.

2 Powertrain and vehicle requirements

Vehicle powertrains can operate in different modes (Happian-Smith, 2001; Jiménez & Cabrera-Montiel, 2014):

- ***Traction mode***: when the vehicle engine or the electric motor is producing a force that propels the vehicle (i.e. the traction force is positive),
- ***Casting mode****:* when the engine is disconnected from the wheels using the clutch, or when the torque from the electric motor is equal to zero (i.e. the traction force is equal to zero), or
- ***Braking mode****:* when brakes are actioned or during engine braking or regenerative braking (i.e. traction force is negative).

It is possible for a vehicle to operate under all these three modes, but only when the road is flat, and the powertrain is in traction mode. This situation will vary at uphill and downhill grade.

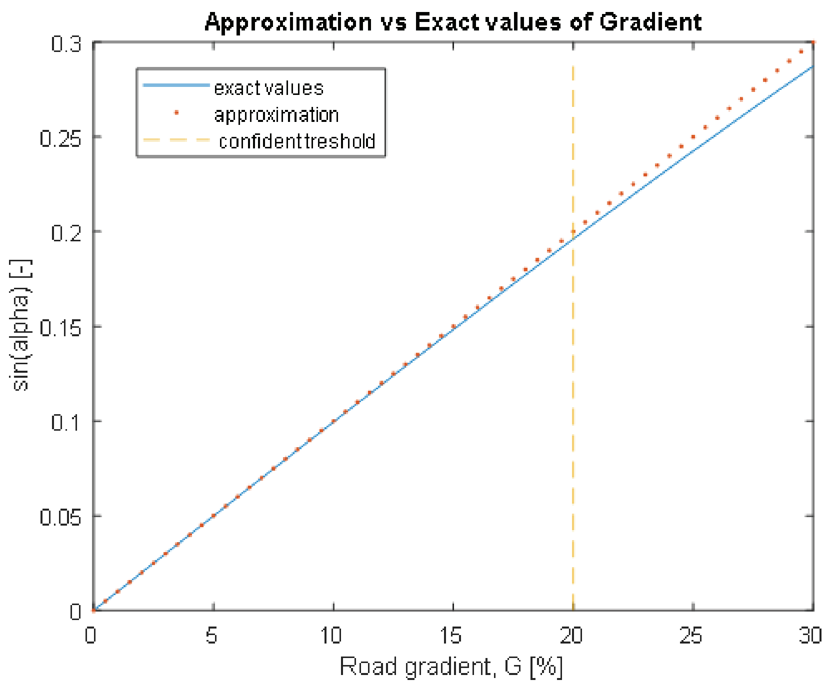


Figure 4. Comparison between approximated and exact values of gradient angle (alpha).

When designing a powertrain for a given vehicle, it is imperative to respect a certain number of requirements. These requirements will be the fundament based on which the design procedure will be unfolded. Vehicle requirements describe the entailed combination of the three main parameters, i.e., the vehicle speed, the vehicle acceleration, and the road angle. They can be translated into traction forces and speed requirements for the powertrain making use of the vehicle model. The vehicle is designed according to the desire of the client who will formulate some wishes in terms of technical capabilities, comfort, safety, security, and total cost. The manufacturer will them try to compromise between the prioritized wishes formulated by the buyer, the inhouse know-how and how-to, and the relevant cost for meeting the requirements.

There are some good reasons for compromising in vehicle design. In one hand, compromising will help avoid requirements which lead to high traction powers, on while on the other hand it will help evade high traction forces. Curving powertrain cost can be achieved in many ways, including for example accepting reduced acceleration at high speed, reduce grade ability at high speed, or tolerate lower acceleration on gradients than on flat road. Other powertrain requirements may include the followings (Happian-Smith, 2001):

- Maximum load
- Acceleration time 0 – 100 km/h
- Driving range (on a full tank or fully charged battery)
- Acceleration response time (needs to be short enough: 1 sec for ICE)
- Noise, vibrations
- Etc.

To summarize, the key requirements for vehicle powertrains are the top speed on a flat road, the driving ability on gradients (both uphill and downhill), the accelerations, and the possibility for long- or short-term regeneration.

3 Traction force and traction power analysis

The analysis of all forces detailed in the previous sections resulted in the so-called traction force. This force will always have its profile dictated by the selected driving cycle (Figure 5). By multiplying the traction force to the vehicle speed, the traction power can be estimated (equation (14)). From the traction power, it is possible to integrate and find the amount of energy that is required for traction and breaking during a given driving cycle (Guzzella & Amstutz, 2005; Jiménez & Cabrera-Montiel, 2014; Kim et al., 2003; Rizzoni, Guzzella, & Baumann, 1999). This quantity is very important for examining how energy demanding a particular driving cycle is. In addition, it can also serve to roughly investigate the amount of energy that can be saved by recuperative breaking on the considered driving cycle. This will also be useful when analyzing energy flows and losses in different parts of the powertrain.

$$P_{Trac}(t) = F_{Trac}(t) \cdot v_{veh}(t) \tag{14}$$

$$W_{Trac} = \int P_{Trac}(t)\, dt \tag{15}$$

The traction energy is obtained by integrating the traction power over the entire driving cycle (equation (15)). Special attention needs to be paid in the unit systems of the physical dimensions. If the result of the tractive energy is in Joules or watt-seconds, then it can be converted in watt-hours through division by 3600 and further in kWh dividing by 1000.

Considering the characteristics given in Table 1 and using the FTP75 highway driving cycle, the traction power of the designed vehicle was calculated. The obtained profile is displayed in Figure 6. The traction power curve portrays both positive and negative values. Negative and positive traction powers are handled differently by the powertrain (Hung, Tong, Lee, Ha, & Pao, 2007; Tzirakis, Pitsas, Zannikos, & Stournas, 2006). Therefore, it is necessary to calculate separated traction energy for each power mode, i.e. positive (Traction) and negative (Braking) (Figure 7). In coasting mode, the energy is always equal to zero.

While it is obvious to understand the origin of positive power values, sources of negative power values are usually not trivial to comprehend. Negative powers correspond to vehicle decelerations. Some of the reason for their occurrence include (Happian-Smith, 2001):

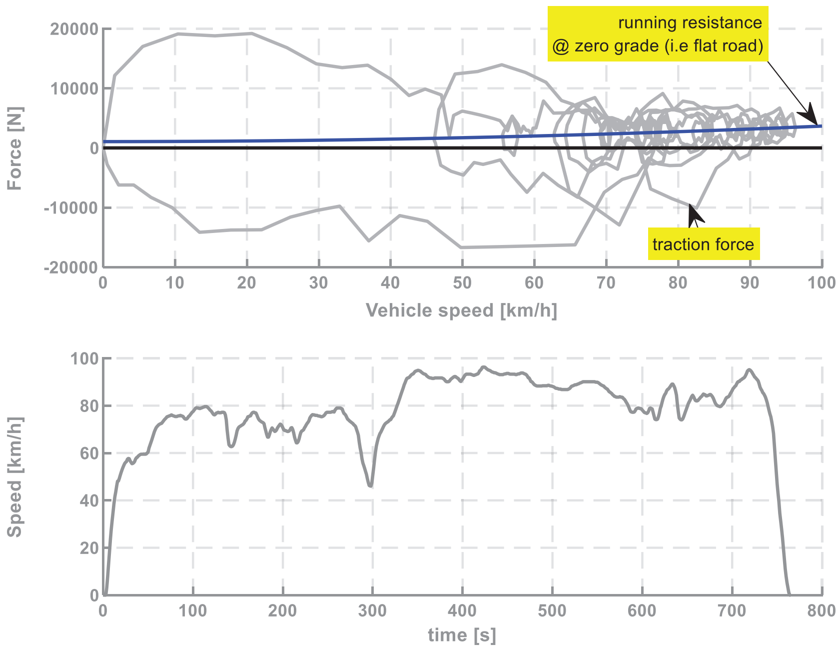


Figure 5. Traction force of the designed trucks.

- While decelerating, the kinetic energies which have been stored in the vehicle during accelerations is returned when the vehicle decelerates, or
- While driving downhill, the potential energy which was stored when driving uphill a gradient, is returned when the vehicle is driving down again.

Mode-related traction energy can be approximated using the following expressions:

$$P_{TracPos}(t) \quad = \quad \max\left(P_{Trac}(t), 0\right) \tag{16}$$

$$W_{TracPos} = \int P_{TracPos}(t)dt \tag{17}$$

$$P_{TracNeg}(t) = \min\left(P_{Trac}(t), 0\right) \tag{18}$$

$$W_{TracNeg} = \int P_{TracNeg}(t)dt \tag{19}$$

With the knowledge of these two energies (traction and breaking modes), it is possible to coarsely determine how energy consuming a specific driving cycle is.

It should be noted that vehicle operations imply energy losses from the powertrain during the entire process (Schechter, 2001). It is important to consider including those losses when designing a powertrain or during driving cycle investigation. In conventional powertrain (No energy recuperation is possible), losses often occur in the brakes. For the recuperating powertrain, they occur in the electric machine, storage system (batteries) and brakes. Generally, energy is lost in the powertrain when the braking energy is converted from mechanical to electric energy and stored in the battery (Happian-Smith, 2001; Schechter, 2001; Tzirakis et al., 2006). Another important share of losses befalls when that energy is later converted back to mechanical energy. Substantial amount of breaking energy may also be lost if the brake needs to be used in a few situations with high braking power. Huge potentials for energy recuperation exist in city driving, for related powertrains.

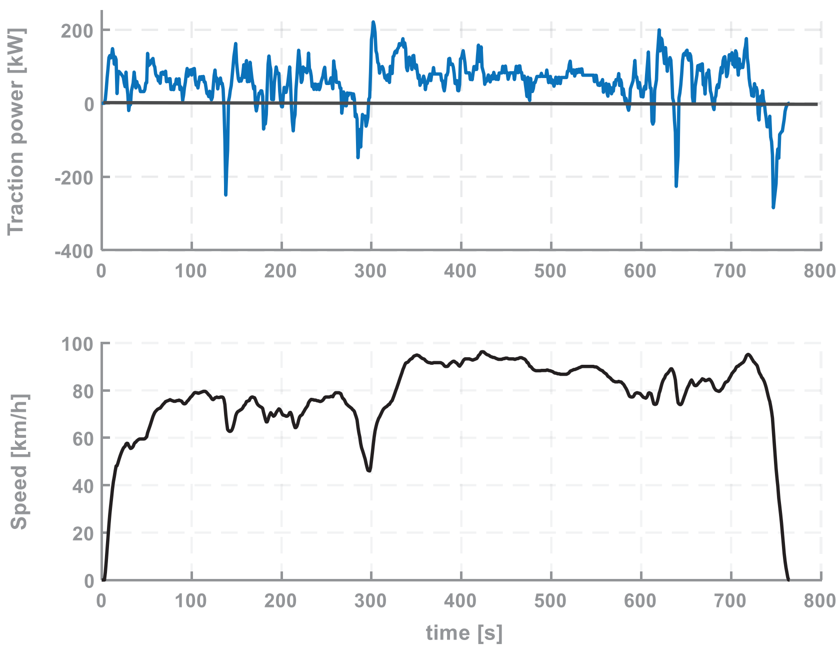


Figure 6. Traction power of the designed trucks.

City buses are probably the road vehicles which can recuperate larger amount of traction energy due to their very frequent acceleration and decelerations. Such opportunities are often very rare in highway driving since it involves more tractive activities and breaking ones, leaving room to only small amount of energy in braking mode compared to that in traction mode.

Combining all the information above and considering the vehicle requirements given in Table 1, it is possible to analyze and draw the power train operating points of the designed trucks using the FTP75 highway driving cycle. Figure 8 shows the operational limits of the trucks designed for the purpose of this study. All requirements are translated in a force-speed diagram, where all possible operating points can be easily seen. The maximum power of the engine is also given. The designed trucks will be able to achieve each requirement in Table 1 under the boundaries shown in the operational limits.

4 Modelling the electric drive systems as components in the powertrain

4.1 Electric motor and related components

An electric drive system comprises the electric machine and its power electronic inverter. A central DC bus (also called High voltage bus) is employed for exchanging power between the various electric components. The flows of the power are controlled by the converters. Four main power converters can be distinguished:

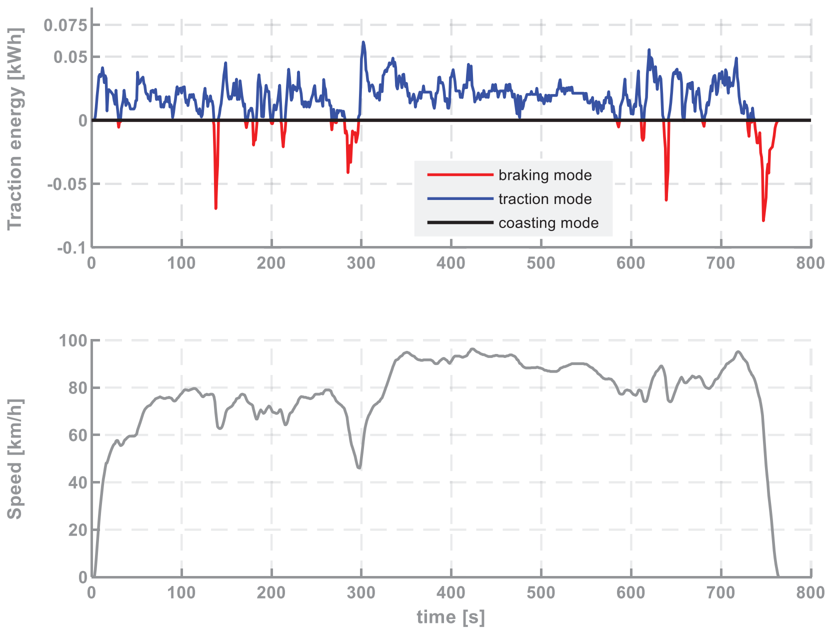


Figure 7. Mode-related traction energy of the designed trucks.

- **The motor drive**: *is a DC (direct current) to AC (alternating current) inverter used to control and operate an AC motor. It is bidirectional and feeds power to the motor for propulsions and* *acts as an AC to DC rectifier by drawing power from the motor during regenerative braking. In cases where the motor is a DC one (Brushless e.g.), the motor drive can be a DC to DC converter.*

- **The traction battery converter**: *controls the charging or discharging of the traction batteries by either drawing or feeding power from the High voltage bus. Hence this is a bidirectional DC to DC converter*.
- **The auxiliary battery converter**: *used to charge the auxiliary battery by drawing power from the High voltage DC bus*.
- **The on-board charger**: *is responsible for converting the AC power from the grid to the central DC bus for the charging of traction batteries. Hence it is an AC to DC power converter.*

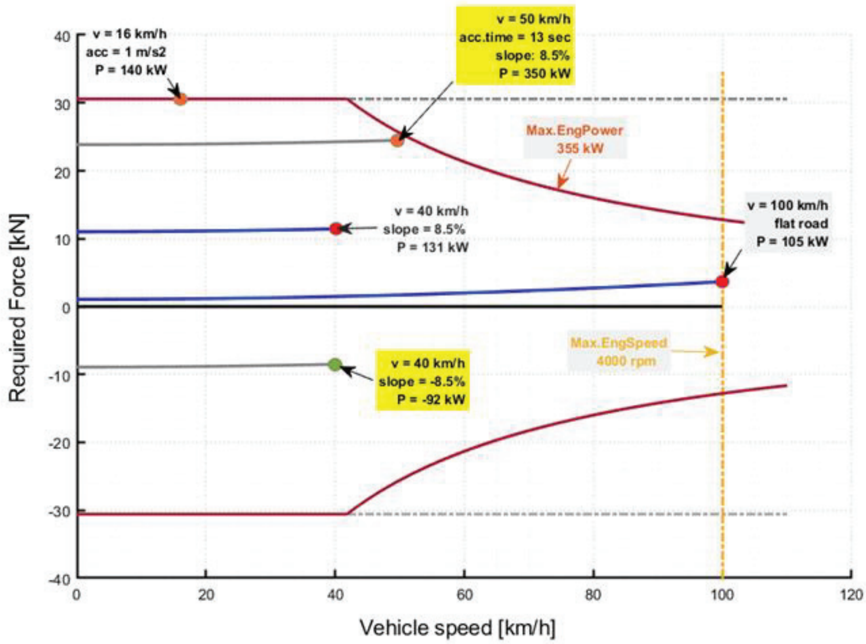


Figure 8. Operating points of the designed trucks.

Three main variables are to consider when modelling an electric drivetrain: the ***shaft torque*** of the electric drive, the ***shaft speed*** and the ***electric power*** (Ahmed & Ramadan, 2020; Bachinger, Stolz, & Horn, 2015; Franca, 2018; Moreno, Economou, Bray, & Knowles, 2013). To control the speed and torque of an electric vehicle, it is essential to employ a motor drive which can control both current and voltage simultaneously (Bachinger et al., 2015). For AC motor, the motor drive must, in addition, facilitate the control of frequency, phase, voltage and the current supplied to the motor resulting in the so called four-quadrant operation. The four-quadrant operation is a diagrammatic representation of the vehicle's motion capabilities translated in Torque and Speed. This diagram is very important since it indicates all the operating points that an electric vehicle can achieve in both transient (i.e. short times) and continuous operation. The following formalisms were used in the battery electric truck design procedure (Ahmed & Ramadan, 2020; Happian-Smith, 2001; Rizzoni et al., 1999):

Efficiencies:

Two types of efficiencies are were considered in this process: one in the motor mode and one in the generation mode. These two definitions are necessaries since the power flow changes direction when switching from one operating mode to another.

$$\eta_{Mot} = \frac{T_{EM} \cdot \omega_{EM}}{P_{DC}} \tag{20}$$

$$\eta_{Gen} = \frac{P_{DC}}{T_{EM} \cdot \omega_{EM}} \tag{21}$$

Power:

The electric motor's power is approached as follow:

$$P_{EM} = \omega_{EM} \cdot T_{EM} \tag{22}$$

The active power of the inverter is given by the following relation:

$$P_{Inv} = \frac{P_{EMmax}}{\eta_{EM}} = \frac{P_{EMmax}}{0.9} \tag{23}$$

The 0.9 represents the conservative order of efficiency for electric motors at peak power (90%). Using the active power, it is possible to estimate the size of the inverter, by calculating its nominal apparent power. Apparent power is the product of voltage and current. For alternating current, the apparent power is the active power P_{inv}, divided by the power factor cos(phi).

$$S_{Inv} = \frac{P_{Inv}}{\cos(\varphi)} \approx \frac{P_{Inv}}{0.8} \tag{24}$$

0.8 is the value of power factor for a typical ED motor at high power.

Assuming a relatively constant power factor and peak power machine efficiency, it can be deduced that the inverter's is proportional to the mechanical power of the electric machine.

$$S_{Inv} \approx 1.4 \cdot P_{EMmax} \tag{25}$$

So, it can be seen, from the above equations, that limiting the maximum power of the electric machine is not linked to saving its cost – machine cost depends mainly on maximum torque and maximum speed – but rather the inverter cost.

4.2 Battery

An electric vehicle battery (EVB) is a device used to store all energy needed to pulse the propulsion system of battery electric vehicle. Today, most of the electric vehicles are equipped with lithium ion and/or lithium polymer batteries, as they offer huge advantages for storing more energy per unit mass.

4.2.1 Components

The main components in the battery of an electric vehicle are the **anode**, **cathode** and the **separator**. The functioning principle of a lithium ion battery is simple and can be described, in few words, by the motion (flow) of lithium ion through in an electrolyte through a separator from the anode to the cathode, living a negative charge of electrode to the anode. The current is generated as the result of potential difference between the two extreme bounds.

4.2.2 Key properties of an electric vehicle's battery *(Dhameja, 2001; Young, Wang, & Strunz, 2013)*

Battery charge level or state of charge (SoC)

The battery state of charge is the measure of its level of charge relative to its capacity, expressed in percentage. The formula below was used to calculate the SoC at any given time point and sizing the battery for the designed battery electric truck, in this study.

$$SOC[-] = SOC_0 - \frac{1}{C}\int_0^t i dt \tag{26}$$

The actual battery SoC depends on the initial SoC_0, the battery capacity (C), and the current (i), at any time t.

Battery efficiency

$$\eta_{Battery}[-] = 1 - \frac{I_1^2\, R_1(SOC)}{(U_0(SOC) - R_1(SOC)I_1)I_1} \tag{27}$$

The efficiency of the battery is linked to the current (I), the resistor R, the SoC and the initial potential U_0.

It is to underline as the battery is used it will age and will lose its capabilities to store more energy (Young et al., 2013). Many factors contribute to accelerate battery aging. One such factor is exploitation at lower voltages. Defining better exploitation conditions will significantly increase battery life and prolongate its better performances. Batteries are to be exploited in strict respect of its usage limitations. Notions like depth of charge, depth of discharge, and/or charging/recharging cycles happen to be of great of importance for longer and prosperous exploitation of electric vehicle's batteries.

4.2.3 Battery sizing for range

Sizing a battery pack for use in an electric vehicle is not a simple task. This will depend on the requirements as translated from the formulated desires of the client, according to the use he or she is intending to make. Several sizing techniques exist, and each has its advantages and disadvantages. The battery electric truck designed for the purpose of the present work employed the energy optimal method for sizing the battery pack as follow (Eren & Gorgun, 2015; Joshi, Ezzat, Bucknor, & Verbrugge, 2011; Tara, Shahidinejad, Filizadeh, & Bibeau, 2010; YS, KT, & CC, 2006):

$$E[kWh] = \int_{ts}^{tf} P(t)dt \tag{28}$$

$$E_{batt}[kWh] = E_{cell}\eta_s\eta_p \tag{29}$$

η_s is the number of cells connected in series and η_p the number of cells connected in parallel. Cells connected in series create together a higher voltage potential for the battery pack.

The optimal energy to base the selected sizing approach is calculated by deducting the recuperated energy from the total traction energy for a considered driving cycle and for a given range (Figure 9). The retained vehicle driving range in this study was 300 km of road using the FTP75 highway driving cycle. The obtained battery operating range is shown in Figure 10.

One needs to grasp notions like capacity, state of charge, C-rate, and energy capacity to better comprehend the battery sizing process.

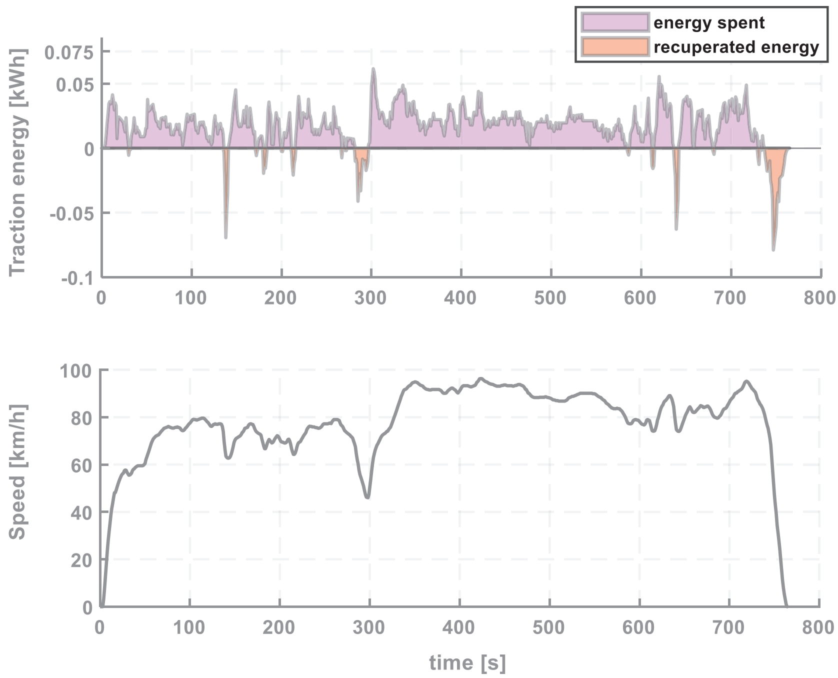


Figure 9. Profile of traction and recuperated energy of the designed trucks.

5 Modelling the hydrogen fuel cell propulsion

A fuel cell vehicle (FCV), also called fuel cell electric vehicle (FCEV) is an electric vehicle with the only difference that the electricity used to power the drivetrain is produced by a fuel cell, instead of a battery, or by a combination of a battery with supercapacitor. The fuel cell truck modelled in this study uses only fuel cell to produce its electricity, i.e., it is powered entirely only by hydrogen, as its fuel. Prerequisites for modelling fuel cell propulsion system may include the followings (Haraldsson, 2005; Moreno et al., 2013; Rizzoni et al., 1999; Schell et al., 2005):

Cell behavior

Cell behavior is characterized in terms of cell voltage and current density.

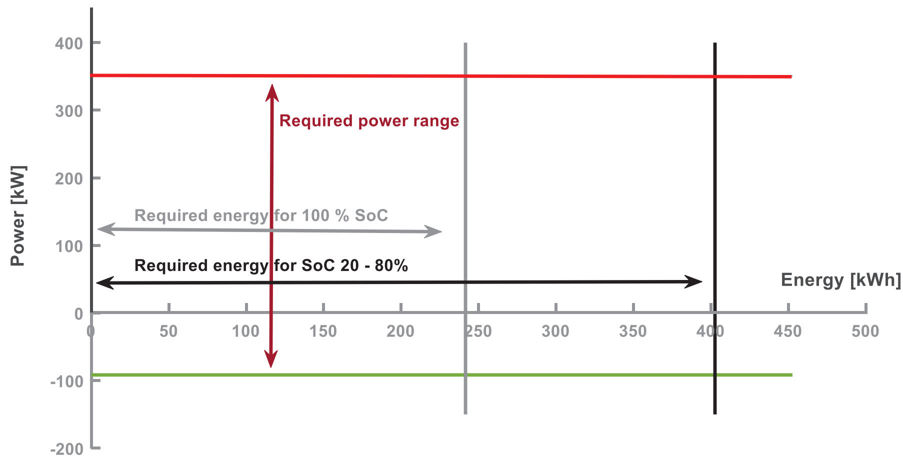


Figure 10. The operational range of the sized battery pack.

$$i_{fc}(t) = \frac{I_{fc}(t)}{A_{fc}} \tag{30}$$

Polarization curve

The expression for approximating the polarization curve in a linear fashion (i.e. affine approximation) is given below

$$U_{fc}(t) = U_{oc} - R_{fc} \cdot I_{fc}(t) \tag{31}$$

The above formula is a linear fitting of the polarization curve of a PEM fuel cell. Figure 11 shows the profile of the curve for N = 100 cells, active area Afc = 200 cm2, Thetafc = 60 C, pca,in = 2.0 bar, pan,in = 1.1 bar, lamba_a = 2.2, Urev = .95 V, Uoc = .82 V.

Stack voltage

The voltage of a fuel cell stack can be approached as follow:

$$U_{st}(t) = N \cdot U_{fc}(t) \tag{32}$$

Output power of a fuel cell stack

The power delivered by a fuel cell stack can be calculated as follow:

$$P_{st}(t) = I_{fc}(t) \cdot U_{fc}(t) \cdot N \tag{3.33}$$

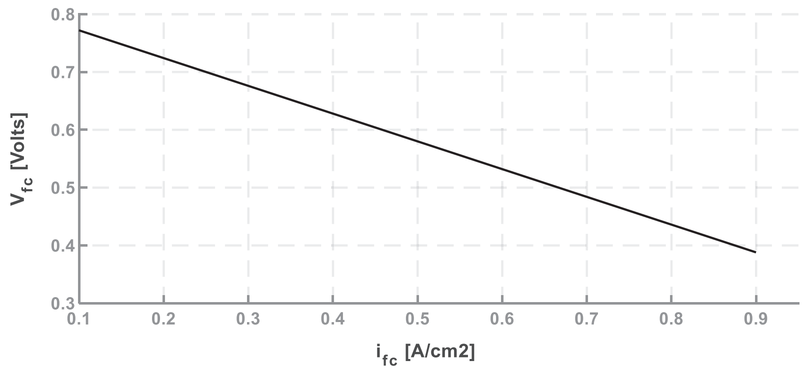


Figure 11. Polarization curve of a typical cell.

Power lost in the form of heat

The portion of power lost by a fuel cell system in form of heat is modelled by total current and the difference in potential through time.

$$P_l(t) = I_{fc}(t) \cdot (U_{id} - U_{fc}(t)) \tag{34}$$

Load power demand

The demanded power for the entire fuel cell system is given by the expression:

$$P_{fcs}(t) = P_{st}(t) - P_{aux}(t) \tag{35}$$

The auxiliary power represents the demanded power to cover uses other than the vehicle propulsion. It can be approached using the following formula.

$$P_{aux}(t) = P_0 + N \cdot \kappa_{aux} \cdot I_{fc}(t) \tag{36}$$

Hydrogen mass flow rate and fuel cell current (Ohira, 2004)

One of the main goals in designing a fuel cell drivetrain is to be able to accurately estimate the hydrogen consumption of the vehicle. To achieve that goal, it is necessary that one considers the flow rate of hydrogen within the system i.e. per demanded amount of current. Models used to estimate these measurements for the designed fuel cell truck are provided below (the mass flow rate is estimated both in the inlet and outlet):

$$\dot{m}_{h,r}(t) = \frac{N \cdot I_{fc}(t) \cdot M_h}{n_e \cdot F} \tag{37}$$

$$\dot{m}_{h,in}(t) = \lambda_h(t) \cdot \kappa_h \cdot I_{fc}(t) \tag{38}$$

The corresponding current is given by

$$I_{fc}(t) = \frac{N \cdot (U_{oc} - \kappa_{aux}) - \sqrt{N^2 \cdot (U_{oc} - \kappa_{aux})^2 - 4 \cdot N \cdot R_{fc} \cdot (P_{fcs}(t) + P_0)}}{2 \cdot N \cdot R_{fc}} \tag{39}$$

The amount of hydrogen consumed can then be estimated as follow:

$$\dot{m}_{h,c}(t) = N \cdot \frac{I_{fc}(t) \cdot M_h}{n_e \cdot F} = \kappa_h \cdot I_{fc}(t) \tag{40}$$

Fuel Cell System Efficiency

To estimate the efficiency of the entire fuel cell system, several measurements are considered, including the system power, the system current, the auxiliary power, the total cell number, and the system voltage.

$$\eta_V(I_{fc}) = \frac{U_{fc}(I_{fc})}{U_{rev}} \tag{41}$$

$$\eta_{st}(I_{fc}) = \frac{P_{fcs}(I_{fc})}{N \cdot U_{id} \cdot I_{fc}} \tag{42}$$

$$\eta_{st,tot}(I_{fc}) = \eta_{st}(I_{fc}) \cdot \frac{I_{fc}}{I_{th}} = \eta_{st}(I_{fc}) \cdot \eta_I \tag{43}$$

The final expression of the system efficiency is then given as:

$$\eta_{st}(I_{fc}) = \eta_{id} \cdot \frac{U_{oc}}{U_{rev}} \cdot \left(1 - \frac{R_{fc} \cdot I_{fc}}{U_{oc}} - \frac{P_0}{U_{oc} \cdot I_{fc} \cdot N} - \frac{\kappa_{aux}}{U_{oc}}\right) \tag{44}$$

Figure 3.12 shows the profile of the different powers and efficiencies of a fuel cell system as a function of the current, for some specified values (N = 250, U_{rev} = 1.23 V, U_{oc} = 0.82 V, A_{fc} = 200 cm2, R_{fc} = .0024 Ohms, Lambda_h = 1.1, P_0 = 100 kW, k_{aux} = 0.05 V.). Figure 2.13 represents the hydrogen consumption profile for the designed hydrogen fuel cell truck.

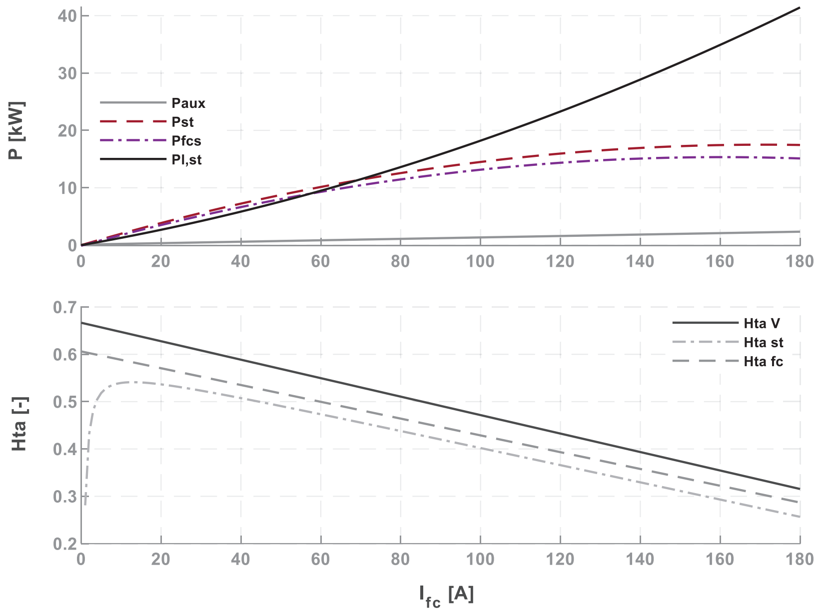


Figure 12. Power and efficiency profiles of a typical fuel cell system.

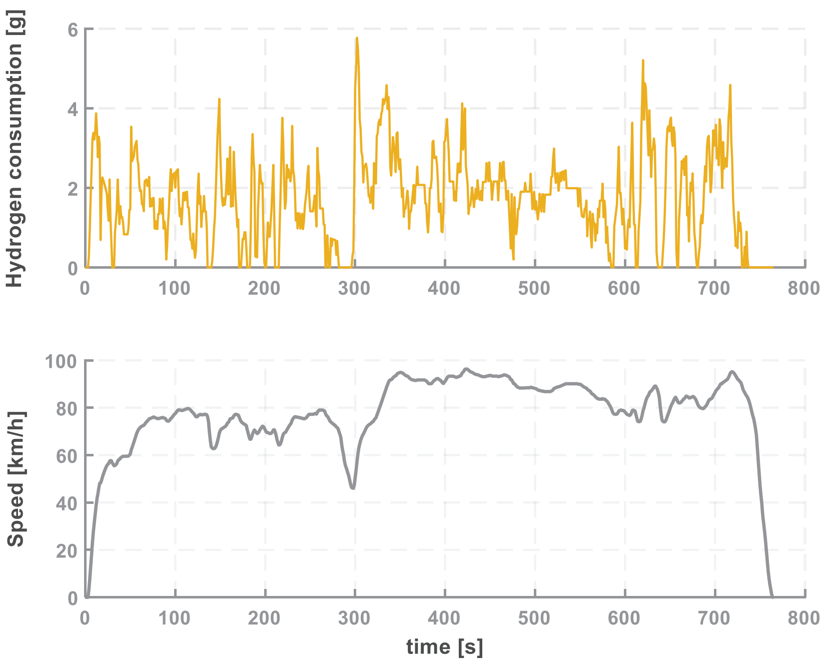


Figure 13. Hydrogen consumption of the designed fuel cell truck.

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Appended papers

Paper 1.

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Road Planning and Route Alignment Selection Criteria in the Norwegian Context

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Abstract. This paper reveals the main factors that guide road alignment design process in Norway. The goal is to discover what constitutes the main priorities for road planners, how these priorities are ranked when it comes to alignment selection, and how they are related to guiding factors identified in official planning documents and government transport plans throughout the life cycle of a road. This is done through a comprehensive literature and data search, involving published academic research in the road alignment design field, and by exploring Norwegian road planning documents and guidelines. Examples from a recently implemented road project are also included as a way to illustrate alignment priorities in theory versus how alignment decisions are made in practice. Particular attention is paid to how key factors influence environmental and social dimensions and how much importance these dimensions are given in the overall decision-making process. The focus on the Norwegian case is relevant in that it will identify which knowledge gaps need to be filled based on actual practices in the Norwegian road sector. The results of this study found that the dominating factors in road planning and alignment selection are the user cost and the environmental and socio-economic as they are directly related to the main national transport strategy of developing a carbon-neutral and resilient transport system. These results can be used to reinforce and amplify existing road planning strategies and to understand where challenges for environmental and social responsible road planning and alignment selection are found.

Keywords: alignment design, cost items, decision-making, environment, road planning, life cycle.

1. Introduction

The increase in highway traffic and the related safety concerns often prompt the need for new highway infrastructure or the expansion, if not the adjustment, of existing routes. This happens to be the case in Norway, a country where positive economic growth boosts industrial development and trade in almost all sectors of the economy nationwide, there is a prescient need for new and upgraded roads [1]. To help cope with the situation, the government has initiated several large projects and mobilized resources to adequately respond. As a logical consequence, the Norwegian highway network is currently undergoing massive upgrading – with an unprecedented investment from the government – aiming at expanding and modernizing the existing road network in order to meet the expected traffic demand while at the same time complying with current standards [2]. The two main road-planning agencies in Norway – namely the Norwegian Public Roads Administration (NPRA or SVV) and New Roads (Nye Veiger AS) – are tasked with planning, determining and designing new alignments, while construction firms have the responsibility follow designs and construct these planned roads accordingly.

In general, the determination of highway alignment is recognized to be not only a complex but also an intensively iterative process, involving multifarious decisions at multiple levels. The degrees of complexity increase even more when the alignment is to be planned within an area with extremely complicated topographical (i.e. mountainous terrain) and geological (difficult soil conditions) features, as is the case in Norway.

Several relevant factors need to be taken into account during alignment design process. Those factors include among others, the availability of suitable parcels of land, earthworks, maintenance activities, life cycle costs, expected traffic demand, land-use, user trip duration, environmental impacts, safety issues, direct influence on performance of other transportation modes, and collateral effects of the chosen project on regional development [3] . According to Jong and Schonfeld [4] and Jian-xin and Qing [5], these factors will largely influence both the total cost of the project during the implementation phase, and the operating cost of the infrastructure during its lifetime. Therefore it becomes necessary to not only consider those factors but also intelligently incorporate them at an early design stage in order to end up with a more preferable alignment to reduce economic and social costs, improve traffic safety and fluidity, avoid restricted zones, and protect the natural environment [6-8]. Effective alignment is thus critical for a proper operation of the infrastructure in both isolated conditions – taken individually – and within a network.

The present work proposes to identify the most influential factors that guide the process of determining road alignment in Norway. The main goal is to understand both the composition and structure of main cost components used to support the decision regarding how the road must be shaped, when it is to connect a defined point origin O, to another defined point destination, D, In that regard, the following points are investigated:

- main priorities for planners with respect to road alignment design in Norway
- factors that embody those priorities
- basis for prioritizing the related factors
- relationship between planners' priorities and factors that symbolize those priorities

2. Studies related to highway alignment design factors

Several studies deal with which factors to consider when designing highway alignment. However, only a select few can be easily identified, as the majority do not explicitly employ the terms "alignment design factors" in their titles. One possible way to identify such studies is to look for expressions such as "highway design models" or "highway alignment modelling", or "highway optimization", in the different databases or search engines. The reason for searching with the suggested key words is that factors are often incorporated into models – developed to assist highway planners and designers in evaluating a finite number of alignment alternatives between any two points – which in most cases appear to be a more suitable term to include in a research title. The term "cost" employed in those studies represents what is understood here as "factor".

The problem of formulating highway design models through a combination of factors and interests was tackled by researchers from two sides [9]. Earlier research focused on cost models aiming at estimating the total cost of alignment from a given set of information [10, 11], while later ones formulated optimization models which relied intensively on computational capabilities of new computers [12, 13].

Recent research concentrates more and more in developing sophisticated and complex models, as well as highly efficient algorithms to solve large-scale alignment design problems within a reasonable time period [14-16]. Several mathematical techniques are employed including calculus of variations [17-20], dynamic programming [21-23], mixed integer programming [24] and linear programming [25, 26].

Another approach makes use of genetic algorithms [3, 5, 27] as a search method, coupling of GA and GIS for simultaneous optimization of alignment with real terrain data [6, 7, 28], and neighbourhood search heuristic with mixed integer programming [29].

More innovative techniques are expected with the use of extension theory to solve contradiction between factors while optimizing highway alignment in a quite complex terrain like the permafrost as a very good example. It should be noted that future works will have to deal simultaneously with computational time, three-dimensional integration of factors of interests, realistic representation of complicated geometrical features, and other technical and engineering issues. The number of factors of interest is also expected to increase and this will need to be reflected in models.

3. Norwegian road sector

3.1. Main stakeholders

Road design and planning in Norway is primarily organized by two main governmental entities: The Norwegian Public Roads Administration (NPRA) and New Roads AS (Nye Veiger). These two entities coordinate communication between stakeholders and government; determine feasible routes, and tender contracts. The stakeholders in road building can be classified between government, planners, road builders and affected parties {table 1}. Each of the stakeholders in the road planning process gives input to how roads are planned and designed from the earliest phases to its completion.

Table 1. Stakeholders and their main roles

Actor	Role
National level NPRA	Determines which routes to focus on for the NTP and develops road construction standards for road builders to follow
National Transportation Plan (NTP)	Assigns main routes to develop, provides provisional budgets, and outlines main national transport goals
National government	Approves NTP routes and overall goals and gives funding to NRPA projects
NPRA Regional/Local offices	Develops local Planning, Municipal and Zoning programs and road designs used in bids
Municipal government	Approves the NPRA Regional plans and budgets for road construction
Contractors and road builders	Bid on the road projects from NPRA tenders and constructs roads
Locally affected parties	Local citizens who voice concerns and give feedback on the road planning process

As demonstrated in Table ***1***, stakeholders in Norwegian road sector are mostly public actors. The only private party is of the contractors and road builders. This group very important as they deal with the execution and completion of projects. There are many corporations in operation across the country, and their total capacity is more than enough to efficiently absorb any type of road projects nationwide. The most influential among them – based on turnover and workforce – are Veidekke (30,000 MNOK and 7400 emp.), Skanska (13,700 MNOK and 3800 emp.), NCC (8,800 MNOK and 2400 emp.) and Mesta (3608 MNOK and 1334 emp.). Although, this particular stakeholder group fluctuates a lot over the years with companies entering or leaving the industry. Corporations included in this group hold important shares of activities in several other construction sectors such as building, railroad, hydropower, etc.

3.2. Network and Traffic

The Norwegian road network comprises five different categories of roads, which are defined by the Norwegian Public Road Administration. This categorization takes into account a certain number of elements in their definition. Those elements include geographic location, type and size of traffic, degree of importance within the region. The category of the road determines its dimensions and, to a certain extent, fixes some design solutions and engineering requirements to be strictly followed during the design process (e.g. surface type, geometry, materials properties, maximum operating speeds, etc.) [30].

To date a total of 254 468 km of paved and graveled roads – all categories included – exist in Norway [31].These platforms provide service to some 5,335 076 vehicles of all types, registered nationwide, out of which about 100,000 (i.e. above 1.5% of total fleet) are fully electric [31]. Table ***2*** shows a distribution of road length [km] within each category and their equivalent share [in percentage]. From the table it reads clearly that private, forest, county and municipal roads constitute the dominant categories within the Norwegian road network.

Table 2. The Norwegian road network distribution [32]

Road category	Total length (km)	Share within the entire network (%)
European road	8 044	3.2
National road	5 075	2.0
County road	49 138	19.3
Municipality road	43 761	17.2
Private road	99 050	38.9
Forest/logging road	49 400	19.4

As the status of roads within the network changes quite quickly, numbers presented in Table ***2*** will vary from year over year. Every now and then, a slightly different distribution will arise, correcting for newly built road sections, as well maintained and/or redesigned roads. This will depend largely on traffic behavior, which constitutes the main reason for road maintenance, redesign or new construction. While detailed road traffic data in Norway presents a less clear pattern, its overall trend remains upward growth, with a relative traffic increase of approximately 1.3% each year, starting from the year 2005. Figure 1 depicts the evolution of road traffic in Norway from 2002 to 2016, for selected types of registered vehicles within the country.

Examining the road traffic situation as portrayed in Figure 1, it is clear that on average, for the majority of vehicle types, there is an overall upward trend. However, the remarkable reduction of related bus traffic is more pronounced and more noticeable than the average upsurge observed in the other four types. In any event, the total vehicle kilometers travelled by each category were slightly higher in 2016 compared to 2015. The registered overall increase (all motor vehicle) of about 2.2% in 2016 suggests that volume of road traffic in Norway will keep growing rather than shrink.

3.3. Planning process and responsibilities

Road planning in Norway strictly follows the Norwegian Law on Planning and Construction [33], in force since 1985 and last amended in July 2017. This must also be done in accordance with national strategies set forth in the quadrennial National Transport Plans (NTP) issued by the Norwegian Ministry of Transport. The planning is done in five steps as pictured in Figure 2.

The process is quite complex and involves several decision-makers including the Ministry of Transport and Communication (MTC), the NPRA, the regional road authorities, concerned government organizations (GO), land owners (LO), local and national governments (LG, NG), and the local and national parliament (LP, NP). It should be noted that the NTP defines all national transportation strategies i.e. not only for the road sector but also, aviation, maritime and rail transport.

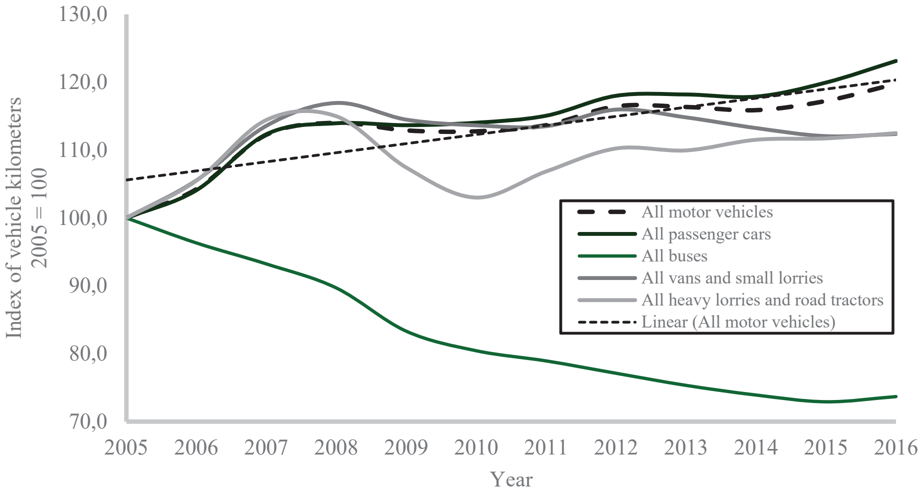

Figure 1. Vehicle kilometers travelled by selected vehicle types in Norway 2005 – *2016*

4. Materials and Method

Data used in this study were collected from two different sources. The one source dealt with published scientific research (i.e. scientific literature or scholarly data) collected from Scopus [35] and Elsevier [36] databases – through the Oria platform [37] – using specific key expressions in the abstract or title. The other source of data involved project reports for a selected highway project that was recently completed in Norway. The analysis conducted here was a qualitative type of analysis, and followed the steps detailed in Figure 3.

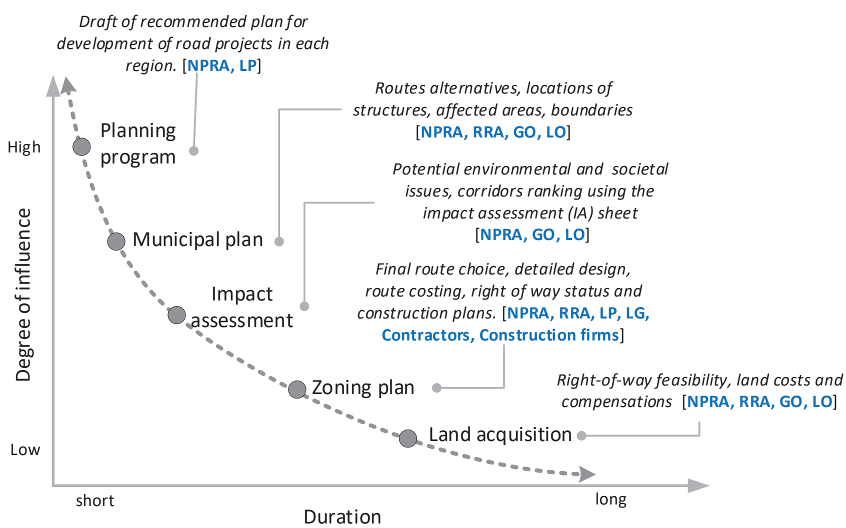

Figure 2. Planning steps, main goals and involved actors (Adapted from [33, 34])

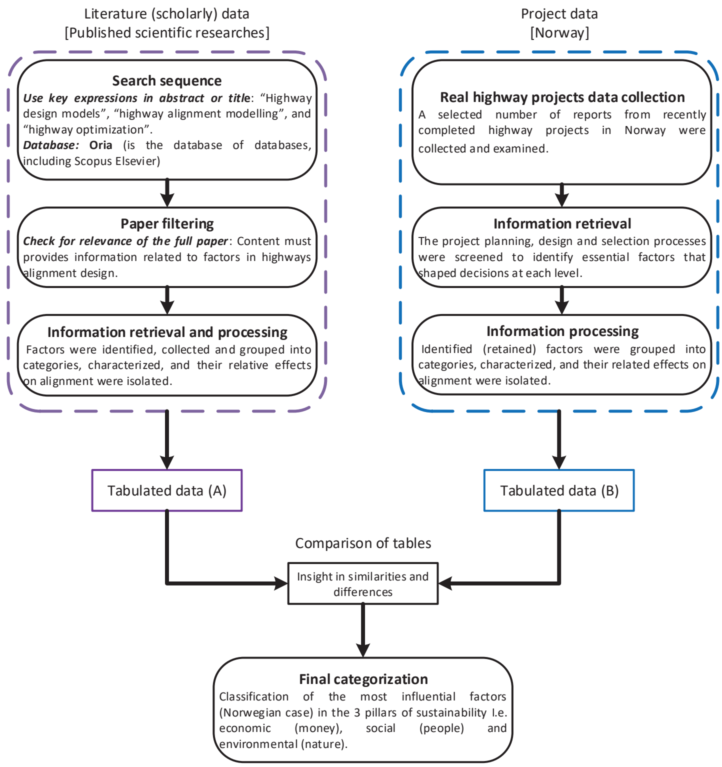

Figure 3. Diagrammatic summary of the study method

First, data from each source were processed and analysed separately before merging them together for comparison and final classification. For each stream, factors connected to alignment design were identified. They were then further compiled, matched and merged, to result in a generic table with the most common factors altering highway alignment's shape. Following, factors' behaviour were examined through simple cause-effect relationship to derive their influence on the overall shape of a given alignment during planning and design phase. Finally, based on the decision process that led to the choice of alignments from the project cases, the most influential factors under the Norwegian case were identified, ranked and classified into economic, social and/or environmental pillars, for final characterization, as was the goal of the work

5. Findings

The outcomes of this study are summarized in tables 3 – 5 as follows: Table 3 shows the common factors used in alignment optimization, their characteristics, as well as the items representing those factors. dominating costs

Table *4* informs on possible effects that factors (or cost items) will have on the alignment when forcing them towards their desired extremums. Table 5 exhibits the practice in use in Norway, displaying the factors of most interests, the pillar(s) in which they belong, the metrics used to capture their behaviour, the type of analysis going with those metrics, and the order of significance of those factors.

Table 3. Most usual factors (costs items) for consideration in highway alignment optimization

Category	Included cost items (not exhaustive)	Characterization
Preliminary engineering, administrative, planning and design	Preliminary survey, consulting, supervision, contractor selection, etc.	-
Construction	Earthwork and subgrade formation, site preparation	(a), (c), D, A

		pavement, super and substructures right-of-way structures, miscellaneous, etc.	(b), A (c), (a), D, A (d), D, A -
Maintenance and operation		Reparation, reinforcement, and rehabilitation	(b), (a),
User	vehicle operation	Direct and indirect consumables (including fuels, tires, spare parts, etc.), vehicle depreciation	(b), (c), D, A
	Travel time	Vehicle hours (daily exploitation time duration)	(b), (c), D, A
	accidents	Accident rate, accident occurrence and their related weights	(b), (c), D, A
Environmental and socio-economic		Environmentally sensitive area, historical and cultural patrimonies, Land use changes (LUC), Air and noise pollutions	(c), A (c), A (b), (c), A

Where (a): volume-dependent costs, (b): length-dependent costs, (c): location-dependent costs, (d): structure costs, A: alignment-sensitive costs, D: dominating costs

Table 4. Effects of related cost items on optimized alignment

Item	Action(s) on the alignment
Preliminary survey, consulting, supervision, contractor selection, etc.	Fixed (constant) non-technical effect
Earthwork and subgrade formation, site preparation	Reduces deviation from initial terrain topography; favours introduction of structures (bridges, tunnels)
Pavement, super and substructures	Reduces alignment's length
right-of-way	Induces more circuitous alignment; favours introduction of intersections, overpassing, …
Structures,	Induces circuitous alignment; reduces alignment's length
Miscellaneous, etc.	-
Reparation, reinforcement, and rehabilitation	Reduces alignment's length ;
Direct and indirect consumables (including fuels, tires, spare parts, etc.), vehicle depreciation	Reduces alignment's length; reduces curves and irregularities (i.e. induces more direct and flat alignment)
Vehicle hours (daily exploitation time duration)	Straightening and flattening
Accident rate, accident occurrence and their related weights	Straightening and flattening
Environmentally sensitive areas and cultural heritage	More circuitous alignment (or high socio-environmental cost if violated)
Land use change	More circuitous alignment (or high socio-environmental cost if violated)
Air pollution and noise	Various actions depending on pollutant types, power trains and project phases.

Table 5. Breakdown of weight for the most influential factors for the Norwegian case. Data are from [38, 39]

Category	Included items	Dimension			Metrics/Analysis	Weight
		Eco.	Soc.	Env.		
Construction	Earthwork and subgrade formation, pavement, and structures			X	NO_x, CO_2 and Energy use / Life Cycle approach (LCa)	**< 10%**
Maintenance	Reparation, reinforcement	X		X	Price, NO_x, CO_2 and Energy use / CBA, LFA	**< 10%**
User	Traffic fuel, accidents, Duration, road tolls		X	X	Non-priced, NO_x, CO_2 and Energy use / CBA, LCa	**65 – 75%**

Environmental and socio-economic	Local landscape, green space, natural areas, resources, cultural heritage, noise		X	X	Non-priced / CBA	**15 – 25%**

6. Discussion

The findings from this study show that the Norwegian highway alignment planning and design process follows a systematic approach, which evaluates several feasible alignment alternatives based on governmental priorities. The decision-makers consider several key factors (Table 5), already at earlier stages, to capture those priorities and guide the process. The factors include both dominating and alignment sensitive ones (Table 3), whose overall weight is confronted to the total investment cost of the project. The findings show that key factors do have various effects on the shape of the alignment (dominating costs

Table *4*). The importance of each key factor is captured based on its relative impacts derived by mean of dedicated metrics (Table 5). Almost all the key factors (or their components or items) are two-dimensional i.e. of either socio-environmental or economic-environmental types.

The environmental impacts are derived through a life cycle approach using the EFFEKT tool [40], while for social and economic dimensions, a cost benefit analysis (CBA) serves as a basis. It is notable that results from the environmental impacts (i.e. life cycle energy use and emissions) are integrated as environmental costs into a cost benefit analysis [40].

Among the key factors, the user cost appears to be the most important one, representing about three fourths of total weight of all key factors. It is followed by the environmental and socio-economic costs, and by construction and maintenance costs following in importance. The very high importance of the user cost is mostly due to the energy demand and emissions of vehicles during exploitation phase of the infrastructure. In fact, this particular cost is considered as dominant in comparison with road construction, operation, maintenance and end-of-life, especially in dense traffic situation [6, 7, 10, 40, 41]. The relatively high weight of the environmental and socio-economic cost is due to its high social impact, which often constitutes a serious source of conflicts between authorities and local communities [4].

However, this distribution must be regularly revised since it may differ from time to time and terrain to terrain. First, it should be kept in mind that construction cost will be larger if many more complicated structures (tunnels, bridges, etc.) are involved, as they are often energy and material intensive components [40]. Second, development in vehicle technology (powertrain) will probably result in abatement of user cost. Lastly, less dense traffic and lower AADT introduce significant reduction in both energy demand and emissions of vehicle during exploitation, and therefore shift the impact loads to other costs such as construction and / or maintenance.

7. Conclusion

This study showed that planning and design of highway alignment in Norway, is influenced by some key factors that need to be included in the process already at earlier stages. The factors can help materialize decision-makers' priorities, handle both energy demand and emissions issues, with great potential for climate change mitigation and adaptation. This emphasizes on the possibility of developing sophisticated models for intelligent and environmentally optimized highway alignment design, based on those key factors. Such design will contribute to enable a faster transition towards a lower-carbon and carbon-neutral transport goal, fixed by national government.

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Paper 2.

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Paper 3.

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Reducing fuel consumption and emissions through optimization of the vertical alignment of a road: A case study of a heavy-duty truck on the Norwegian Highway Route E39

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Abstract

In this paper, a method to assess, optimize and modify the vertical alignment of a road is developed. The aim is to optimize the alignment with respect to fuel consumption and quantify the induced reduction in terms of both fuel consumption and emissions from vehicles' operation, already at early design. The idea consists in employing an averaged-speed-gradient model to a single heavy-duty vehicle (HDV), considering different operating speeds and engine loads. Three optimization models are proposed and can be used to induce different reduction levels – in fuel consumption or emissions – each corresponding to a given road vertical alignment profile, generated using nonlinear optimization techniques. Five performance indicators are estimated based on their gradient-speed dependency. The method is then applied to an existing highway alignment in Norway to compare the performance of generated alignments with that of the initial one. The results show significant reduction potentials for fuel consumption, CO2, and PM at operation stage obtained at the cost of intense modification of the initial alignment. Better performances occur at higher operating speeds. The study offers a clear understanding for the nature and magnitude of the influence exerted by some key variables, when a vertical alignment is adjusted to optimize fuel consumption and emissions of HDVs during their operation.

Keywords: Road transport, emission reduction, vertical alignment, optimization, fuel economy.

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1. Introduction

Transportation systems constitute an integral part of any society. They reveal a quite close relationship to humans' life style, influencing their way of leaving and supporting the organization and development processes within societies. In the same fashion, the transportation sector is also an important source of revenues, since its services generate incomes that sustain national economies (5% of GDP in Europe, (European Commission, 2016)). Nevertheless, transportation does also have downsides as it implies substantial use of resources (e.g. fossil fuels), accidents, noises, as well as release of significant amounts of pollutants in the atmosphere. Consequently, the transportation sector is continuously facing several waves of changes to ensure that it can provide more sustainable services to its users.

Road transport is probably the most used of all transport modes. This is partly because of its better proximity with its users, as it enables exchanges on a point-to-point fashion. However, this higher use of road transport makes it also one of the major contributors to greenhouse gas (GHG) emissions in the atmosphere. According to the European Environmental Agency (EEA), about 72% of total greenhouse gas emitted from the transport sector, in the European Union (EU), come from road transport activities (Figure 1). Moreover, CO_2 emissions from road heavy good transport (HGT) is expected to increase for the coming three decades, despite the considerable efforts in improving the efficiency of transport (Figure 2).

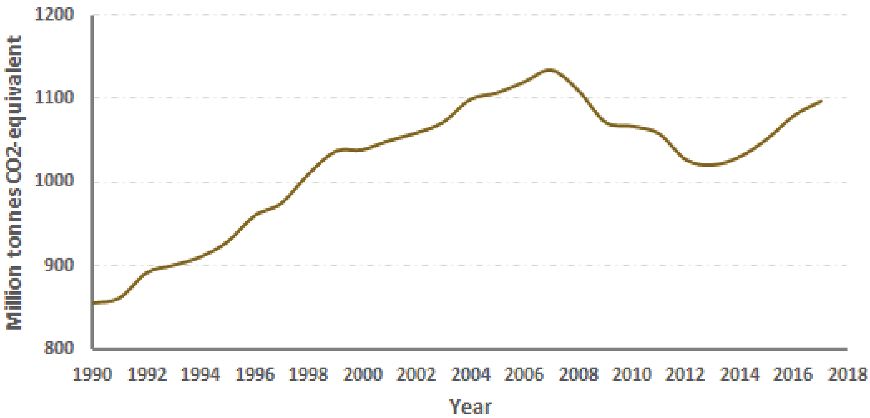

Figure 1: Evolution of greenhouse gas emissions from transport, EU (1990 - 2017). International aviation is included while international shipping is not.
Source: European Environment Agency, 2018

In the Norwegian context, similar overall trends can be observed. The contribution of road transport activities to the total GHG emitted from the transport sector in the country is estimated to about 60% and counts for up to 17% of the country's total GHG emissions (Figure 3). Overall, the emissions increased by 22% (end of year 2017) compared with 1990 levels. This increase occurred regardless of the relatively younger age of the Norwegian vehicle fleet, particularly those providing heavy transport services (Figure 4 and Figure 5). The increase is partly explained by the prevailing use of diesel in heavy transport, as the related fleet is largely dominated by vehicles weighting more than 12 tons (Figure 4, Figure 5 and Figure 6).

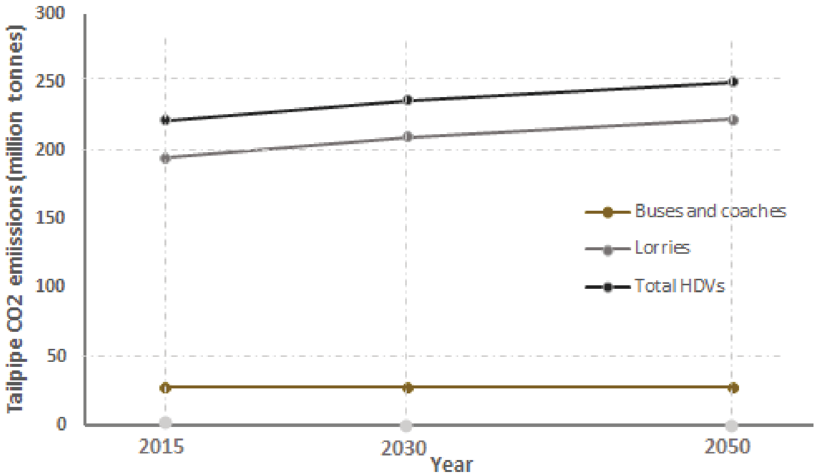

Figure 2: Heavy Duty Vehicles CO_2 emissions projections 2020 – 2050 (EU 28)
Source: PRIMES TREMOVE, 2016

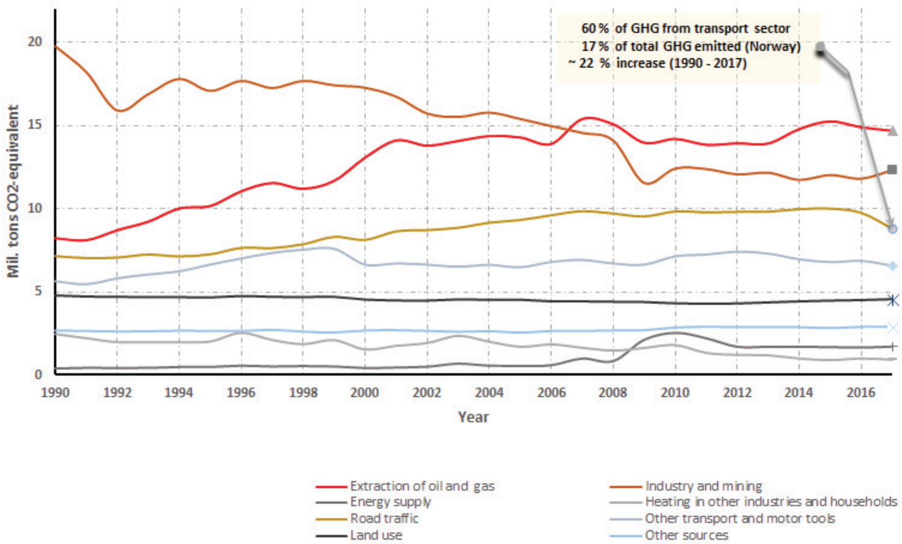

Figure 3: Norwegian greenhouse gas emissions per sector (1990 - 2017)
Source: Statistics Norway, 2018

Most emissions from road transport occur during the use phase, as a result of fuel combustion in the internal combustion engine (ICE) (O'Born et al., 2016). Many factors influence vehicles' energy demand and their resulting emissions during their operations. Wyatt et al. (2014b) found that the vehicle size and weight, the powertrain, the emissions control technology, road conditions and variabilities in longitudinal slope, were among the most influential ones. Other potential factors to be accounted include the driving pattern (accelerations, idling, speed), and weather conditions alongside a given road.

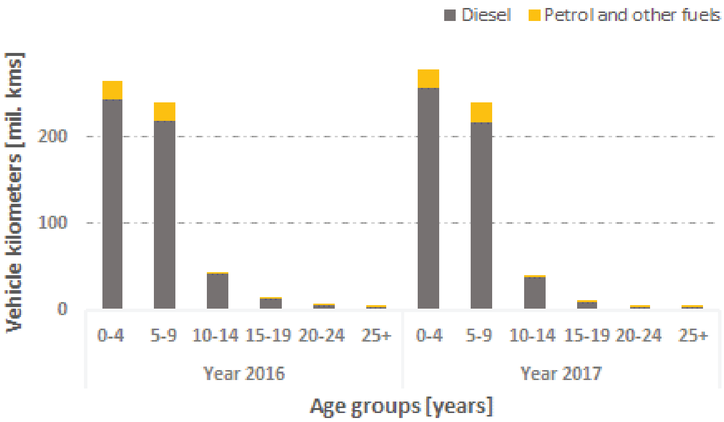

Figure 4: Traffic volume for all Norwegian busses per fuel type and vehicle age (2016, 2017)
Source: Statistics Norway, 2018.

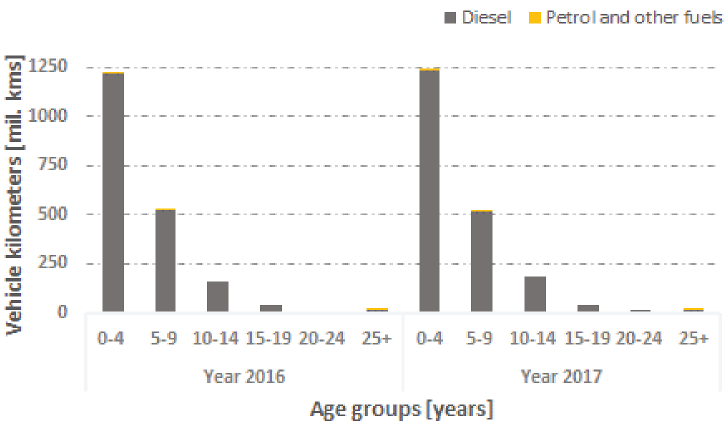

Figure 5: Traffic volume for all Norwegian heavy lorries and road tractors per fuel type and vehicle age (2016, 2017)
Source: Statistics Norway, 2018.

Attempting to reduce emissions from road vehicles operations could imply finding the best compromise between all or some of the above factors through optimization. However, not all factors can be easily modeled, and significant research efforts are still needed in the field (e.g. power train, emissions control technology, composite materials for lighter size and weight, etc.) to achieve that goal (Wyatt et al., 2014b, Frey et al., 2006, Cecchel et al., 2018).

The present work deals reducing both energy demand and emissions through optimization of the vertical alignment of a road. The main motivation for this choice remains the strong evidence of the negative influence of roadway longitudinal slopes in both vehicle fuel consumption and operating cost (de Abreu e Silva et al., 2015, Klaubert, 2001, Park and Rakha, 2006, Zaniewski et al., 1982). The authors propose a method to modify the vertical alignment of a given road to achieve considerable reductions in the overall fuel consumption and emissions, using optimization techniques. Such method can be used in early design phases of new roads allowing more accurate estimation of both emissions and fuel consumption, thus providing designers with possibility to design for clearly defined targets.

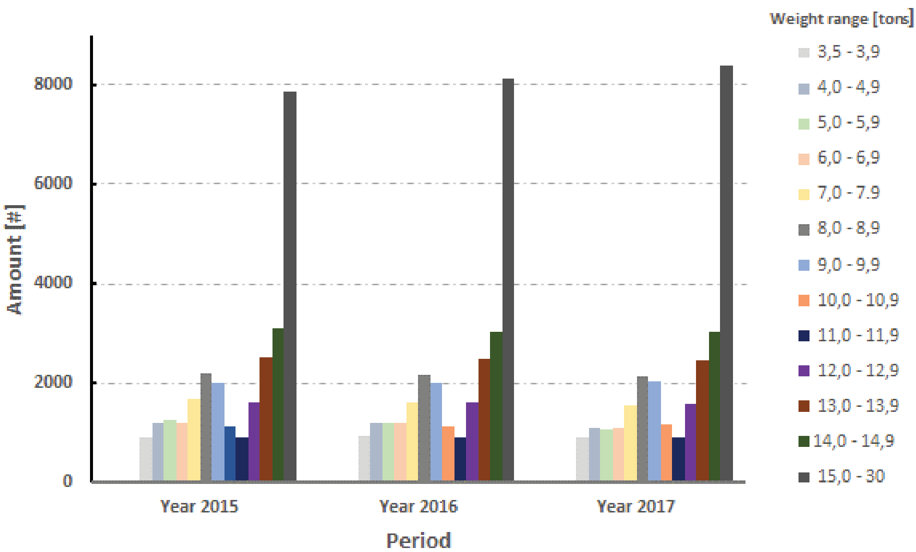

Figure 6: Norwegian registered lorries by carrying capacity (2015 - 2017)
Source: Statistics Norway, 2018

The idea of optimizing road alignments is not new. A number of research works exist that have dealt with this topic before, and different optimization techniques were employed to tackle the problem. Already in a distant past, Howard et al. (1969), Shaw and Howard (1981), Shaw and Howard (1982), Thomson and Sykes (1988), and Wan (1995) approached the problem by mean of calculus of variations to optimize only the horizontal alignment. For the same purpose, Nicholson (1973) and Nicholson et al. (1976) used dynamic programming, while Easa and Mehmood (2008) employed mixed integer programming. To optimize the vertical alignment, Chapra and Canale (2001) and Revelle and Whitlach (1996) formulated the problem as a linear programming one, with material balance and financial constraints among others. The most popularly adopted approach was the genetic algorithms (GAs), used for the first time by Jong (1998), for the alignment optimization problem, in the horizontal and vertical planes. This approach was reused by Jong and Schonfeld (1999) and improved by Fwa et al. (2002) to optimize the alignment in three dimensions. One common point in all those studies was that they all focused on finding the most economic path to connect a point A to a point B, considering various tangible and intangible factors, such as design specifications, earthwork cost, right-of-way cost, land-use, topography of the terrain, as well as some social and political issues (Kang et al., 2012).

Recently, a number of vertical alignment optimization studies were conducted, and several new techniques were developed. Most of these studies focused on implementing new algorithms to increase calculations speed and accuracy (Ghanizadeh and Heidarabadizadeh, 2018, Fonseca et al., 2017, Parente et al., 2016, Hare et al., 2014), while others aimed at including a bit more information in the models and assess many more factors whilst keeping things simple (Hare et al., 2015, Yang et al., 2014, Kang et al., 2013, Hare et al., 2011, Moreb, 2009, Goktepe et al., 2009, Göktepe et al., 2009). Nonetheless, the main goal remained more or less the same, i.e. to minimize earthwork cost and achieve a relatively low construction cost.

This paper introduces a method to evaluate fuel consumption and emissions performance of a given vertical alignment, and to generate alternative vertical alignments that meet a certain number of reduction requirements for both fuel consumption and emissions, based on an initial vertical alignment. The term emissions here refers to tail-pipe pollutants from a fossil-fueled vehicle.

The main motivation for targeting fuel consumption remains the higher importance of user costs that has been constantly observed in road transport operations worldwide. This cost is accentuated in mountainous countries, given their particularly difficult land topography.

The innovation brought by this study consists in evaluating and optimizing a road vertical alignment with the aim of minimizing environmental impacts during the use phase rather than in the construction phase. This in fact, is supported by the relatively higher amount of pollutants released in the use phase, compared with the others phases of the life cycle of the infrastructure. The proposed method goes deep in detail, in terms of input information. First, it uses a set of average-speed models as the basis for the estimations. Second, it takes into account the segment-by-segment slope variation of a road to derive fuel consumption factors and emission factors considering average speeds. Finally, the influence of the vehicle power train, the specific emission control technology, and the engine load, are also accounted into the estimation process. Average-speed models constitute the most used category worldwide, when it comes to estimation of energy demand and emissions for road vehicles (Smit et al., 2010). The approach developed here is termed “Single Level Approach – SLA”, stemming from the fact that one vehicle type of one specific technology, is considered for the analysis. Calculations considered the followings:

1. Five different operating speeds: 40, 60, 80, 100 and 105 km/h;
2. Seven longitudinal slopes (from -6% to +6%, incremented by 2%)
3. Three engine loads (0% = empty, 50% = half loaded and 100% = fully loaded);
4. Four pollutants (CO, NO_x, PM and CO_2) plus fuel consumption.

This paper continues with a method section that describes the proposed approach for evaluating a given vertical alignment and generating alternative ones. The method section is divided into five parts: 1. geometric data; 2. vehicle data; 3. emissions estimation; 4. new alignments generation, and 5. uncertainty consideration. A case study section then illustrates how the proposed approach can be applied to an existing road alignment (a section of the Norwegian E39 Coastal Highway Route), before selected results are presented, and main findings and effects of key variables are elaborated in the discussion section. The paper ends with a conclusion section that sums up the study based on the developed approach.

2. Method

To conduct this study, three main inputs are needed. First, information regarding the geometry of the intended road must be available. This design information may include the alignment (vertical and horizontal), pavement characteristics, road width, carriageway enlargements and speed limits. Second, one specific vehicle type needs to be appropriately selected based on different criteria meeting local traffic conditions; the selected vehicle will serve as a test agent. Finally, an appropriate model is to be chosen to estimate fuel consumption and emissions of the test agent, taking into account the effects of the geometry of the road and vehicle performances. The following sections offer a description of the proposed method, while more details on the emissions estimation as well as other calculations are provided in the annexes.

2.1. Geometric data.

As the study aims at reducing emissions of road vehicles at the use phase focusing on the road profile, the only geometric information of pertinent importance is the vertical alignment. Therefore, road slopes constitute the main geometrical input of consideration here. More explicitly, the road is discretized into a number of segments, each of which is characterized by a constant slope and its length. This information will then be arranged as follow: slopes' values are grouped in 12 classes, ranging from -6% to +6%. The length (D) of all segments found in the same class (n) is termed D_n and is calculated as the sum of lengths of individual segments whose slopes belong to that particular class (see Appendice B).

The profile must be continuous and preferably with homogenous pavement properties. In case of non-homogenous pavement characteristics, it is better to consider grouping vertical alignment by pavement type, especially if the relative contribution of different pavement types of the road is significant with respect to the results and evaluation. In such case, the resulting table may include an additional column (eventually designated as pavement type) which will be a subset of the range, and the corresponding distance will be calculated analogously.

2.2. Vehicle data.

The vehicle constitutes the central element for conducting this study. When selecting a test vehicle for evaluating road alignments based on emissions and fuel consumption, the share of traffic, fuel type and related pollutants will serve as basis for decision-making (see Table 1).

Table 1: Criteria for selection of the type/category and Emission Control Technology of test(s) vehicle(s)

Indicator	*Criteria*		
Type/Category			
Distance travelled (type/category)	≥10% of total travelled distance[1]		
Power train	Fossil fueled / blended vehicles[2]		
Fuel type	Fossil / biofuel / conventionally produced electricity		
Fuel consumption (type/category)	≥10% of total fuel consumed[1]		
Vehicle activity (exploitation)	Commercial / private[3]		
Share among operating vehicles[1]	Percentage[1]		
Emission Control Technology			
Average Age & Regional trends	*In Europe:*	*1992 - 1996 (Euro I); 1996 - 2000 (Euro II); 1996 - 2000 (Euro III);*	2000 - 2005/2008 (Euro IV/V); after 2014 (Euro VI);
	In the US:	*1960 - 1970 (Clean Air Act, California standards); 1970 - 1990 (CAA, EPA) ; 1990/1991 - 1999 (Low Emission Vehicles, Tier 1) ; 1999 - 2012 (LEV II & Tier 2) ; 2012 - 2014 (LEV III) ;*	
Policy in force[1]	In Europe:	European directives 91/44/EEC, 94/12/EC, 199/96/E, etc.	
	In the US:	EPA directives, CAFE, CAA, etc.	

1 Nationwide / for a given road / within a given zone or region
2 Electric/hybrid vehicles will be considered in regions with conventionally produced electricity
3 Commercial exploitation will be preferred against the private one; the nature of the commercial exploitation needs to be considered as well as their future trends (growth, lessening, etc.)

Vehicle's performances dictate the parameters of the models and allow for deciding on appropriate fuel consumption and emission factors (FCF and EF) for assessing the performance of different vertical road alignments with respect to fuel consumption and emissions. Traffic share informs about the contribution of a given vehicle category or group on the overall traffic. This can be nationwide or within a given region, for the whole vehicle fleet or just a subset of it. On the other hand, fuel type is related to the vehicles' powertrain and provides insights on the nature of pollution to expect during their operations.
Another element to consider is the emission standard of the vehicles. So far, in EU/EAA, seven concepts have been introduced to regulate exhaust gas emissions of road vehicles in both cold start and hot start conditions. These concepts are also known as Emission Standard Technology – EST. They include Euro I to Euro VI emission standard technology, with Euro V being divided in Euro V-SCR (Selective Catalytic Reduction) and Euro V-EGR (Exhaust Gas Recirculation). Each concept establishes clear limits to exhaust gas emissions of road vehicles. The level of strictness increases with the increase of the characteristic roman number. A result is that vehicles produced more recently have to emit less pollutant than those that were produced elderly. A good description of vehicle categories and emission concepts can be found in the EMEP-EEA Guidebook (Ntziachristos and Samaras, 2014, Ntziachristos et al., 2010, Ntziachristos et al., 2009). It is important to underline here that one may stick with national statistical data to facilitate the choice of test vehicle. However, in the event where a given road (highway) is considered and specific traffic data are available, such information must be used.

2.3. Performance indicators.

Many fuel consumption and transport emissions estimation models have been developed during the last decades and research efforts in that direction are still ongoing. Different categorizations exist for those models, each necessitating different requirements with different restrictions (Corvalán et al., 2002, Fontes et al., 2015, Mak and Hung, 2008). For this study, we chose speed-gradient dependent models. Such models have the advantage of including the effects of road grades and vehicles performances in the estimation of fuel consumption and emissions factors (FCF and EF).

In the EU/EEA, the PHEM model (the acronym for Passenger car and Heavy-duty vehicle Emissions Model) and the VERSIT+ model represent the most used vehicle simulation models (Ermes Group EU). Fuel consumption factors and emission factors derived by means of simulations done using PHEM model is used in this work. Those factors are provided in the HandBook of Emission Factors for road transport (HBEFA version 3.2). HBEFA v3.2 is well adapted for capturing speed dependency variations of both fuel consumption and pollutant emission factors for all relevant vehicle categories (Rexeis et al., 2013). In addition, HBEFA allows considering both vehicles' nominal factors (i.e. vehicle type, technology and emission type) and relevant context-specific factors (such as road gradients and vehicle loadings). The method developed in this study considers both nominal factors and context-specific factors.

In its full version, HBEFA v3.2 contains 7.8 million HDV (heavy-duty-vehicle) fuel consumption and emission factors. Those factors are documented for nineteen distinct categories of HDVs under three vehicle loadings (empty, half loaded and fully loaded), considering nine emission concepts, 272 traffic situations and seven road slopes (-6%, -4%, -2%, 0%, +2%, +4%, +6%). Factors include fuel consumption and seven exhaust gas pollutants (CO_2, NO_X, NO_2, HC, CO, PM, PN).

The version used in this study is the one provided as separate annex file, in excel format – freely available online from the guidebook website (European Environment Agency, 2016), because of a joint activity from the European Monitoring and Evaluation Programme (EMEP) and the European Environmental Agency (EEA). The model provides speed-based fuel consumption and emission factors for nineteen HDVs, considering three engine loads, seven road grades and three emission concepts (HDV Euro 5 SCR, HDV Euro 5 EGR and HDV Euro VI). For the remaining part of this study, we will refer to the HBEFA v3.2 model as the EMEP-EEA model, for clarity and short form.

For this paper, the estimated factors are FC, NO_x, PM, CO and CO_2, here termed as "performance indicators". Only hot start emissions were considered, since not many trips start on highways. This practice is quite common when applying EMEP-EEA model for fuel consumption and emission estimation as found in Ahn et al. (2002b); El-Shawarby et al. (2005); Csikós and Varga (2012) and Cen et al. (2016). The method used is articulated as follow:
First, a test vehicle is chosen with help of Table 1. Then, based on the test vehicle, the initial alignment is evaluated using the EMEP-EEA model. Alignment evaluation consists in calculating the performance indicators for each segment of the considered road, considering their respective slopes. These performance indicators are estimated for constant speeds and for three different engine loads. The corresponding indicator is denoted as follow:

$$E[X]_{l,c}(v) \tag{1}$$

where:
X: Vector of the decision variables $[x_1, x_2, x_3 \ldots\ldots\ldots x_n]$ (the segment slopes);
l: Engine load;
c: Desired performance indicator (i.e. FC, NO_x, PM, CO or CO_2);
v: Operating speed.

Factors for the performance indicator CO_2 are not provided in the EMEP-EEA model and are therefore indirectly derived from those of FC. The corresponding performance indicator for CO_2, derived according to Ntziachristos and Samaras (2014), is given as follow:

$$\begin{aligned} E[X]_{l,CO_2}(v) = {} & \frac{44.011}{12.011 + 1.008 \times r_{H:C} + 16 \times r_{O:C}} \cdot E[X]_{l,fuel}(v) \\ & + \frac{44.011}{12.011 + 1.008 \times r_{H:C} + 16 \times r_{O:C}} \cdot E[X]_{l,Lo}(v) \\ & + 0.238 \times UC_f \cdot E[X]_{l,fuel}(v) \end{aligned} \tag{2}$$

where:
Lo: Lubricant oil consumption rate (mass of oil consumed per 10000 km of road);
UC_f: Urea solution consumption for NO_x reduction (fuel consumption fraction 5-7%);
$r_{H:C}$ and $r_{O:C}$: Ratio of hydrogen to carbon atoms and oxygen to carbon atoms for a given fuel.

The first evaluation metric to consider is the overall value of a given performance indicator $O_c(v)$ in mass unit (g), considered in both direct and reverse traffic directions and at constant speed.

$$O_c(v) = \sum E[X]_{l,c(d,r)}(v) \cdot L_i \tag{3}$$

Following, the value of a given performance indicator for each segment is calculated, in unit of mass (g).

$$ES_i(v) = E[X]_{l,c}(v) \cdot L_i \qquad i = 1, 2, 3, \dots, n \tag{4}$$

where:
ES_i: Estimated desired performance indicator for segment of slope i;
L_i: Corresponding segment length.

The calculated performance indicators are summed up within their respective slope ranges to get a range subtotal.

$$EE_n = \sum ES_i\,(v) \tag{5}$$

$$ER_n = {}^{EE_n}/_{D_n} \tag{6}$$

Those subtotals are corrected by their corresponding range distances to give a rate (fuel consumption or emissions) in mass per unit distance (g/km) for each slope range. The rates are then averaged over the classes to give the Average Emission Rate (AER), also expressed in mass per unit distance (g/km), which is the second metric proposed for overall evaluation of road alignments.

$$AER = \frac{1}{N}\sum_{n=1}^{N} ER_n \tag{7}$$

2.4. Performance indicators.

The generation of new alignments is guided by the reduction levels one may wish to get, as compared to the initial alignment. The easiest way to think of road vehicle fuel consumption reduction while focusing on the infrastructure itself is the single-grade profile. This is an ideal road profile for connecting two locations. Its advantage is being the least energy demanding profile, but it does not necessarily guarantee better behavior for all performance indicators, and for the whole life cycle of the infrastructure. However, if only the operation stage is considered, a single-grade road profile may present more advantages with respects to both energy demand and emissions. Therefore, a single-grade road profile can be regarded as the base line for the evaluation of different alignment scenarios with respect to energy demand and emissions of road vehicles at operation stage.

Three types of reduction levels are introduced in this work and all of them act on the fuel consumption. The reduction levels include minimum total fuel consumption (TotFC minimum), minimum slope variation (delta slope minimum) and, percentage-target reduction (i.e. a certain percentage of O_c of the initial alignment).

Among the possible single-road profiles that can be achieved, the flat one (i.e. slope is constant and equal to zero) constitutes the lowest limit regarding reduction for energy demand. Thus, two extreme reduction levels exist beforehand: the initial level (from the initial alignment) and the lowest level (which is obtained by setting road gradients equal to zero). These two levels are termed as “nominal levels”. Between those levels, many other reduction levels are achievable. In this work, the focus has been set to two “practical levels” obtainable through the optimization process. Those practical levels represent, respectively, the one of the lowest possible overall fuel consumption (TotFC minimum), and the one inducing the lowest possible slope variation (delta slope minimum). Any achievable reduction level comprised within the above two practical levels, are termed “percentage-target reduction level”. The latter are also obtained through optimization within the feasible region bounded by the practical levels. Thus, generating new alignments corresponds to solving an optimization problem that can be modelled as follow:

$$F(X) = \sum E[X]_{l,c(d,r)}(v) \cdot L_i \tag{8}$$

This equation is the integral of individual values of a given performance indicator c evaluated for each slope x_i over the entire road, in mass unit (g). c(d,r) refers to both direct and reverse traffic directions. Fuel consumption was retained as the desired performance indicator in this work.

$$\Delta S(X) = \sum_i (X_I - X)^2 \tag{9}$$

The above equation is the integral of squared slope differences where X_I and X refer to segment slopes in the initial and generated alignment respectively. With the above two quantities, the problem can be formulated as shown in Table 2. The difference between the optimal values of ΔS(X) and F(X) resulting from target cases #2 and #3 determines the range of reduction that can be achieved for the intended alignment.

In total, two objective functions, three equality constraints and two bounds can be identified in the presented models. F(X) represents the vector of slopes that guarantees the minimum quantity of fuel to be consumed by the selected test vehicle, at fixed speed, for a roundtrip travel on the intended road. ΔS(X) aims at introducing the lowest difference possible between the initial and the optimized (i.e. generated) alignments. Hence, it helps control the impact of the optimization process on the overall estimated cost of the road project by keeping the generated alignments as close as possible to the alternative proposed by the design team, i.e. the initial alignment.

Table 2: Optimization plans, target functions and constraints[4]

Target	*Function to be minimized*	*Constraints*
(#1) Minimum Fuel Consumption	$F(X) = \sum E[X]_{l,fuel(d,r)}(v) \cdot L_i$	$h_1(X):\ x_{I,1} \cdot L_1 - x_1 \cdot L_1 = 0$
(#2) Minimum Slope Variation	$\Delta S(X) = \sum_i (X_I - X)^2$	$h_2(X):\ \sum X_I \cdot L_i - \sum X \cdot L_i = 0$ $h_3(X):\ -0.06 \le X \le 0.06$
(#3) Percentage-target Reductions[6]		$h_4(X): \sum E[X]_{l,fuel(d,r)}(v) \cdot L_i \ldots$ [5] $-(1-\beta) \cdot \sum E[X_I]_{l,fuel(d,r)}(v) \cdot L_i = 0$

4 Possible values for beta parameter are: 0.05, 0.10, 0.15, 0.20, 0.25, etc.
5 Valid only for target case #3
6 Achievable reduction levels whose values are bounded by that of the lower and upper practical levels bound.

The first equality constraints $h_1(X)$ fixes the elevation of the start point in all generated alignments, whereas the second equality constraints $h_2(X)$ fixes the elevation of endpoint. $h_3(X)$ constitutes the lower and upper bounds for the different segment slopes. This range of values was selected considering the road grade controls actually used in several European countries and in North America. According to those grade controls, appropriates extreme values for road gradients lie between - 6% and +6% for a design speed of 110 km/h, and between – 8% and + 8% for a design speed of about 50 km/h (Aashto, 2001, Statens Vegvesen, 2014). Slope values ranging from -6% to + 6% were selected to remain consistent with both existing road gradient controls' specifications and the EMEP/EEA emission model used in this work. h_4 (X), in the last target case, makes sure that the fuel consumed by the test vehicle after a roundtrip travel on the generated alignment equates a certain percentage of that consumed by the same vehicle on the initial alignment, at same operating speed.

It should be noted that the alignments generated using the approach proposed in this work are to be redirected to the design team, which will analyze ways of their implementation in light of their proposed alternatives, considering all necessary design inputs (including all cost options) and targets.

2.5. Uncertainties consideration

According to Hausberger et al. (2009), uncertainties in the EMEP-EEA models originate from

Both the measurement and the modelling processes. Relatively lower levels of uncertainties were recorded for fuel consumption estimation (around 4%), whereas for some other component such as CO, considerably higher values (approaching 75%) were observed for higher slope values.

3. Case study

To better illustrate the method, a numerical application that involved a real-life alignment is considered. The selected testbed is a road section from the existing part of the Norwegian Coastal Highway Route E39. Norway's emission standards follow the European ones, which is the same as those implemented in the EMEP-EEA guidebook, on which this study is based. However, the approach developed in this study will support any other speed-gradient emission model.

3.1. Study area and materials

The E39 is an 1100 km European road corridor located in western Norway, which connects the city of Kristiansand (south) to Trondheim (north). It is currently under investigation at the Norwegian Public Road Administration (NPRA) and the Norwegian Ministry of Transport and Communications. The main goal of this project is to develop that route as a ferry-free highway to decrease travelling time, facilitate trade and industry development, and create more business opportunities in that part of the country. If fully implemented, 11 fjords will have to be crossed along that route, making it possible to reduce the average travel time by approximately 10 hours.

Georeferenced vertical alignment information of a section of E39 were extracted through ArcGIS, from the online roadmap portal Vegkart (NPRA, 2017). In total, 407 slope data points were retrieved from the online roadmap, covering a section of approximately 57 km long, with a two-way, two-lanes, single carriageway (no median) design. The considered section extends between Søgne and Lyndgal located in southern Norway (see Figure 2). This road section pertains to class H8 in the Norwegian road classification, designed to bear an Annual Average Daily Traffic (AADT) of 12000 – 20000, with a maximum allowed speed of 100 km/h.

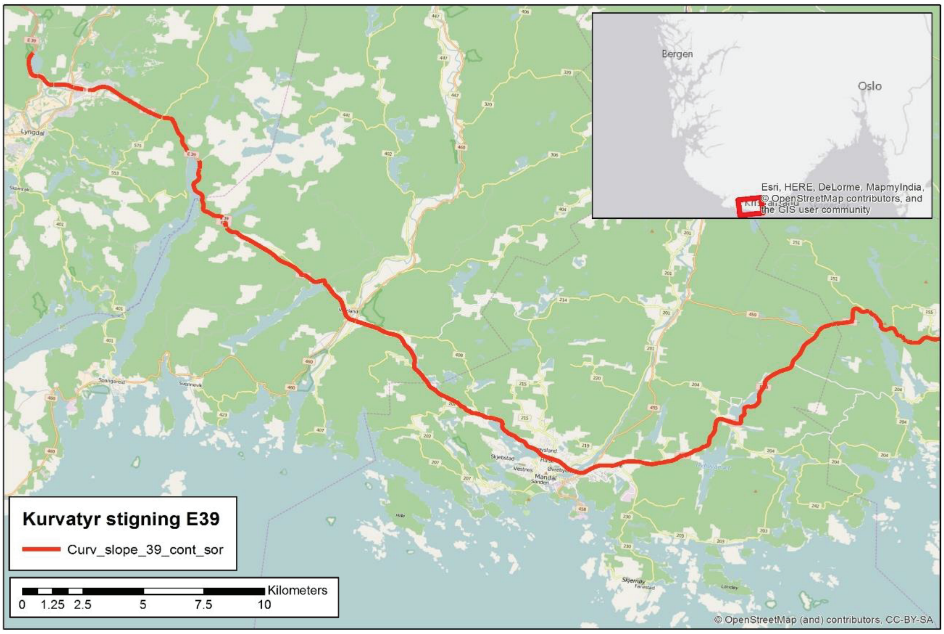

Figure 7: Location of the road project under study.

The selection criteria for this particular section included important variabilities in slopes (i.e. higher terrain elevations), homogeneity of the pavement type (asphalt), low number of roundabouts and no ferry connections. The criteria justify as much as possible the assumption of free flow conditions, considering free flow speeds for each trip. They also enhance the effect of road slopes on the performances of heavy-duty vehicles (HDV).

To select a test vehicle, registered vehicle information and road traffic data, at both local and national level, were considered. In Norway, registered vehicles that are licensed for operation are arranged in different groups. These include passenger cars, taxis, ambulances, motor homes, mini-buses, buses and coaches, small lorries, small combined vehicles, large combined vehicles, small vans, large vans, lorries with gross vehicle weight (GVW) ≤ 12 tons, lorries with GVW > 12 tons and road tractors. As this study deals with alignment adjustment using a single level approach, only one test vehicle has to be selected. Therefore, a diesel-fueled articulated coach with gross vehicle weight (GVW) higher than 18 tons was chosen for the analysis. This vehicle belongs to the HDV category as described in the EMEP-EEA Guidebook (Ntziachristos and Samaras, 2014). The associated emission standard technology was Euro-V, equipped with a selective catalytic reduction (SCR) device for treatment of the exhaust gas. Reasons for this choice include, among others, the share of buses and coaches in the Norwegian HDVs traffic. According to Statistic Norway, buses and coaches drove about 515 million vehicle-kilometers in 2015, i.e. nearly 21% of the total HDV traffic of the country (Table 3). Of that mileage, more than 90% were travelled using diesel as fuel (Table 3). The average age of vehicles in that group ranges from 5 to 6 years, with about half of the cartage being less than 4 years old (Table 3 , Figure 6).

Table 3: HDV traffic volume (million vehicle-kilometers) by category, age and fuel type

Vehicle Type		Age (years)						Fuel Type		
		0-4	5-9	10-14	15-19	20-24	≥25	Petrol	Diesel	Other
Buses and coaches		256.2	205.7	42.2	7.0	1.7	2.2	0.1	478.7	36.2
Lorries	GVW ≤ 12 t	18.8	14.1	6.3	3.1	1.3	2.4	0.0	45.8	0.1
	GVW > 12 t	690.6	409.2	119.0	42.4	9.3	13.6	0.0	1278.8	5.3
Road tractors		481.4	126.8	19.1	4.3	0.9	1.6	0.1	634.1	na

Source: statistics Norway, 2016.

The choice of Euro-V emission standard technology was prompted mainly because of the relatively young age of the vehicles in that specific group. Indeed, not all buses and coaches in Norway meet that specification. However, relying on the age of the cartage in that particular group, and considering an average pattern of it, such a choice proves to be a conservative one. Likewise, selective catalytic reduction (SCR) was retained as the main emission control concept in this work. The reason for that is its predominant use in Europe. It is estimated that up to 75% of Euro-V HDV in EU/EEA are equipped with SCR for NOx emissions reduction, the remaining 25% being armed with exhaust gas recirculation (EGR) emission control devices (Ntziachristos and Samaras, 2014). Therefore, the choice of a Euro V-SCR articulated coach as our test agent seemed to be a plausible one and would yield representative results in the Norwegian context.

3.2. Analysis

The MATLAB optimization toolbox has been used in this work. The FMINCOM optimization routine was employed with sequential quadratic programming (SQP) algorithm for simulation of optimized alignments. The maximum function evaluation was set to its highest value (i.e. INF). For each run, a maximum of 5000 iterations was required. Factors for intermediate slope values were derived through cubic spline interpolation, from those of discrete slope values provided in the EMEP/EEA model. The MATLAB "pchip" function was employed for the extraction of those factors. Using MATLAB, a compromised programming method was used for generating alignments belonging to the percentage-target reductions levels. This implied a different modelling scheme (for this specific category of optimized alignment) involving a multi-objective problem (two objectives here) solved using the weighting objectives method (see appendice C).

Simulations were ran for several reduction levels including the minimum total fuel consumption, minimum slopes variation and achievable percentage-target reductions. As a base line for running the algorithms and applying the reduction levels, the performances of the test vehicle on the initial alignment was considered for selected operating speeds at 100 % load (fully loaded).

The generated alignments where then evaluated using the same test vehicle operated at same speeds and for three engine loads (0%, 50% and 100%). For the parameters considered in the calculation of CO_2, see Table 4. The analysis performed in this case study was restricted to the calculation of $O_c(v)$, $\Delta S(X)$, AER and external cost of pollution as metrics for comparison of the initial and the generated alignments.

Table 4: Parameters for CO2 estimation

Item	*Parameter*	*Considered value*
Diesel fuel	$r_{H:C}$	2.00
	$r_{O:C}$	0.00
Lubricant oil	$r_{H:C}$	2.08
	$r_{O:C}$	0.00
	L_o	1.91 kg / 10000 km
Urea agent	UC	6% of FC

Source: (Ntziachristos, 2014)

4. Results

Six types of results are presented in this study. They include the elevations of the generated alignments for selected operating speeds and reduction levels (Figure 8), $O_C(v)$ for five indicators, three engine loads and the considered reduction levels (Figure 9 to Figure 13), ΔS(X) for five operating speeds and their respective achieved reduction levels (Figure 14), external cost of pollution (including climate change) (Figure 15) , differences of performance indicators ($\Delta c_{[AB-BA]}$), between the two traffic senses (Table 5 to Table 7), and AER (Table 8 and Table 9).

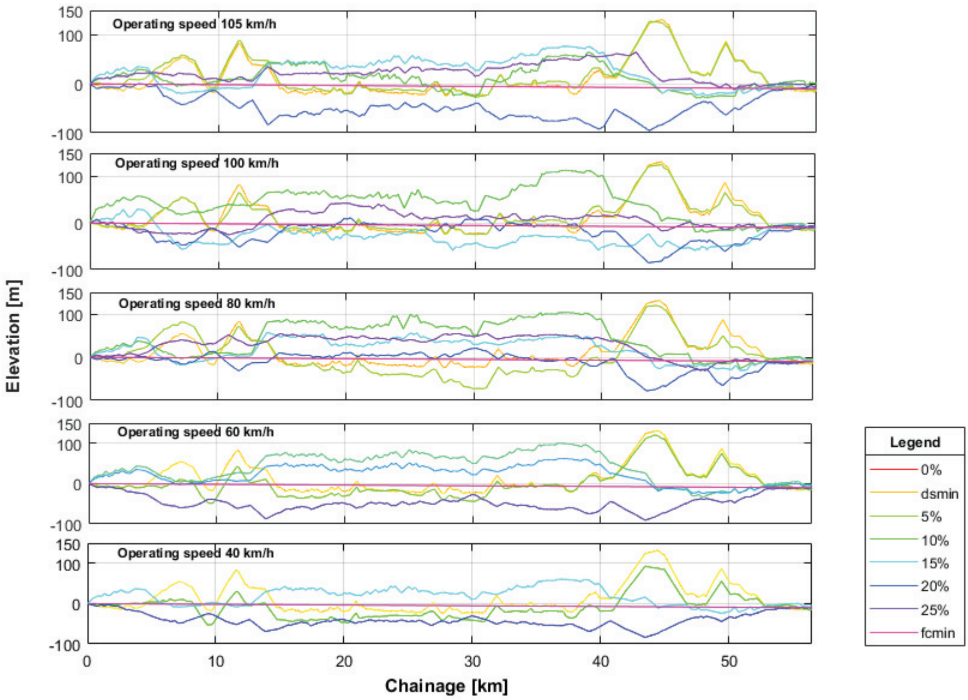

Figure 8: Trends of generated alignments for each reduction target and specified operating speed

In Figure 8 legend 0% represents the initial vertical alignment, dsmin is the alignment with the minimum possible slope reduction introduced, 20% is the elevation of the vertical alignment that achieves 20% less fuel consumption compared to the initial alignment, fcmin is the elevation of the alignment that achieves the lowest possible fuel consumption

The x-labels from Figure 9 to Figure 13 designate the reduction level of the considered alignment with respect to fuel consumption. The height of the bars represents the overall amount of the considered performance indicator, for the selected test vehicle, on that specific alignment.

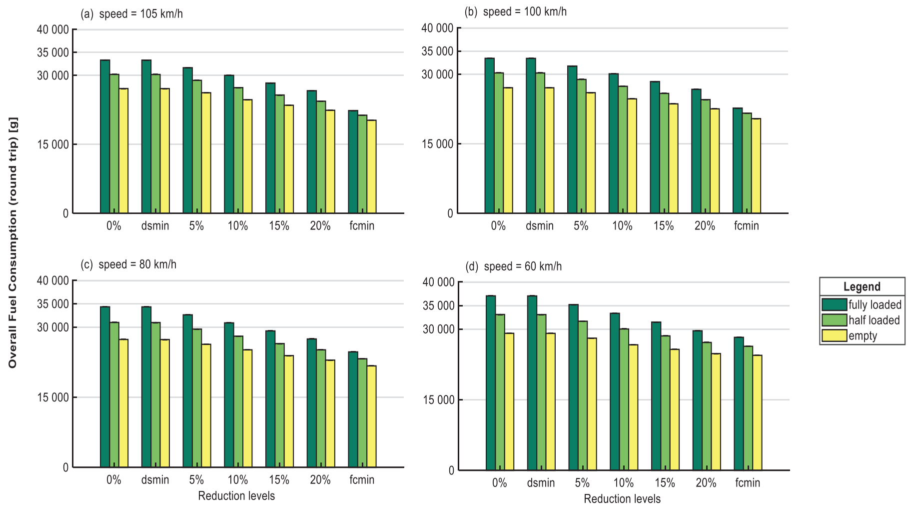

Figure 9: Fuel consumption performance of generated alignments with respect to operating speed and engine loads

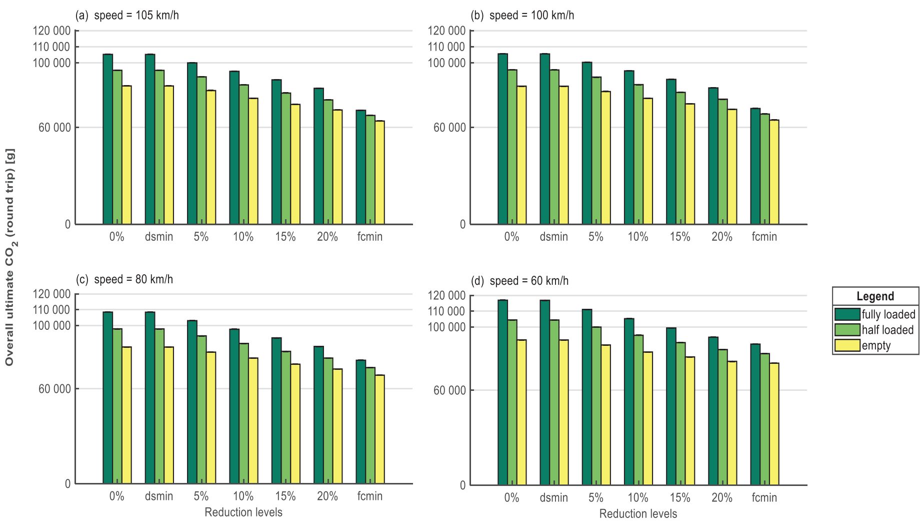

Figure 10: CO_2 performance of generated alignments with respect to operating speed and engine loads.

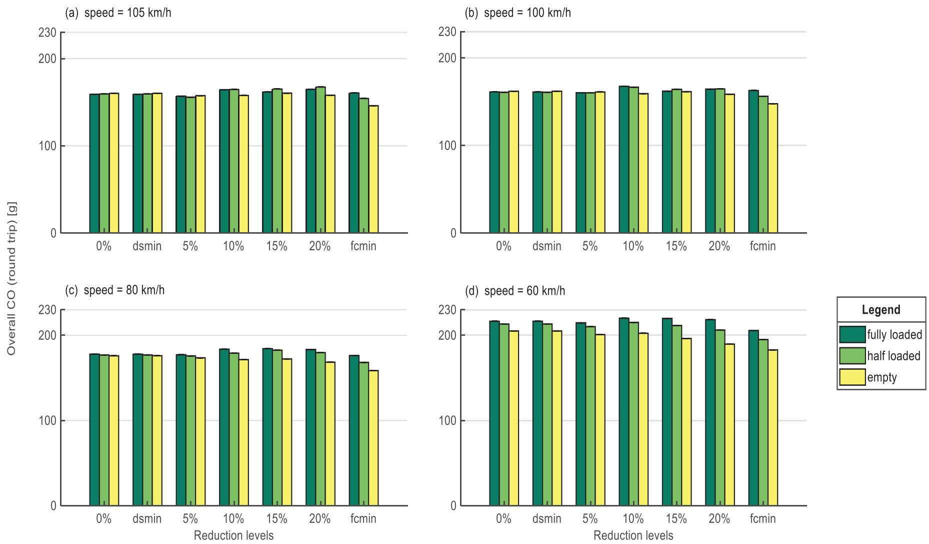

Figure 11: CO performance of generated alignments with respect to operating speed and engine loads.

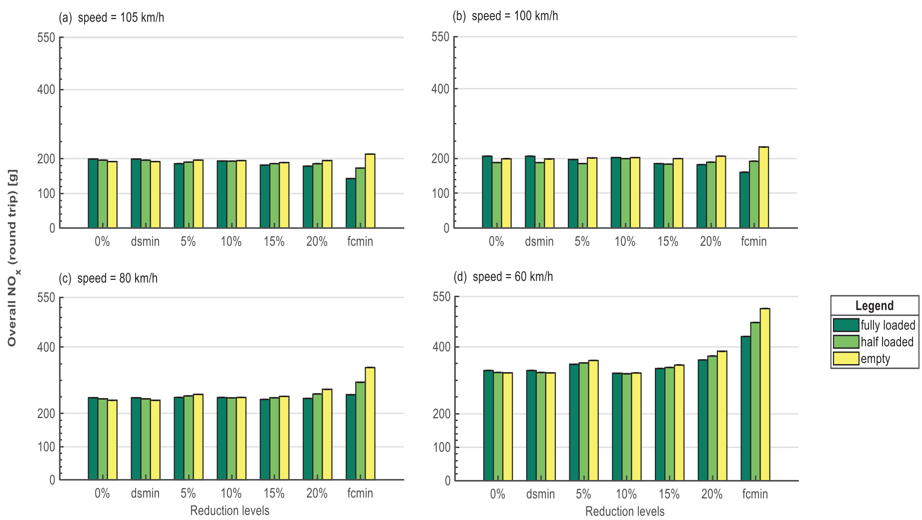

Figure 12: NO_x performance of generated alignments with respect to operating speed and engine loads.

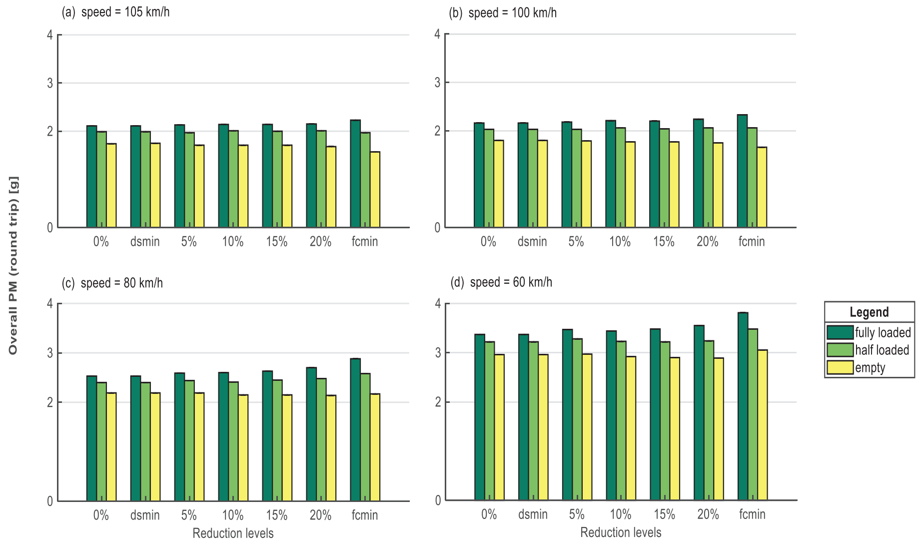

Figure 13: PM performance of generated alignments with respect to operating speed and engine loads.

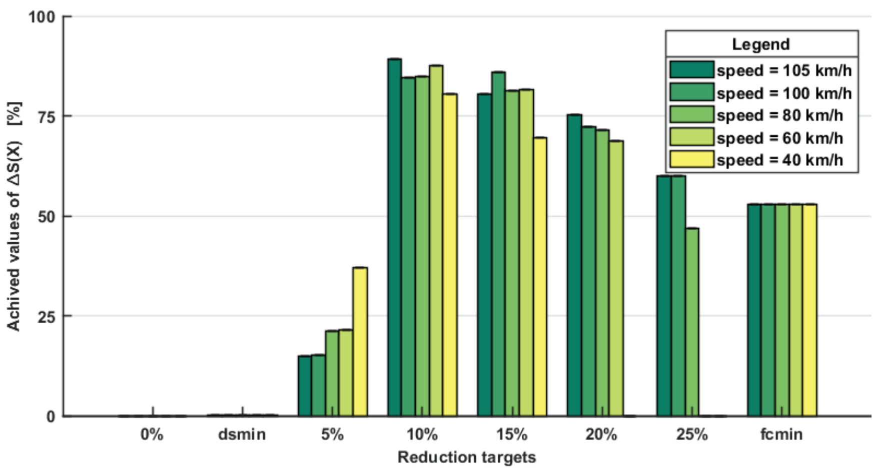

Figure 14: Achieved overall slope difference ΔS(X) with respect to reduction targets.

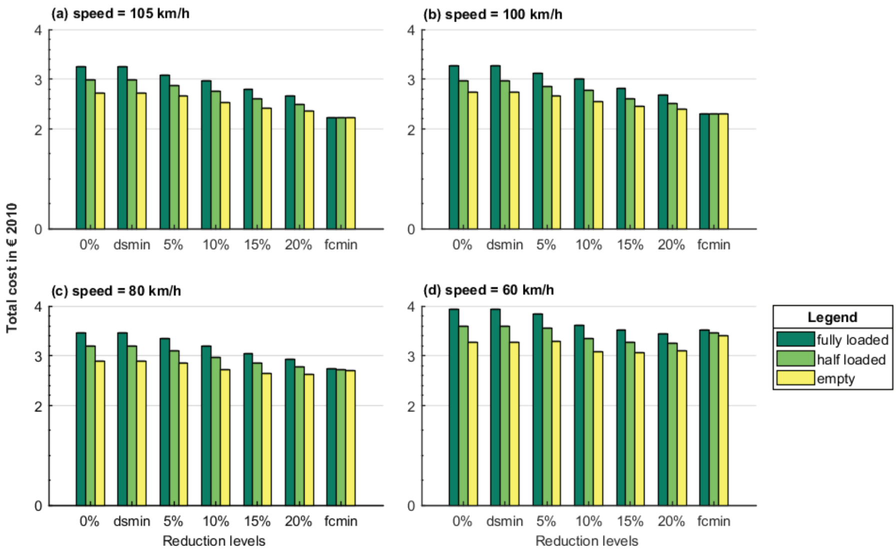

Figure 15: External cost of pollution (climate change). (for cost factors see appendices)

Table 5: Difference in total fuel consumption (ΔFC) on both directions, expressed in grams

Speed	*Load*	*0%*	*DSmin*	*5%*	*10%*	*15%*	*20%*	*25%*	*FCmin*
	100%	-99.15	-98.54	-204.39	-297.69	-132.79	-112.36	-141.10	-217.69
105	50%	-114.27	-113.88	-194.84	-242.73	-121.90	-99.84	-121.64	-194.87
	0%	-60.06	-59.53	-134.44	-243.75	-110.56	-106.67	-126.93	-164.54
	100%	-96.92	-96.31	-184.33	-77.42	71.14	-208.76	-223.85	-215.65
100	50%	-112.01	-111.62	-165.67	-102.83	54.39	-184.10	-194.68	-192.32
	0%	-66.47	-65.99	-141.54	-50.77	-13.15	-156.63	-161.91	-162.03
	100%	-89.20	-88.59	-267.18	-158.85	-167.87	-34.70	-253.48	-207.73
80	50%	-111.40	-111.05	-214.06	-140.55	-154.95	-41.71	-219.69	-182.81
	0%	-92.29	-92.01	-181.62	-122.33	-126.81	-45.49	-178.56	-153.30
	100%	-130.93	-130.57	-33.24	-141.88	-199.11	-169.72		-199.94
60	50%	-114.99	-114.67	-32.56	-124.74	-172.68	-148.66		-174.31
	0%	-106.35	-106.15	-38.57	-103.67	-143.83	-124.82		-146.63
	100%	-140.16	-139.86	-167.05	-98.69	-174.43			-192.15
40	50%	-124.45	-124.21	-147.06	-83.47	-150.47			-166.87
	0%	-107.86	-107.67	-127.65	-63.42	-125.54			-141.45

Table 6: Difference in total fuel consumption (ΔFC) on both directions, expressed in grams

Speed	*Load*	*0%*	*DSmin*	*5%*	*10%*	*15%*	*20%*	*25%*	*FCmin*
	100%	-0.783	-0.781	-1.808	-1.307	0.040	0.596	0.334	-1.294
105	50%	-0.182	-0.177	-1.472	-1.791	0.042	0.547	0.238	-1.289
	0%	0.645	0.654	-0.596	-2.490	-0.187	-0.077	-0.319	-1.158
	100%	-0.799	-0.797	-0.730	-0.793	3.988	-1.054	-1.245	-1.304
100	50%	-0.191	-0.186	-0.751	-0.191	3.729	-1.061	-1.238	-1.286
	0%	0.709	0.718	-0.726	0.977	1.671	-1.027	-1.147	-1.149
	100%	-0.415	-0.411	-1.515	-0.119	-0.726	2.391	-2.242	-1.345
80	50%	0.493	0.502	-1.910	-0.284	-0.632	1.792	-2.028	-1.271
	0%	0.694	0.704	-2.030	-0.650	-0.399	0.678	-1.421	-1.106
	100%	0.160	0.169	2.437	0.046	-1.277	-0.619		-1.378
60	50%	0.350	0.359	2.218	-0.133	-1.198	-0.804		-1.256
	0%	0.325	0.331	1.552	-0.368	-1.060	-0.922		-1.053
	100%	0.212	0.219	-0.395	0.710	-1.063			-1.391
40	50%	0.187	0.194	-0.211	-0.173	-1.117			-1.233
	0%	-0.260	-0.255	-0.414	-0.829	-0.997			-0.987

Table 7: Difference in total fuel consumption (ΔFC) on both directions, expressed in grams

Speed	*Load*	*0%*	*DSmin*	*5%*	*10%*	*15%*	*20%*	*25%*	*FCmin*
	100%	-0.005	-0.005	-0.024	-0.023	0.001	0.009	0.004	-0.019
105	50%	-0.005	-0.005	-0.023	-0.022	0.001	0.009	0.003	-0.018
	0%	0.000	0.000	-0.015	-0.023	-0.001	0.004	0.000	-0.015
	100%	-0.005	-0.005	-0.012	-0.008	0.058	-0.015	-0.017	-0.019
100	50%	-0.006	-0.006	-0.011	-0.008	0.054	-0.015	-0.016	-0.018
	0%	0.001	0.001	-0.010	0.001	0.035	-0.013	-0.014	-0.015
	100%	-0.001	-0.001	-0.026	-0.001	-0.011	0.041	-0.037	-0.021
80	50%	0.004	0.004	-0.027	-0.003	-0.011	0.032	-0.033	-0.020
	0%	0.003	0.003	-0.025	-0.005	-0.008	0.022	-0.026	-0.017
	100%	0.007	0.007	0.050	0.003	-0.022	-0.008		-0.023
60	50%	0.002	0.002	0.038	0.001	-0.020	-0.010		-0.021
	0%	0.001	0.001	0.029	-0.001	-0.018	-0.010		-0.019
	100%	0.000	0.000	-0.013	0.024	-0.016			-0.026
40	50%	0.000	0.000	-0.011	0.014	-0.016			-0.023
	0%	-0.004	-0.004	-0.012	0.008	-0.015			-0.020

Table 8: Difference in total fuel consumption (ΔFC) on both directions, expressed in grams

Speed	*Load*	*0%*	*DSmin*	*5%*	*10%*	*15%*	*20%*	*25%*	*FCmin*
	100%	631.35	643.81	631.62	640.79	547.43	562.30	521.90	394.08
105	50%	569.18	580.43	568.97	578.44	493.28	506.78	471.68	376.36
	0%	508.19	516.83	508.74	514.44	447.57	459.14	429.58	356.99
	100%	632.76	645.09	639.40	600.81	546.22	529.49	496.09	400.37
100	50%	570.28	581.42	575.53	544.45	492.31	477.63	450.59	381.09
	0%	506.53	515.17	511.29	483.81	444.87	432.46	410.85	360.29
	100%	646.32	657.97	643.15	615.15	597.98	563.95	477.45	435.73
80	50%	580.36	590.97	576.07	558.23	535.45	506.38	436.07	409.84
	0%	507.22	515.65	503.44	492.61	471.81	449.74	398.80	383.01
	100%	690.63	702.61	687.96	612.61	545.74	543.37		498.04
60	50%	613.03	622.85	610.81	549.28	496.30	494.45		464.52
	0%	533.62	541.41	531.64	484.54	448.34	447.09		430.72
40	100%	783.92	794.41	782.87	713.48	673.60			622.53
	50%	702.07	710.71	701.30	644.86	614.08			579.45

	0%	619.67	626.31	619.24	576.73	555.15			536.71

Table 9: Difference in total fuel consumption (ΔFC) on both directions, expressed in grams

Speed	*Load*	*0%*	*DSmin*	*5%*	*10%*	*15%*	*20%*	*25%*	*FCmin*
	100%	3.65	3.72	3.61	3.75	3.30	3.33	3.24	2.52
105	50%	3.50	3.54	3.48	3.56	3.30	3.33	3.28	3.05
	0%	3.30	3.32	3.29	3.34	3.23	3.26	3.26	3.76
	100%	3.75	3.81	3.73	3.81	3.39	3.37	3.33	2.82
100	50%	3.24	3.28	3.18	3.53	3.13	3.19	3.31	3.38
	0%	3.40	3.41	3.39	3.49	3.36	3.36	3.49	4.11
	100%	4.33	4.37	4.26	4.52	4.17	4.16	4.31	4.53
80	50%	4.18	4.18	4.15	4.39	4.11	4.16	4.45	5.19
	0%	3.99	3.97	3.98	4.30	3.99	4.11	4.59	5.97
	100%	5.55	5.54	5.54	5.59	6.02	6.04		7.59
60	50%	5.34	5.29	5.35	5.54	6.11	6.13		8.32
	0%	5.22	5.15	5.24	5.53	6.27	6.29		9.06
	100%	8.65	8.53	8.70	9.21	9.89			13.78
40	50%	8.43	8.30	8.50	9.18	10.04			14.45
	0%	8.54	8.39	8.61	9.50	10.53			14.94

5. Discussion

From the results presented in this study, four main elements are to underline.

First, it is demonstrated that if the road vertical alignment is adjusted and adapted to certain prescribed conditions, significant reductions in fuel consumption and emissions from a Euro V-SCR type HDV, can be achieved. In fact, as it can be observed from Figure 8, changes in configuration of vertical alignment can lead to up to 25% reduction in fuel consumption, for a particular vehicle. This statement confirms the many findings that document on the pronounced influence of road gradients on energy demand and emissions of HDVs (Ahn et al., 2002a, Devesa and Indinger, 2012, Hashim, 2011, Hunt et al., 2011, Tong et al., 2000, Wyatt et al., 2014a, Yazdani Boroujeni and Frey, 2014, Svenson and Fjeld, 2016).

Second, it is shown that both the overall $O_c(v)$, external cost of pollution, and average-normalized AER values of the calculated performance indicators are highly impacted by the operating speed, engine load and reduction level. These three parameters act in the following ways:

- Both the external pollution cost and performance indicators' values increase when the selected test vehicle goes down in speed. The proportion lies between 22% – 37% higher, when the agent passes from operating speed of 105 km/h to 40 km/h (Figure 9 to Figure 13, Figure 15).
- At constant speed, values of performance indicators decrease to about 19% between load 100% to load 0% (Figure 9 to Figure 13).
- The difference in fuel consumption due to load factors gets lower when the alignment goes from its initial profile to that of minimum fuel consumption i.e. from around 19% to approximately 9%. (Figure 9, Table 5).

Another remarkable point to notice from the presented results is the tradeoff between fuel consumption – equivalently CO_2 – and nitrogen oxides (NO_x). Lower fuel consumption – and eventually CO_2 – road profiles correspond to higher NO_x emissions, with peak values being registered at lower load factors (Figure 9, Figure 10 and Figure 12). One last element, noteworthy to refer at, is the constant behavior of the CO performance indicator over the different reduction levels. Overall CO values at fixed speed (especially at higher ones) depict a constant behavior, irrespective of the reduction level and load factor (Figure 11).

Findings discussed above cannot be taken as unique since they comply with those of the many studies documented in the literature. The increase of some performance indicators (FC, CO_2 and PM) with the decrease of the operating speeds is due to rich air-fuel mixture at corresponding operating points. In fact, internal combustion engines perform better at higher speed given the easiness in converting chemical energy contained in the fuel into useful work, because of rich air-fuel mixture (Dunn et al., 2013, Ojapah et al., 2013). This maybe a reason to advise higher speed limits in highways, especially when it is meant to be affected to high AADT with higher HDV share, and to restrict HDV traffic within cities, as they tend to drive at lower speeds in urban areas. The direct variation of FC, CO_2 and PM with load factors is due to the additional effect of weight i.e. more energy is needed to move larger weights whereas less energy is used to displace lower weights. This results from simple physic principles. Thus, fully loaded HDVs will be less polluting if operated on highways with higher speed limits.

The observed tradeoff between FC, CO_2 and PM in one hand and NO_x in the other hand is not simple to interpret even if it is intensively discussed in the literature (Jung et al., 2010, Aatola et al., 2008, Steeper and De Zilwa, 2006, Steeper and De Zilwa, 2007, Gomaa et al., 2011). One possible explanation for having higher NO_x emissions at lower fuel consumption alignment profiles is the favorable engine operating conditions enabled by those alignments. The created environment then favors thermal dissociation of molecular oxygen to produce atomic oxygen, which then react with nitrogen molecules to form NO – the Zeldovich mechanism (Gomaa et al., 2011, Willems et al., 2012). Both nitrogen and oxygen molecules are contained in the air injected into the engine for fuel combustion. The reverse effect of load factors can be attributed to change in the in-cylinder temperatures because of load differences. Thus, it is advisable to consider both FC and NO_x as targets in the alignment-adjustment process in order to achieve optimal results.

Beside the abovementioned points, other findings of great interest are also observed from presented results. Figure 8 shows that lowering fuel consumption to about 25%, in this work, implied reducing the elevation to around 100 meters. Although generated alignments, as seen in Figure 8, present patterns that are difficult to characterize, the main action of the proposed model remains flattening and shifting the initial alignment to result in a straight line. The trends of all generated alignment profiles of minimum fuel consumption confirm this statement.

The proposed models apply to two elements, which can be seen as our targets: total fuel consumption i.e. the overall fuel consumption for the considered road section, and overall elevation difference, which denotes the overall changes in slopes for the entire road section, by taking the squared root (Figure 14). It is necessary to underline here that patterns of generated alignments for the five considered speeds, as well as all metrics related to those alignments will have different trends depending on the employed optimization technique. The effect of weighting factors of the compromise programming optimization technique used in this work, combined to the employed criteria for selecting the optimal alignment (1 out of 100 alignments generated here), constitute the main reason of the less organized patterns seen in Figure 8. The same statement holds true for Figure 14 and numerical values produced in Table 5 to Table 7. In fact, when higher weight factors (i.e. 0.65 to 1) were assigned to a given objective, a much lower minimum value was returned compared to when lower weight factors were applied. At equal weight, the fuel consumption objective was found to be dominant due to the numerical importance of its values. The slope difference objective were found to be strictly dominant for weight values above 90%.

As the total fuel consumption comprises the fuel consumption for both senses of displacement of the vehicle (direct and reverse), a given reduction level will not necessarily result in same percentage of reduction for each sense, if taken individually. This can be understood by examining Table 5 to Table 7, which gives numerical values for the difference of performance indicators between the two-traffic senses, with respect to operating speeds and engine loads. Positive figures denote the cases where values of specific performance indicators in the direct sense were higher than that of the reverse sense. The general trend is yet the opposite.

Figures in Table 8 and Table 9 reveal that different behaviors can be observed at lower scale. In fact, values of the average-normalized performance indicators (efficacy and emission rates) do not necessarily decrease with the reduction levels. This behavior is also understood as the effect of the used optimization technique and selection process. Therefore, selection process and weighting techniques need to be done with solid expert judgement, in order to guide the whole process and thus, guarantee that obtained results reflect the goal fixed by decision makers.

As to each reduction level corresponds a vertical alignment generated for a given operating speed, it is obvious that one would have to decide on which alignment to go for and how to implement it in the planning phase. The main idea being to reduce the elevation differences alongside a road, two main strategies can help achieve this: a) introduce tunnels and overpass structures where elevation differences are more pronounced while sticking as much as possible with the initially proposed alignment, and b) choose a completely different corridor, which will have less variabilities in the vertical plan. The first case may imply the application of piecewise optimization to preidentified sections of the road (section-related optimization) whereas in the last option, a given alignment may be selected among the ones that are generated and implemented according to the enumerated planning goals. In either case, clear tradeoffs will need to be dealt with. Larger investment costs, longer driving distances, various environmental impacts and other social costs will occur. The optimum choice will be strictly project-related and will need to be carefully analyzed.

The optimization models developed in this study are based on the EMEP-EEA models and their related data. Thus, it inherits the limitations and weaknesses of the EMEP-EEA models. One such pitfall is the slope limitation, which restricts practitioners to consider only seven slope points, from -6% to +6% with increment of 2%. Slopes higher than 6% and lower than -6% cannot be assessed using this model. In addition, values of FC and Emissions factors are given only for those slope points, and are themselves suggested to large uncertainties. Derivation of intermediate slope values are then done by interpolation. This will yield different values with respect to the selected interpolation method. Another element to point out is the fact that some factors are taken as being exactly equal at certain speed and loads (see yellow cells in appendices).

As the EMEP-EEA models are revised quite often, it is important to notice that different versions will definitely yield different results. Practitioners must have enough knowledge of pros and cons of each version to decide on their use. All this said, it is therefore the responsibility of the decision-makers to decide on implementing such models in the perspective of sustainable road transport activities while focusing on the infrastructure.

Future investigations need to be conducted to explore the effect of other factors such as traffic mix, share of different drivetrains in the mix, the influence of construction cost, maintenance and operating cost, the life cycle environmental impacts, etc. on road vertical alignment optimization. The authors are considering moving towards those directions.

6. Conclusion

This paper proposes methods for the evaluation of the influences of key variables when modelling the effects of modifying highway's vertical alignment at early design phase, to generate new alignments that could potentially meet some fuel consumption and emissions requirements. Here, a single level approach was applied, which consisted in considering only one single vehicle of one selected technology, as a test agent for the overall evaluation process. Adjusting alignment of highways may result in huge reduction in road vehicle emissions and external pollution cost, thus induce important savings in various cost components such as emissions, fuel and money. However, careful analysis on case-to-case basis needs to be done, for selection of best options. This is due to tradeoffs that arise during the implementation of such processes. Reducing energy demand as a general concept is also important for all kind of road vehicles from conventional to hybrids, to electrics. Therefore, alignment adjustment studies will be of capital importance for the future of modern societies, in supporting governments' efforts towards establishment of carbon-neutral and resilient economies.

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Appendices

Appendice A

Tables about fuel consumption and emission factors of the test vehicle at different operating speeds

Table 10: Values of the factors at full load (Load = 100%)

Speed [km/h]	*Component*	*Slope [%]* -6	-4	-2	0	2	4	6
105	*FC*	3.136	3.518	24.266	197.035	477.861	736.176	954.733
	CO	0.001	0.020	0.214	1.415	2.754	2.423	2.978
	PM	0.000	0.000	0.000	0.020	0.037	0.035	0.037
	NOx	0.025	0.120	1.034	1.261	2.475	3.484	5.486
100	*FC*	3.568	4.365	27.387	200.183	474.349	736.176	954.733
	CO	0.001	0.026	0.234	1.434	2.799	2.423	2.978
	PM	0.000	0.000	0.000	0.021	0.038	0.035	0.037
	NOx	0.033	0.149	1.126	1.412	2.476	3.484	5.486
80	*FC*	6.386	10.496	45.209	217.866	468.279	738.219	954.733
	CO	0.015	0.072	0.360	1.553	3.023	2.764	2.978
	PM	0.000	0.000	0.002	0.025	0.044	0.041	0.037
	NOx	0.111	0.368	1.678	2.265	2.489	3.519	5.486
60	*FC*	13.214	26.038	77.655	249.022	480.358	749.320	1013.699
	CO	0.111	0.210	0.617	1.812	3.369	3.646	3.449
	PM	0.001	0.002	0.006	0.034	0.053	0.056	0.047
	NOx	0.379	0.938	2.762	3.796	2.594	3.704	5.397
40	*FC*	34.671	68.386	143.433	311.267	528.466	783.433	1042.402
	CO	0.413	0.660	1.234	2.450	4.016	5.015	5.022
	PM	0.005	0.010	0.021	0.051	0.073	0.083	0.085
	NOx	1.378	2.547	5.157	6.893	3.501	4.331	5.369

Table 11: Values of the factors at half load (Load = 50%)

Speed [km/h]	*Component*	*Slope [%]* -6	-4	-2	0	2	4	6
105	FC	0.868	3.588	26.853	188.178	424.092	650.513	872.781
	CO	0.000	0.041	0.255	1.359	2.832	2.567	2.508
	PM	0.000	0.000	0.000	0.017	0.035	0.034	0.036
	NOx	0.024	0.120	1.189	1.527	2.214	3.278	4.529
100	FC	1.144	4.441	29.930	190.544	420.579	650.513	872.781
	CO	0.000	0.048	0.277	1.376	2.849	2.567	2.508
	PM	0.000	0.000	0.001	0.018	0.036	0.034	0.036
	NOx	0.033	0.149	1.271	1.691	2.215	2.278	4.529
80	FC	3.506	10.572	47.130	204.920	414.255	647.154	872.781
	CO	0.012	0.098	0.401	1.483	2.952	3.082	2.508
	PM	0.000	0.000	0.002	0.023	0.040	0.042	0.036
	NOx	0.111	0.366	1.770	2.596	2.235	3.281	4.529
60	FC	11.097	26.040	77.744	232.261	425.436	652.611	879.009
	CO	0.115	0.229	0.640	1.719	3.163	3.832	3.555
	PM	0.001	0.002	0.006	0.031	0.049	0.056	0.053
	NOx	0.384	0.933	2.772	4.163	2.391	3.306	4.432
40	FC	37.233	68.239	139.590	289.724	471.539	683.376	907.223
	CO	0.431	0.653	1.213	2.315	3.667	4.994	5.228
	PM	0.005	0.010	0.021	0.047	0.067	0.080	0.083
	NOx	1.408	2.539	5.042	7.226	3.666	3.642	4.696

Table 12: Values of the factors at no load (Load = 0%, empty vehicle)

Speed [km/h]	*Component*	*Slope [%]* -6	*-4*	*-2*	*0*	*2*	*4*	*6*
105	FC	1.076	3.921	37.989	178.495	369.623	579.779	740.108
	CO	0.016	0.025	0.287	1.287	2.606	3.078	2.511
	PM	0.000	0.000	0.000	0.014	0.030	0.033	0.033
	NOx	0.031	0.034	1.518	1.881	1.751	2.828	3.847
100	FC	1.395	4.819	40.605	180.144	366.277	573.117	740.108
	CO	0.019	0.032	0.310	1.301	2.612	3.125	2.511
	PM	0.000	0.000	0.001	0.015	0.031	0.034	0.033
	NOx	0.041	0.074	1.582	2.055	1.756	2.828	3.847
80	FC	4.016	11.164	54.937	191.507	360.273	549.452	738.845
	CO	0.046	0.084	0.440	1.397	2.658	3.411	2.892
	PM	0.000	0.000	0.002	0.019	0.035	0.041	0.038
	NOx	0.129	0.342	1.991	2.983	1.826	2.831	3.847
60	FC	12.025	26.845	80.555	215.361	370.963	546.780	742.398
	CO	0.127	0.231	0.686	1.612	2.790	3.833	3.883
	PM	0.001	0.002	0.006	0.027	0.043	0.052	0.053
	NOx	0.418	0.963	2.869	4.530	2.213	2.867	3.850
40	FC	38.690	69.091	135.678	268.358	415.245	582.444	767.222
	CO	0.437	0.697	1.262	2.172	3.218	4.564	5.358
	PM	0.005	0.010	0.020	0.043	0.061	0.073	0.081
	NOx	1.458	2.586	4.988	7.471	4.332	3.373	3.947

Appendice B
Tables summarizing the way road sections longitudinal slopes have been subdivided and then grouped based on the length of each section.

Table 13: Arrangement of alignment information (appropriate grouping)

#	*Range (R_n)*	*Distance in range (D_n)*
1	5%≤ S≤6%	D_1
2	4% ≤ S <5%	D_2
3	3% ≤ S <4%	D_3
4	2% ≤ S <3%	D_4
5	1% ≤ S <2%	D_5
6	0% ≤ S <1%	D_6
7	-1%< S <0%	D_7
8	-2%< S ≤-1%	D_8
9	-3%< S ≤-2%	D_9
10	-4%< S ≤-3%	D_{10}
11	-5%< S ≤-4%	D_{11}
12	-6%≤ S ≤-5%	D_{12}

Appendice C
Compromised programming problem formulation for the percentage-target reduction levels.
It is set:

$$\Delta S(X) = \sum_{i} (X_I - X)^2 \qquad \text{C. 1}$$

$$F(X) = \sum E[X]_{l,fuel(d,r)}(v) \times L_i - (1-\beta) \times \sum E[X_I]_{l,fuel(d,r)}(v) \times L_i \qquad \text{C. 2}$$

and the function to be minimized is

$$AOF(X) = [\Delta S(X),\ F(X)] = \omega_1 \times \Delta S(X)^m + \omega_2 \times F(X)^m \qquad \text{C. 3}$$

with the following constraints

$$subject\ to \begin{cases} h_1(X) = x_{I,1} \times L_1 - x_1 \times L_1 = 0 \\ h_2(X) = \sum X_I \times L_i - \sum X \times L_i = 0 \\ \quad -0.06 \leq X \leq 0.06 \end{cases} \qquad \text{C. 4}$$

$$E[X]_{l,fuel(d)}(v) = pchip\ (Discrete\ slopes, Factors\ corresponding\ to\ discrete\ slopes, X)$$
$$E[X]_{l,fuel(r)}(v) = pchip\ (Discrete\ slopes, Factors\ corresponding\ to\ discrete\ slopes, -(X))$$

Where

$$\beta \in \{0.05, 0.10, 0.15, 0.20, 0.25, etc.\}$$

m : Even integer less than or equal to 8;

$$\sum_{i=1}^{k} \omega_i = 1 \qquad ;\ here\ k = 2\ i.e\ columns\ of\ \omega, with\ \omega\ a\ N \times 2\ array\ containing\ weights.$$

$AOF(X)$ is the aggregated objective function, which converts the multiobjective optimization problem to a scalar problem by mean of weighting sum; ω_i are the weighting coefficients that represent the relative importance of each objective.

The number of generated alignment is equal to the number of possible combinations ω_1 ω_2 that can be achieved, from problem definition. In this work 100 optimized alignments were generated each times, and the one returning $\Delta S(X)$ and $F(X)$ within the range of 10% difference, and the lowest standard deviation, simultaneously, was selected.

Appendice D

Table 14: Targeted and achieved optimization results (constraints, bounds and goals) at each target levels and for considered speeds**.**

Speed [km/\h]	*Target level*	*Targeted FC*	*Achieved FC*	*iSP [m]*	*aSP [m]*	*iEP [m]*	*aEP [m]*	*tmS [%]*	*amS [%]*	*tMS [%]*	*aMS [%]*
	0 %	33342.45	33342.45	0.000	0.000	-10.134	-10.134	-6.00	-6.00	6.00	6.00
	Dsmin	…	33329.52	0.000	0.000	-10.134	-10.134	-6.00	-5.97	6.00	5.97
	5 %	31675.32	31674.16	0.000	0.000	-10.134	-10.134	-6.00	-5.59	6.00	5.81
	10 %	30008.20	30010.94	0.000	0.000	-10.134	-10.134	-6.00	-6.00	6.00	6.00
105	*15 %*	28341.08	28343.98	0.000	0.000	-10.134	-10.134	-6.00	-4.34	6.00	3.91
	20 %	26673.96	26677.53	0.000	0.000	-10.134	-10.134	-6.00	-4.26	6.00	4.24
	25 %	25006.83	25004.04	0.000	0.000	-10.134	-10.134	-6.00	-3.62	6.00	3.94
	Fcmin	…	22354.66	0.000	0.000	-10.134	-10.134	-6.00	-0.02	6.00	0.00
	0 %	33444.90	33444.90	0.000	0.000	-10.134	-10.134	-6.00	-6.00	6.00	6.00
	Dsmin	…	33432.08	0.000	0.000	-10.134	-10.134	-6.00	-5.97	6.00	5.97
	5 %	31772.65	31775.24	0.000	0.000	-10.134	-10.134	-6.00	-5.74	6.00	5.72
	10 %	30100.41	30103.49	0.000	0.000	-10.134	-10.134	-6.00	-6.00	6.00	6.00
100	*15 %*	28428.16	28430.46	0.000	0.000	-10.134	-10.134	-6.00	-4.00	6.00	4.19
	20 %	26755.92	26757.68	0.000	0.000	-10.134	-10.134	-6.00	-3.72	6.00	3.49
	25 %	25083.67	25081.58	0.000	0.000	-10.134	-10.134	-6.00	-2.92	6.00	3.43
	Fcmin	…	22711.70	0.000	0.000	-10.134	-10.134	-6.00	-0.02	6.00	0.00
	0 %	34361.66	34361.66	0.000	0.000	-10.134	-10.134	-6.00	-6.00	6.00	6.00
	Dsmin	…	34349.31	0.000	0.000	-10.134	-10.134	-6.00	-5.97	6.00	5.97
	5 %	32643.57	32645.79	0.000	0.000	-10.134	-10.134	-6.00	-5.64	6.00	5.64
	10 %	30925.49	30927.88	0.000	0.000	-10.134	-10.134	-6.00	-6.00	6.00	6.00
80	*15 %*	29207.41	29204.50	0.000	0.000	-10.134	-10.134	-6.00	-4.99	6.00	4.82
	20 %	27489.32	27486.08	0.000	0.000	-10.134	-10.134	-6.00	-4.28	6.00	3.06
	25 %	25771.24	25768.60	0.000	0.000	-10.134	-10.134	-6.00	-2.07	6.00	2.82
	Fcmin	…	24717.67	0.000	0.000	-10.134	-10.134	-6.00	-0.02	6.00	0.00
	0 %	37050.97	37050.97	0.000	0.000	-10.134	-10.134	-6.00	-6.00	6.00	6.00
	Dsmin	…	37034.27	0.000	0.000	-10.134	-10.134	-6.00	-5.97	6.00	5.97
	5 %	35198.42	35200.59	0.000	0.000	-10.134	-10.134	-6.00	-5.70	6.00	5.70
	10 %	33345.87	33348.15	0.000	0.000	-10.134	-10.134	-6.00	-4.52	6.00	3.89
60	*15 %*	31493.32	31489.93	0.000	0.000	-10.134	-10.134	-6.00	-2.99	6.00	2.86
	20 %	29640.78	29637.62	0.000	0.000	-10.134	-10.134	-6.00	-2.82	6.00	2.69
	25 %	…	…	…	…	…	…	…	…	…	…
	Fcmin	…	28252.29	0.000	0.000	-10.134	-10.134	-6.00	-0.02	6.00	0.00
	0 %	42708.99	42708.99	0.000	0.000	-10.134	-10.134	-6.00	-6.00	6.00	6.00
	Dsmin	…	42693.29	0.000	0.000	-10.134	-10.134	-6.00	-0.02	6.00	0.00
	5 %	40573.54	40576.46	0.000	0.000	-10.134	-10.134	-6.00	-5.70	6.00	5.70
	10 %	38438.09	38437.67	0.000	0.000	-10.134	-10.134	-6.00	-4.52	6.00	3.89
40	*15 %*	36302.64	36299.44	0.000	0.000	-10.134	-10.134	-6.00	-2.99	6.00	2.86
	20 %	…	…	…	…	…	…	…	…	…	…
	25 %	…	…	…	…	…	…	…	…	…	…
	Fcmin	…	35314.16	0.000	0.000	-10.134	-10.134	-6.00	-2.82	6.00	2.69

where:

FC: Fuel consumption [in grams]

iSP: Elevation of initial stating point (from the initial alignment)

aSP: Achieved elevation of the starting point after optimization

iEP: Elevation of the initial endpoint (from the initial alignment)

aEP: Achieved endpoint elevation after optimization
tmS: Fixed lower bound of Slopes (target minimum slope)
amS: Achieved lower bound of slopes (achieved minimum slope);
tMS: Fixed upper bound of slopes (target maximum slope);
aMS: Achieved upper bound of slopes (achieved maximum slope).

Appendice E
Data for calculation of External Cost of Pollution (Including Climate Change)

Table 15: Direct cost expressed in € 2000 per ton of pollutant Emissions 2010

NOx	*NMVOC*	*SO_2*	*$PM_{2.5}$*	*PM_{10}*
2000	300	2500	30100	12000
1100	300	900	30100	12000

Source: (Maibach et al., 2008)

Table 16: Cost of CO

Sources	*Time horizon*		
	20 years	*100 years*	*500 years*
(Daniel and Solomon, 1998)	2.8	1.0	0.3
(Fuglestvedt et al., 1996)	10.0	3.0	1.0

Table 17: Recommended values for Climate Change cost in € per ton CO_2 eq.

Year	*Values*		
	Min	*Mean*	*Max*
2010	7	25	45
2020	17	40	70
2030	22	55	100
2040	22	70	135
2050	20	85	180

Source: (Maibach et al., 2008)

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