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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).

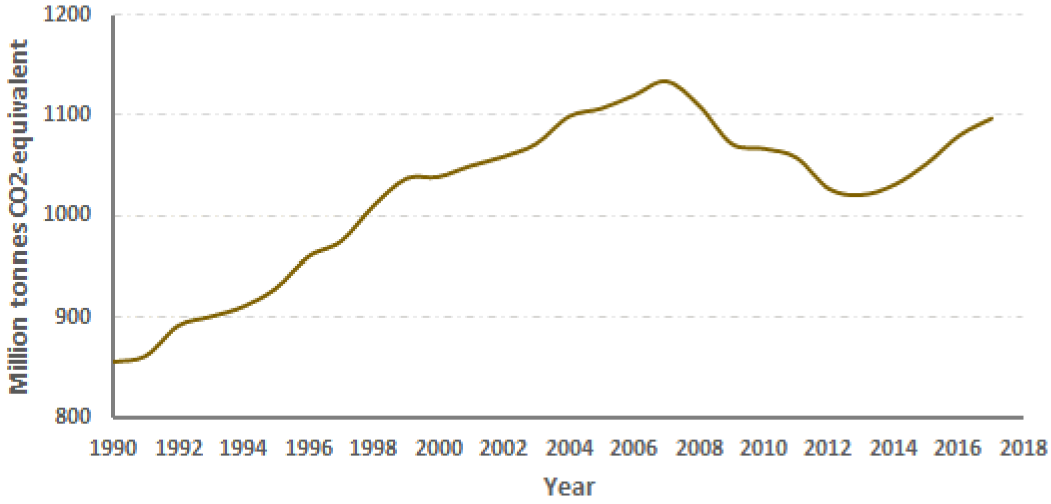

Figure 1: Evolution of greenhouse gas emissions from transport, EU (1990 - 2017). International aviation is included while international shipping is not.
Source: European Environment Agency, 2018

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).

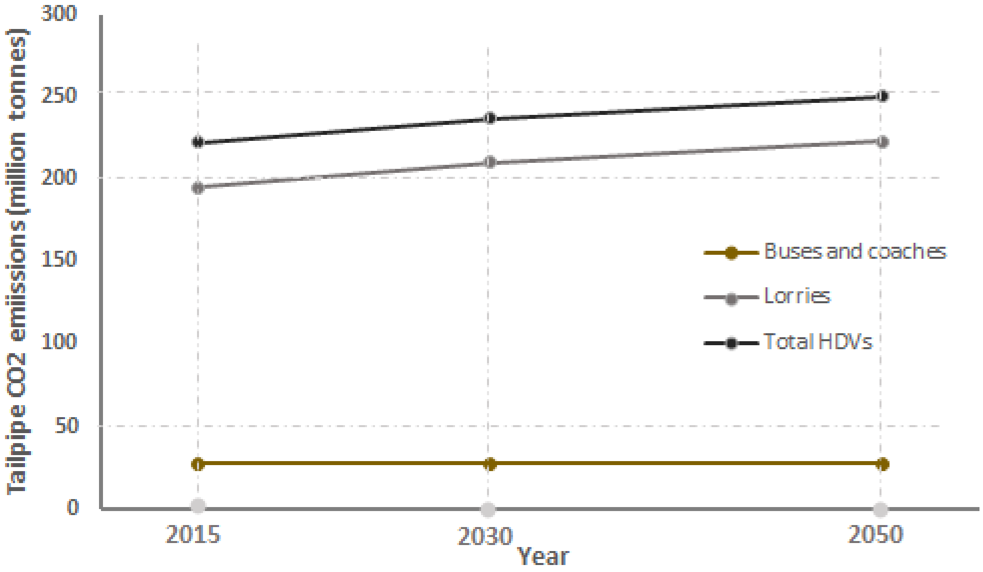

Figure 2: Heavy Duty Vehicles CO_2 emissions projections 2020 – 2050 (EU 28)
Source: PRIMES TREMOVE, 2016

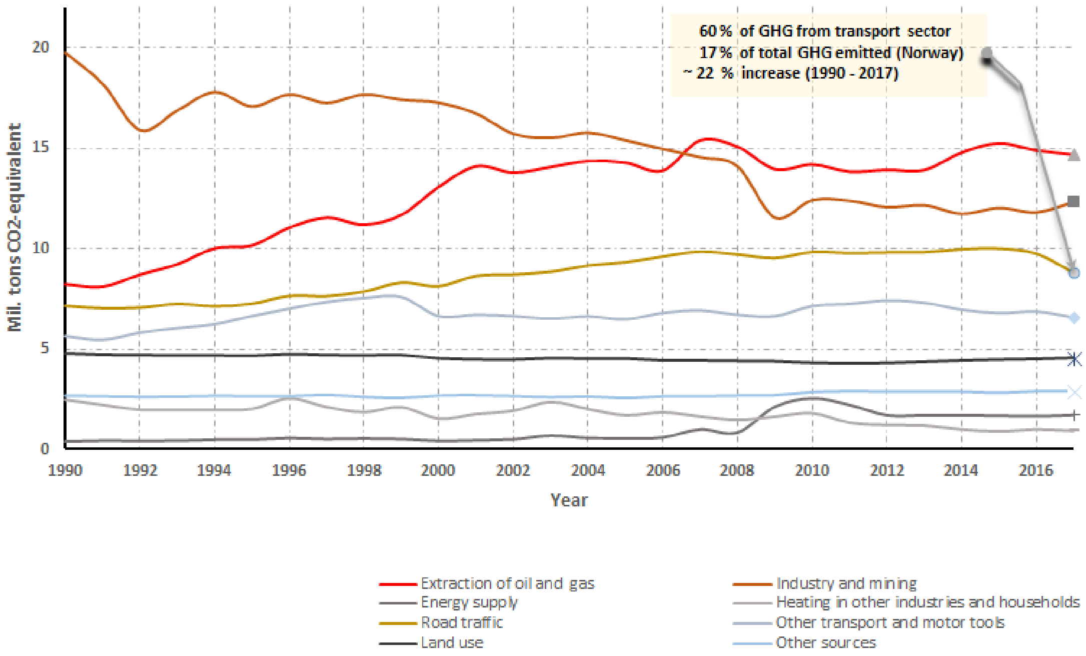

Figure 3: Norwegian greenhouse gas emissions per sector (1990 - 2017)
Source: Statistics Norway, 2018

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 influences 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.

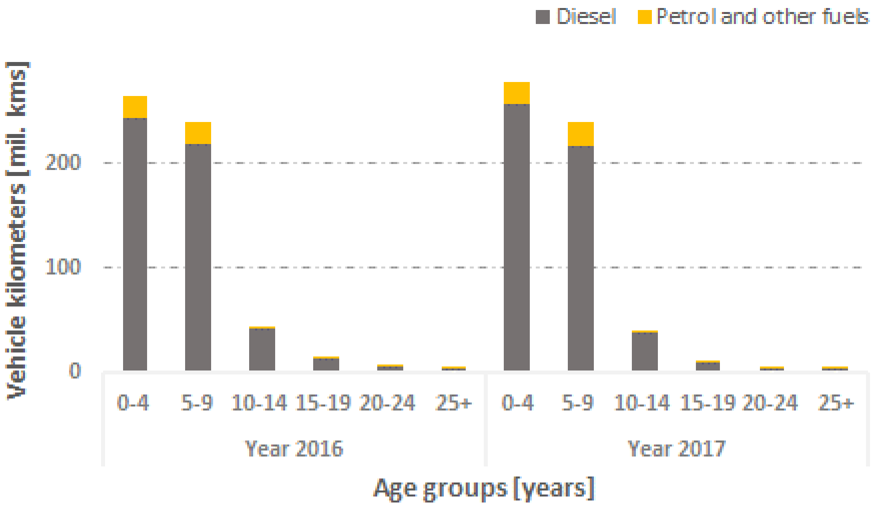

Figure 4: Traffic volume for all Norwegian busses per fuel type and vehicle age (2016, 2017)
Source: Statistics Norway, 2018.

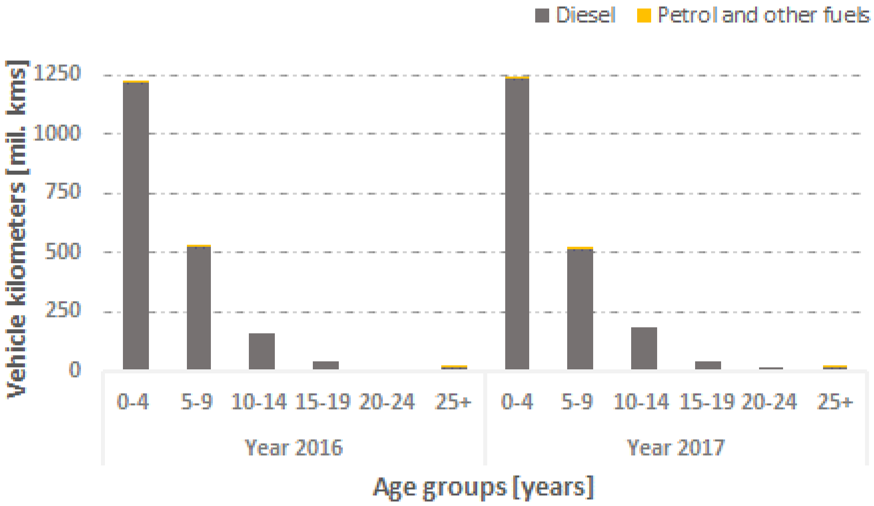

Figure 5: Traffic volume for all Norwegian heavy lorries and road tractors per fuel type and vehicle age (2016, 2017)
Source: Statistics Norway, 2018.

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.

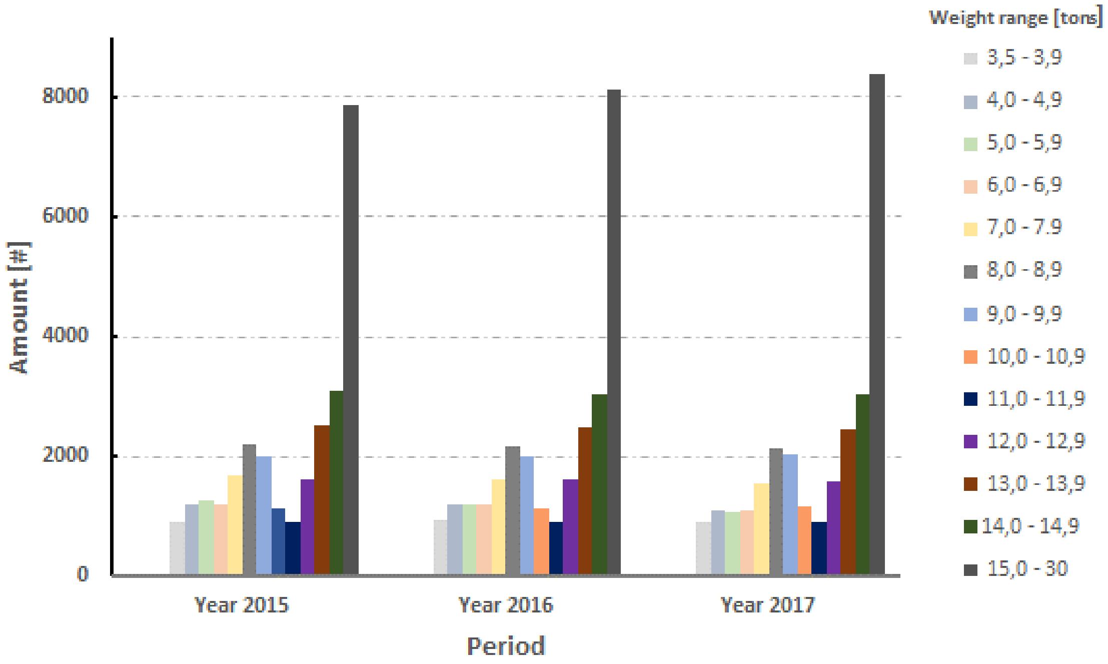

Figure 6: Norwegian registered lorries by carrying capacity (2015 - 2017)
Source: Statistics Norway, 2018

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		*1992 - 1996 (Euro I);*	2000 - 2005/2008 (Euro
	In Europe:	*1996 - 2000 (Euro II);*	IV/V);
		1996 - 2000 (Euro III);	after 2014 (Euro VI);
		1960 - 1970 (Clean Air Act, California standards);	
		1970 - 1990 (CAA, EPA);	
	In the US:	*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,	
	In the US:	199/96/E, etc.	
		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, taking into account 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 $[x_1, x_{2,} {}_{x3}\dots\dots\dots x_n]$ (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).

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

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 exists 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	$\Delta S(X) = \sum_i (X_I - X)^2$	$h_2(X) : \sum X_I \cdot L_i - \sum X \cdot L_i = 0$ $h_3(X) : -0.06 \le X \le 0.06$
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, StatensVegvesen, 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*	*Consideredvalue*
Diesel fuel	$r_{H:C}$	2.00
	$r_{O:C}$	0.00
Lubricantoil	$r_{H:C}$	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), $\Delta S(X)$ 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).

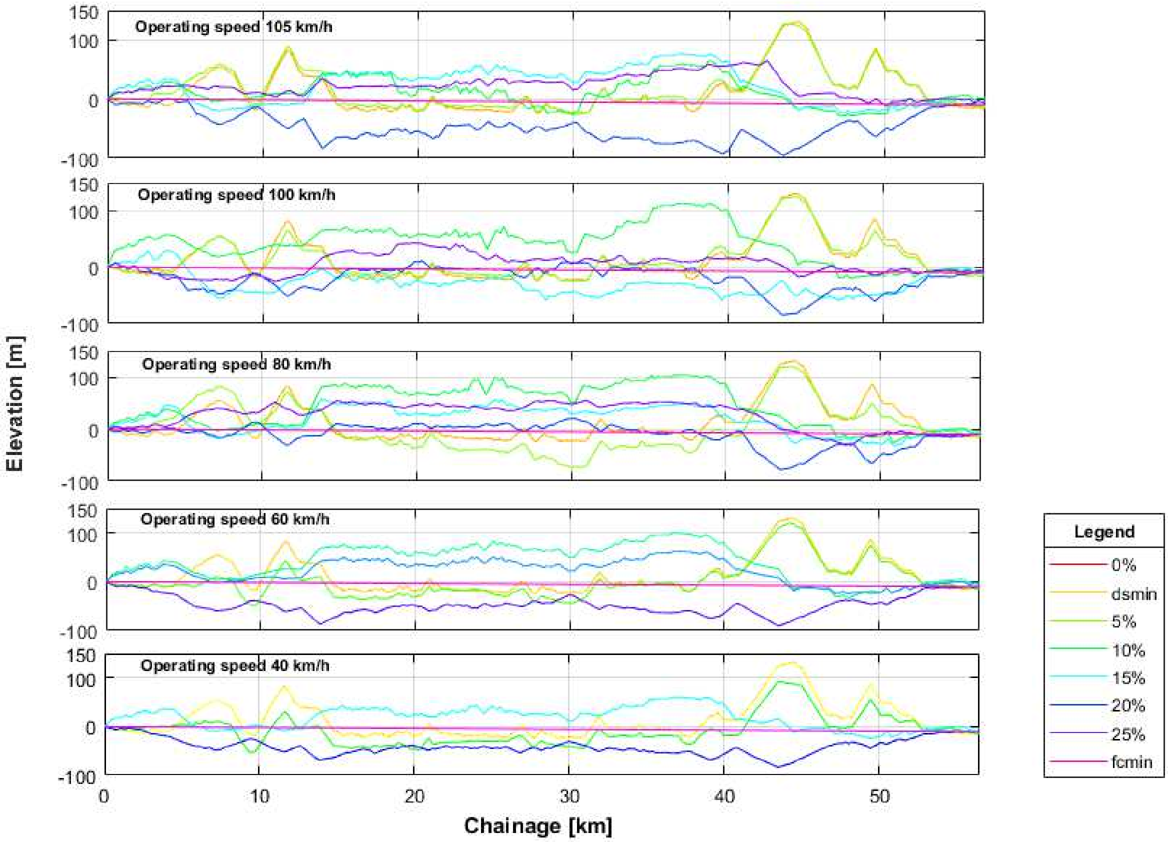

Figure 8: Trends of generated alignments for each reduction target and specified operating speed

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.

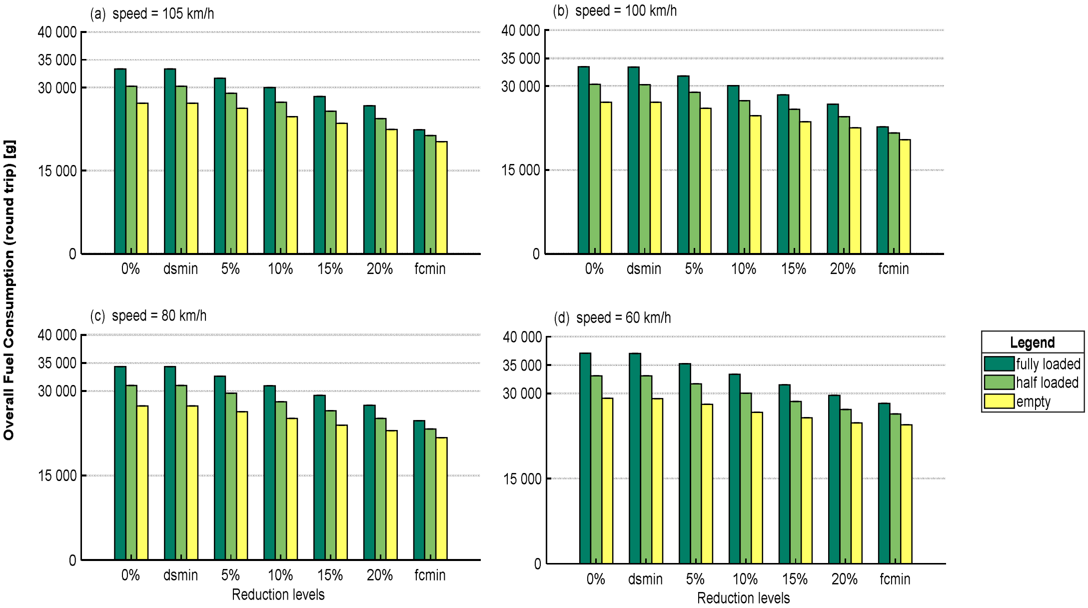

Figure 9: Fuel consumption performance of generated alignments with respect to operating speed and engine loads

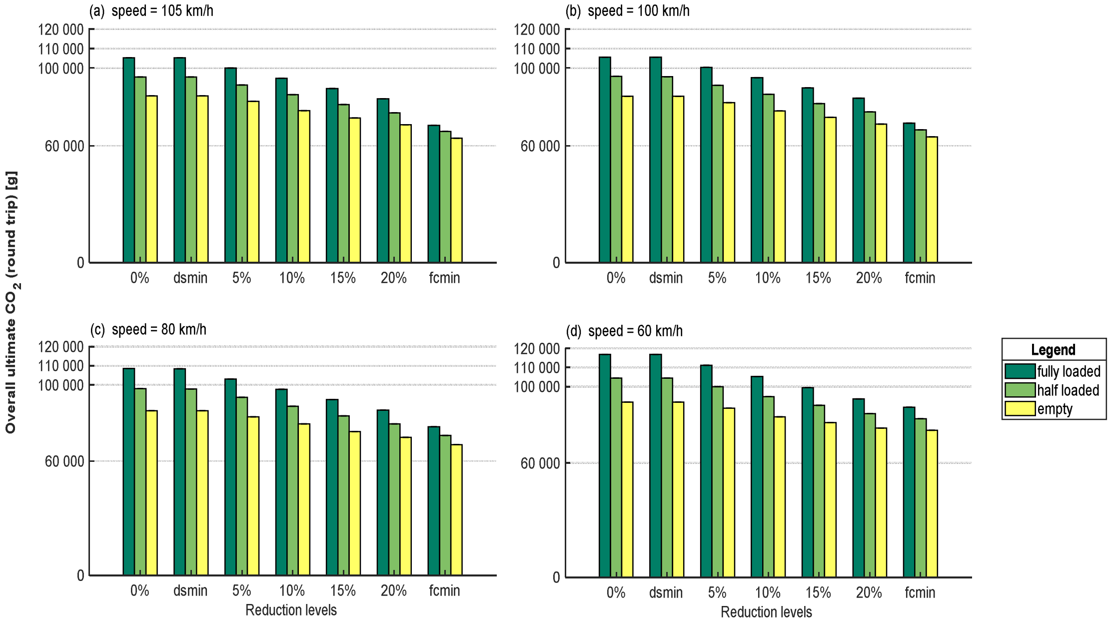

Figure 10: CO_2 performance of generated alignments with respect to operating speed and engine loads.

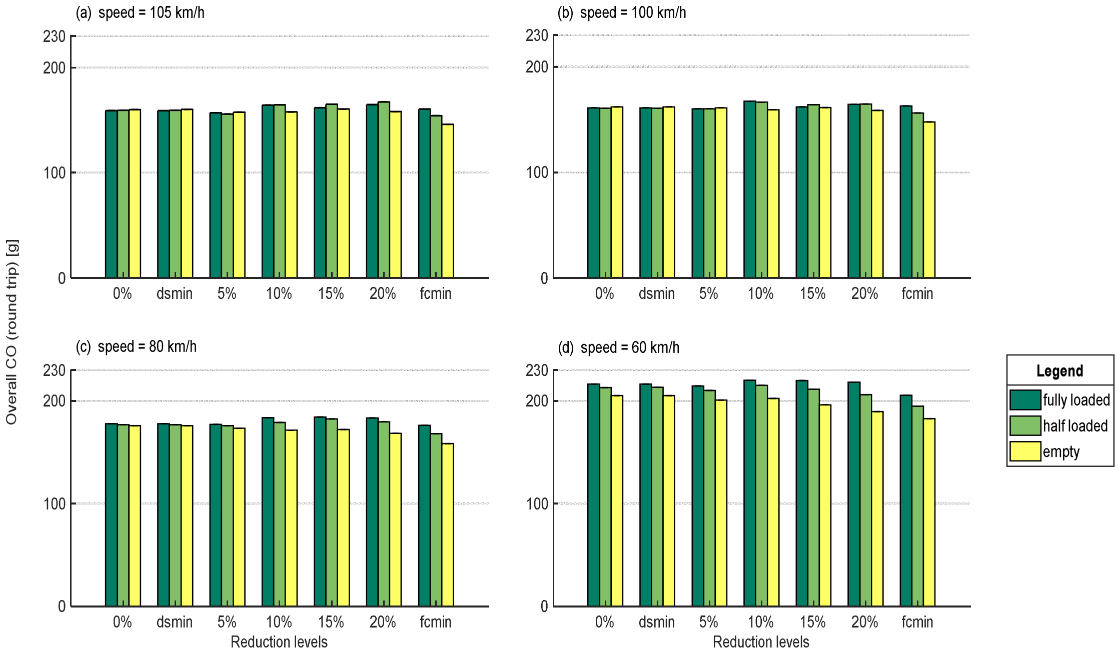

Figure 11: CO performance of generated alignments with respect to operating speed and engine loads.

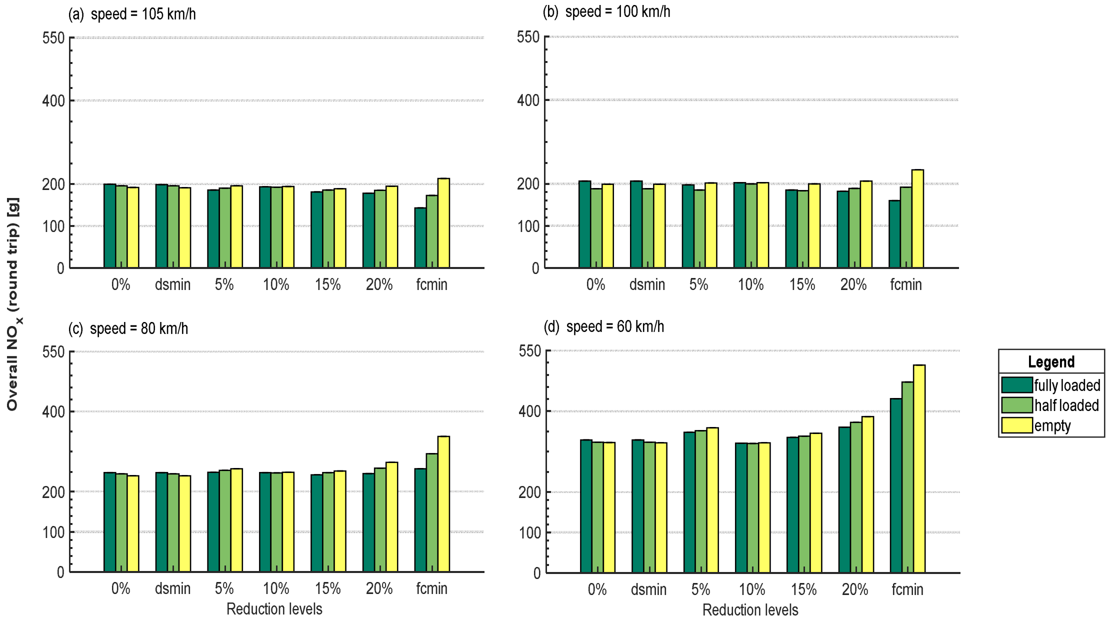

Figure 12: NO_x performance of generated alignments with respect to operating speed and engine loads.

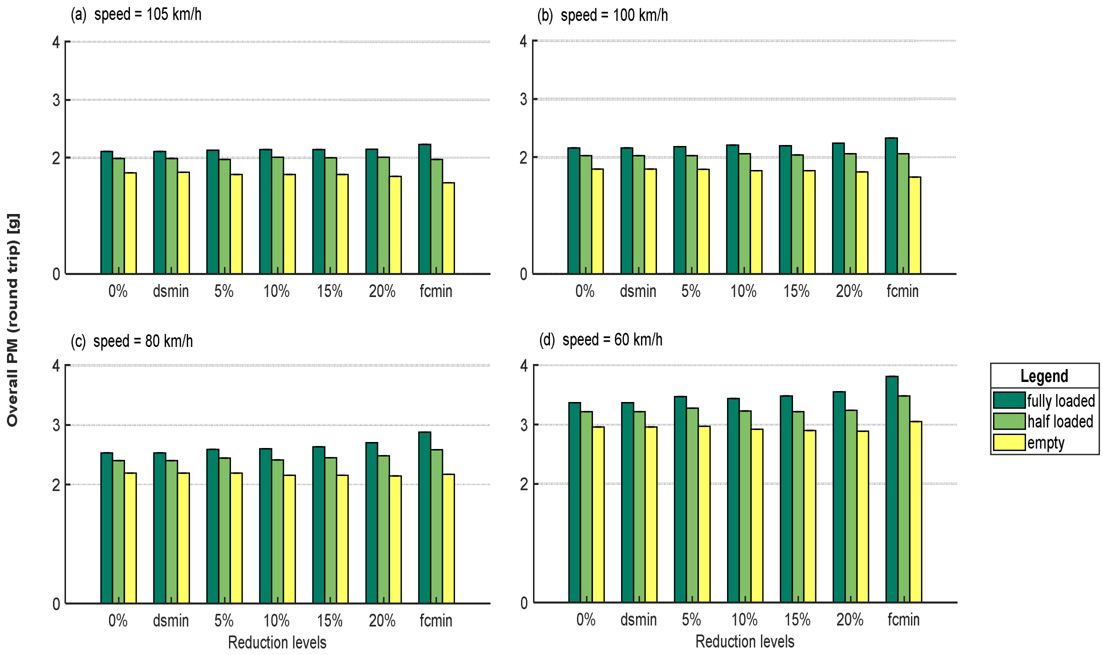

Figure 13: PM performance of generated alignments with respect to operating speed and engine loads.

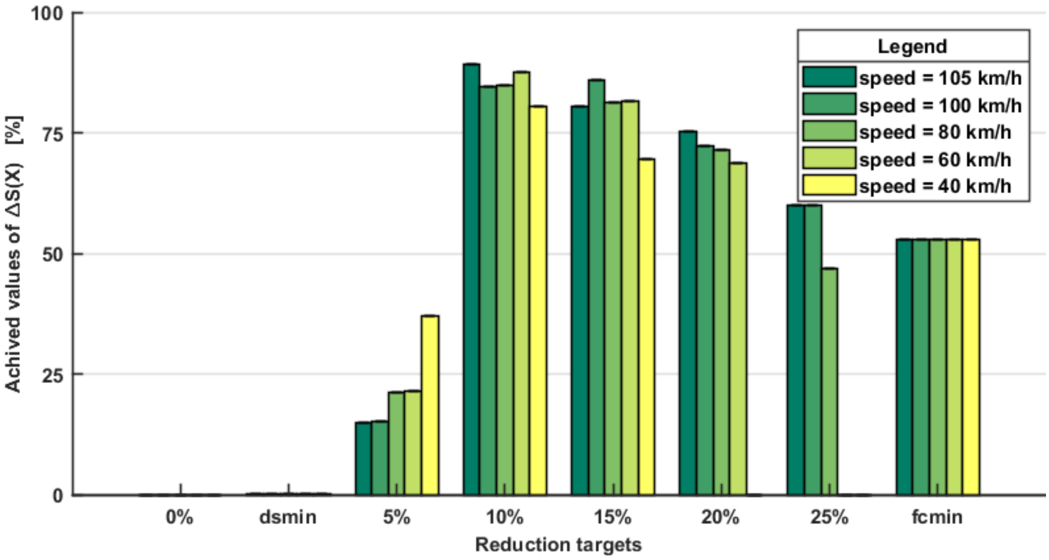

Figure 14: Achieved overall slope difference ΔS(X) with respect to reduction targets.

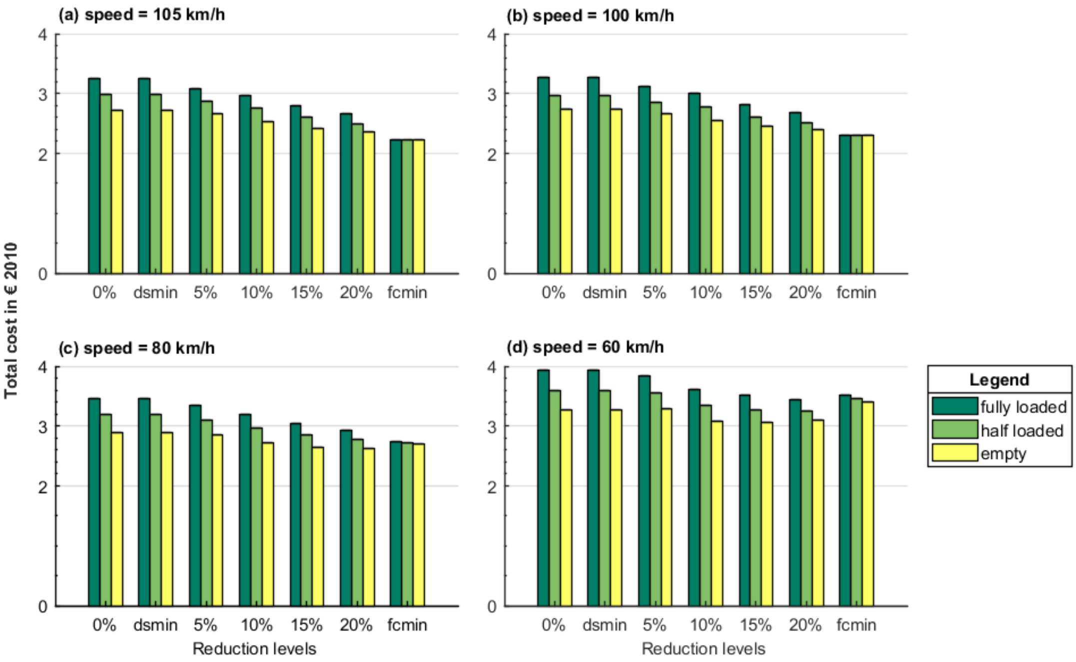

Figure 15: External cost of pollution (climate change). (for cost factors see appendices)

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, YazdaniBoroujeni 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 conventionals 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

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

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

Where

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

m : Even integer less than or equal to 8;

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

$AOF(X)$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 $\omega_1\omega_2$ 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 [%]*
105	*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
	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
100	*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
	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
80	*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
	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
60	*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
	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
40	*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
	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)