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Theoretical Considerations from the Modelling of the Interaction between Road Design and Fuel Consumption on Urban and Suburban Roadways

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Abstract: A roadway path is most commonly perceived as a 3-D element structure placed within its surrounding environment either within or outside urban areas. Design guidelines are usually strictly followed to ensure safe and comfort transportation of people and goods, but in full alignment with the terrain configuration and the available space, especially in urban and suburban areas. In the meantime, vehicles travelling along a roadway consume fuel and emit pollutants in a way that depends on both the driving attitude as well as the peculiar characteristics of road design and/or pavement surface condition. This study focuses on the environmental behavior of roadways in terms of fuel consumption, especially of heavy vehicles that mainly serve the purpose of freight transportation within urban areas. The impact of horizontal and vertical profiles of a roadway structure is theoretically considered through the parameters of speed and longitudinal slope, respectively. Based on theoretical calculations with an already developed model, it was found that the slope plays the most critical role, controlling the rate of fuel consumption increase, as an increase ratio of 2.5 was observed for a slope increase from 2% to 7%. The variation was less intense for a speed ranging from 25 to 45 km/h. The investigation additionally revealed useful discussion points for the need to consider the environmental impact of roadways during the operation phase for a more sustainable management of freight transportation procedures, thereby stimulating an ad hoc development of fuel consumption models based on actual measurements so that local conditions can be properly accounted for and used by road engineers and/or urban planners.

Keywords: road design; longitudinal slope; speed; urban infrastructure; fuel; environmental impact; sustainability; theoretical model calculations

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1. Introduction

1.1. Problem Statement

The geometric design of safe road structures produces a three-dimensional layout for a roadway that comes as a counterbalance between three individual parts. These include the establishment of (i) the horizontal alignment (i.e., tangents, curves, etc.), (ii) the vertical alignment (i.e., longitudinal slope, vertical curves, sight distance, etc.), and (iii) the cross-sectional profile (i.e., lanes, shoulders, curbs, sidewalks, etc.). A rational design is expected to ensure sufficient traffic flow at normal operating speeds with safety, functionality, and an aesthetic interaction with the surrounding environment [1,2].

The use of roadway paths by travelling vehicles is consistent with the fact that a considerable contribution rate to worldwide energy consumption and greenhouse gas emissions occurs. This becomes even more critical for urban areas, considering, for example, that more than 70% of the European population lives in urban areas [3], with similar trends elsewhere. As an ecosystem type, an urban area produces a disproportionate amount of road traffic emissions compared to its geographic extent, because of insufficiently designed road infrastructures, increased traffic congestion, and an aged vehicle fleet [4]. Globally, efforts are being made towards the mitigation of vehicle emissions and overall energy consumption [4,5]. Two strategic pillars are responsible for fulfilling this goal: infrastructure status and the vehicle industry.

Indeed, the automotive industry has already faced the imperative challenge to reduce energy consumption and carbon emissions, by introducing new vehicle technologies like hybrid electric vehicles, full electric vehicles, and fuel cell vehicles [6–8]. Even for the future case of the full adoption of Connected Autonomous Vehicles (CAVs), the potential to reduce fuel consumption has been reported from preliminary research investigations, thanks to the ability of CAVs to better control the acceleration rate and regenerative braking [9]. Nevertheless, even for the time being, where a mixed vehicle fleet is applied including traditional thermal vehicles (i.e., internal combustion engine vehicles) and other more environmentally friendly ones, the aspect of fuel consumption continuously revives as a matter of concern within the infrastructure community.

However, the potential contribution of road infrastructure components and geometric design features to the energy efficiency of vehicles has yet to be clearly understood by the related stakeholders and decision-makers within the road and vehicle industry disciplines. Recent studies suggest that improvements in transport infrastructure conditions are helpful for increasing traffic efficiency and reducing the overall fuel consumption and/or unhealthy emissions of the transport system [6].

1.2. Background

A major component of the urban transportation needs includes trucks and heavy vehicles that are responsible for freight logistics management. The longitudinal slope of roads during urban freight distribution routes has a strong impact on fuel consumption [10]. The higher the positive slope (i.e., uphill movement), the higher the rate of fuel consumption. Indeed, a parabolic relationship between positive slopes and fuel consumption rates with an R^2 of 0.93 has been reported [11]. In terms of the road horizontal profile, the rate of curvature changes and the resulting average speeds have a significant impact on the average fuel consumption and gas emissions [11]. Furthermore, with respect to the pavement condition, low roughness levels are known to improve fuel efficiency and general vehicle costs [12]. Finally, structural soundness and the absence of surface distresses act in favour of users' comfort that, in turn, leads to normal operating speeds [13,14].

Considering the connection between fuel consumption and air pollution in urban and suburban areas, several estimation models for vehicle emissions have been developed [15–17]. Overall, there is a wide consensus that the road vertical profile (i.e., longitudinal slope) is one of the major road design factors controlling the rate of fuel consumption and/or vehicle emissions [11,17–19]. Supplementary to this aspect, the impact of the horizontal profile of a roadway can be indirectly considered through the travelling speed. According to Figure 1, there is a green range of speed where fuel consumption can be optimized and be kept at the lowest possible levels for both thermal and other eco-friendly vehicles.

The combined impact of both the horizontal and vertical profiles of a road section on fuel consumption is shown in Figure 2. It can be seen that the optimal speed range varies depending on the road slope [20]. The interaction between fuel consumption and road design consistently attracts research interest [21,22]. Notably, Coreit et al. [23] recently developed an energy-based modelling criterion to support road managers to adopt fuel consumption patterns for a given speed through the consideration of road design features, including longitudinal slopes and sight distances.

Of course, the factor of vehicle weight can significantly alter the green range of optimal speeds. The amount of freight being carried by a vehicle is important, as it affects the power required by the vehicle and, thus, fuel consumption. Furthermore, it is well-known that freight transportation is mainly performed through road routes within urban and suburban areas. As such, an optimal road infrastructure design is important for keeping the cost of freight transportation as low as possible in order to maintain an economic and competitive edge [17].

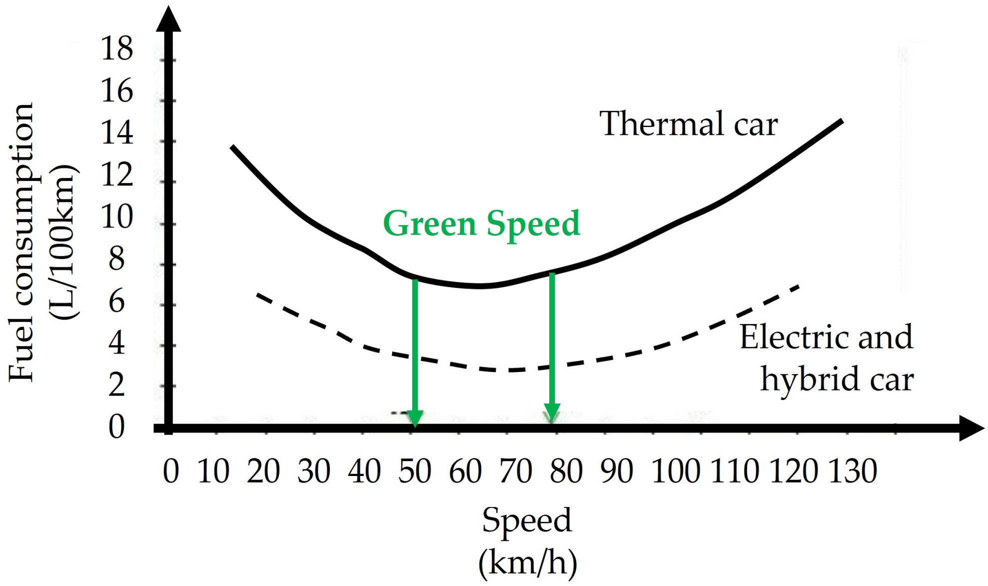

Figure 1. Fuel–speed relationship for thermal and eco-friendly vehicles (adapted from [19]).

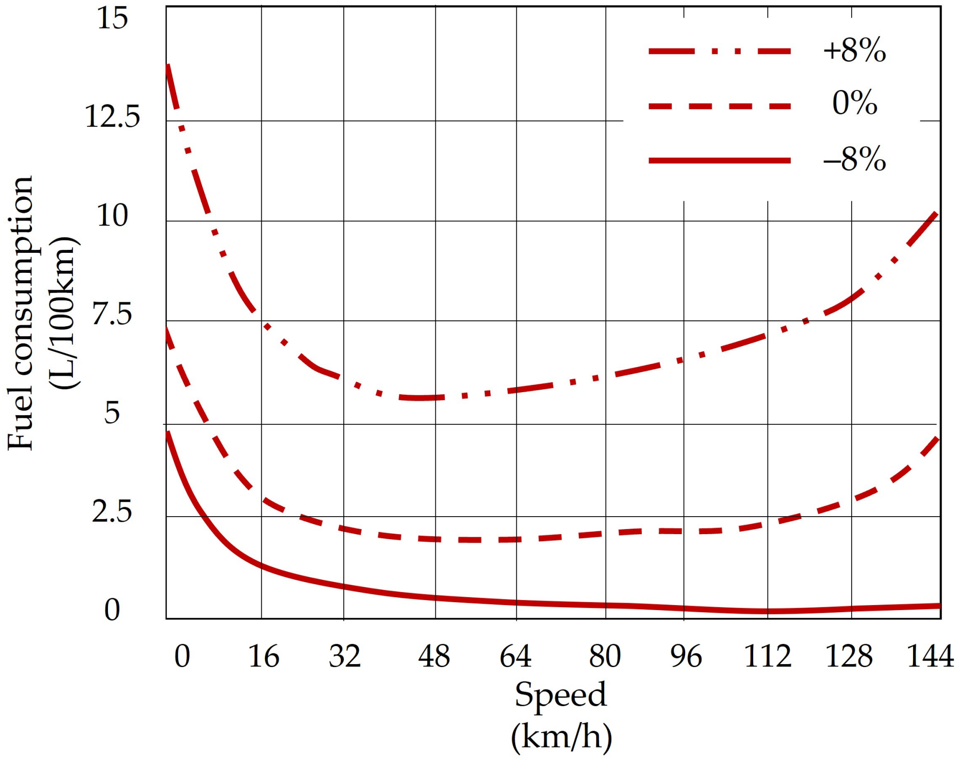

Figure 2. Combined effect of speed and slope on fuel consumption (adapted from [20]).

Considering these remarks, it must be acknowledged that many modelling efforts internationally exist about this subject. Jang et al. [15] invested in the development of vehicle emission estimation models on the basis that fuel consumption directly affects emissions. They have categorized their efforts into macroscopic and microscopic models by concluding that microscopic emission estimation models can fully consider the changes in driving behavior by utilizing the trajectory data of each vehicle.

Ferreira et al. [16] attempted to classify the energy efficiency of different roadways based mainly on physical principles. They used data from free traffic flow of a Portuguese highway for validation purposes and they proposed a methodology that characterizes traffic energy-efficiency as a function of the origin–destination movements, or road use, discriminating the vehicle mechanical energy from motion-related energy losses.

Posada-Henao et al. [17] aimed to consider vehicle operating costs in the benefit–cost analysis of roads and their methodology included the design of experiments and factorial design as statistical techniques to obtain data, as well as linear and non-linear regressions to obtain models for two types of trucks: rigid (three axles) and articulated (six axles). They reported improved prediction accuracy.

Indeed, these are the trucks mainly used for freight transportation in urban and suburban roadways. Therefore, modelling their energy behavior appears to be challenging.

1.3. The Case of Urban and Suburban Roads

Freight corridors are widely located within an urban area or a suburban area with the form of a bypass motorway, comprising of multitude of horizontal and vertical road elements. Typical examples of an urban bypass motorway with horizontal and vertical profiles as well as its speed limits, set as a result of the design elements, are shown in Figures 3 and 4. This motorway that was theoretically considered was an arterial roadway consisting of two lanes per direction; each lane had a width of 3.75 m.

Figure 3. Example of an urban bypass motorway in an urban setting with both horizontal and vertical profiles.

As expected, heavy-duty vehicles are supposed to operate at lower speeds for safety reasons. Therefore, their fuel consumption rate substantially differentiates from that of lighter vehicles. In addition, there is a strong interaction between fuel consumption rates and carbon dioxide emissions. Llopis-Castelló et al. [24] proved that smooth road segments without sharp changes in the vertical profile normally allow drivers to reach higher speeds and maintain them with fewer accelerations, thereby leading to fewer emissions. On the other hand, lower mean speeds produce high carbon dioxide emission rates, that can be even magnified on roadways with high-speed dispersions [24]. An increase in the curvature change rate positively affects carbon dioxide emission rates too.

Figure 4. Example of a speed limit set on an urban bypass motorway because of its vertical and horizontal profiles.

It can be concluded that investigation of the environmental implications of road design in terms of the geometric elements can help towards optimizing freight transportation costs. Therefore, continuous research with model development for energy-related issues during vehicle movement continuously revives as an open and timely issue within the scientific community. This means that road engineers should consider the design aspects on a case-by-case basis, so that they can reveal a powerful tool for road operators and urban development decision-makers towards a more sustainable direction.

2. Aim and Objectives

On these grounds, the aim of this paper is to demonstrate the impact of road geometric data and vehicle weight on the fuel consumption rate through theoretical calculations based on an already developed predictive model. In terms of this paper's novelty, the investigation of the variability in the prediction of fuel consumption enables one to make suggestions towards enhancing and optimizing route selection for freight transportation and potentially modifying or improving road design aspects during the initial planning of new urban or suburban roads and/or safety interventions in existing parts of the urban road network. Of course, potential restraints because of the terrain configuration and the available space should be considered. To meet the research's aim, the following objectives are set:

- First, a brief review of the current related practice for fuel estimation is presented and a proper model is selected to perform sensitivity analysis for the theoretical estimation of fuel consumption;
- Thereafter, an investigation of the parameters affecting fuel consumption is performed, including vehicle weight and features of the horizontal and vertical road profiles. Change rates of fuel demand are comparatively discussed;
- Based on the presented theoretical results, critical discussion points are made with useful environmental implications for the decision-makers and those engaged in freight transportation management following a sustainable perspective.

Overall, the ultimate goal is to highlight the need to perform an ad hoc development of fuel consumption models based on actual measurements on a variety of urban and/or suburban roadways with varying horizontal and vertical profiles, so that local conditions can be properly accounted for and used by road engineers and/or urban planners. The engineering community together with local authorities should be prepared to jointly invest in similar investigations so that the quality of life in urban areas can be even more improved.

The focus mainly on urban areas lies upon the fact that the carbon footprint of urban roadways is enough high, considering all the phases of a typical roadway, especially that of the "use phase", where vehicles roll over the pavement surface. Furthermore, being one of the primary sources of carbon emissions, road traffic faces a significant challenge in terms of reducing carbon emissions [25]. The Organization for Economic Co-operation and Development (OECD) states that nearly 70% of the world's population is expected to live in urban areas by 2050, therefore emissions from transport will rise [26]. Each transport activity shall not be solely reliant on fossil-fuel power internal combustion engines [26]. New mobility patterns, like electrification, are under discussion and selective implementation is expected in many countries worldwide to address climate change issues. However, until the complete transition to this new era, the engineering community should continuously seek for optimization and ecological balance considering the current mobility patterns that dominate in urban and suburban areas, in close cooperation with urban planners.

3. Methodology

3.1. Current Practice for Fuel Estimation

Estimating fuel consumption based on the road infrastructure conditions (i.e., geometric design features, pavement surface parameters, etc.) represents an opportunity for the road agencies to evaluate the performance of their assets in the use phase, or else the operation period, and support decision-making in regard to maintenance and rehabilitation of the infrastructure [27]. Many sparse tools and models are being developed in a worldwide scale, e.g., [5,17,28].

Despite these attempts, the HDM-4 model (Highway Design Manual) is still the most widely used in practice [27]. The HDM-4 model assumes that fuel is consumed proportionally to the engine's total power needs, comprising: (i) the traction power, required to counteract forces opposing to the movement, (ii) the engine drag, required to counteract the internal engine drag (or friction), and (iii) the additional power required to move vehicle accessories, such as power steering, air conditioning, etc. Its mathematical expression for Instantaneous Fuel Consumption (IFC) is as follows:

$$IFC = f\left(P_{tr}, P_{accs} + P_{eng}\right) = \max(a\,;\xi \times P_{tot} \times (1 + d_{Fuel})) \tag{1}$$

where: IFC is the instantaneous fuel consumption (mL/s), P_{tot} is the total power required (kW), P_{tr} is the power required for traction (kW), P_{accs} is the power required by accessories in the vehicle (kW), P_{eng} is the power required to overcome the internal friction in the engine (kW), α is the fuel consumption at idling (mL/s), ξ is the engine efficiency (mL/kW/s), and d_{Fuel} is the excess fuel consumption caused during congestion events (mL/s).

The model is commonly adopted by road engineers for the assessment of road and pavement life-cycle and the execution of socio-economic or environmental analyses that are triggered by a poor condition of the road surface [29]. However, its use requires proper calibration and adaptation to local conditions in order to reach safe and meaningful conclusions. A proper configuration of the HDM-4 model requires the consideration of road data (e.g., geometric features, type of pavement, etc.), vehicle and traffic data, weather data, etc. The acquisition of all these parameters is usually a matter of concern for the related agencies, so the use of assumptions and the inclusion of some extent of bias must be evaluated and properly judged by experienced analysts.

Furthermore, advances in the automobile, the use of vehicles with many axles, and variable loads make the issue of calibration an even more difficult task to pursue. Limited field tests on predefined road subsections of small length under a limited span of weather variations and under a driving pattern with constant speed may hinder the wide applicability of the above model in a wide range of real-driving conditions.

In an effort to improve the accuracy of fuel estimations, Posada-Henao et al. [17] have developed new predictive equations for two types of heavy-duty vehicles, including three-axle and six-axle trucks. In their equations, factors including the weight, the longitudinal slope, and the vehicle speed were considered as significant predictors of the fuel consumption rates. It is noted that the slope and speed are known to be related to the vertical and horizontal profiles of the road design, respectively, whereas the weight factor reflects the freight transportation practice, since trucks do not always travel at the same load degree. The developed models have been characterized by a high reliability due to their confidence level of 95% [17], thereby enabling further use and exploration in the framework of the present theoretical study.

3.2. Analysis Framework

Following the rational assumption that a six-axle truck is supposed for wide use in rural road corridors, this study considered only the model developed for a typical three-axle truck, which can be more frequently met within urban and suburban areas at high distribution rates across the road network. The model in question, proposed in [17], is defined as follows:

$$\begin{gathered} C = -8.00992 \cdot W + 105.635 \cdot S - 3.64516 \cdot V + 15.2035 \cdot W \cdot S - 20.5096 \cdot S^2 \\ -0.0270028 \cdot W^2 \cdot S^2 \end{gathered} \tag{2}$$

where: C is the consumption rate (mL/km), W is the total vehicle weight (ton), S is the longitudinal slope (%) reflecting the impact of the vertical road alignment, and V is the vehicle speed (km/h) reflecting the impact of horizontal road alignment on the basis that the radii of horizontal curves have a definitive impact on the speed adjustment choice of drivers [30].

It is to be clarified that the regression constants of this model were assigned to the values of the initial model development in order to theoretically demonstrate the impact of slope and vehicle changes in the fuel consumption rates. Following the purpose of this study, the aim was not to develop an additional model; therefore, the generalizability of model parameters in this study simply aims at assisting the sensitivity analysis. Recalibration is needed so that the model can be used for real-scale predictions elsewhere, followed by ad hoc case-by-case studies to reflect local conditions.

Table 1 includes the values of the model parameters that are shown in Equation (2). Variation in vehicle weight reflects the wide spectrum of loaded vehicles that are responsible for freight transportation and may come as a result of supply chain management principles and needs.

Table 1. Values of model parameters.

Parameter	Values
Weight (ton)	12, 16, 20, 24, 28
Slope (%)	2, 3, 4, 5, 6, 7
Speed (km/h)	25, 30, 35, 40, 45

In regard to the analysis, the consumption levels are comparatively assessed for a wide spectrum of the influencing factors shown in Table 1. With an emphasis on the road geometric features, it is further attempted to evaluate the contribution of the horizontal and vertical profiles of the road network to fuel consumption levels.

4. Results

The results for fuel consumption estimates using the model of Equation (2) are shown in Figures 5–7 for three indicative cases of the longitudinal slope. These include the case of 2% corresponding to a nearly flat level; this slope is considered as reference for the comparative assessment. The second slope includes the value of 5%, which corresponds to vertical alignments of moderate levels. Such a level can be usually met on regional arterials near to mountainous or hilly areas. The upper limit of slope was set equal to 7% according to the assumptions made during the initial model development [17]. It is noted that slopes more than 6% have been rarely considered for investigation in related research [17,18].

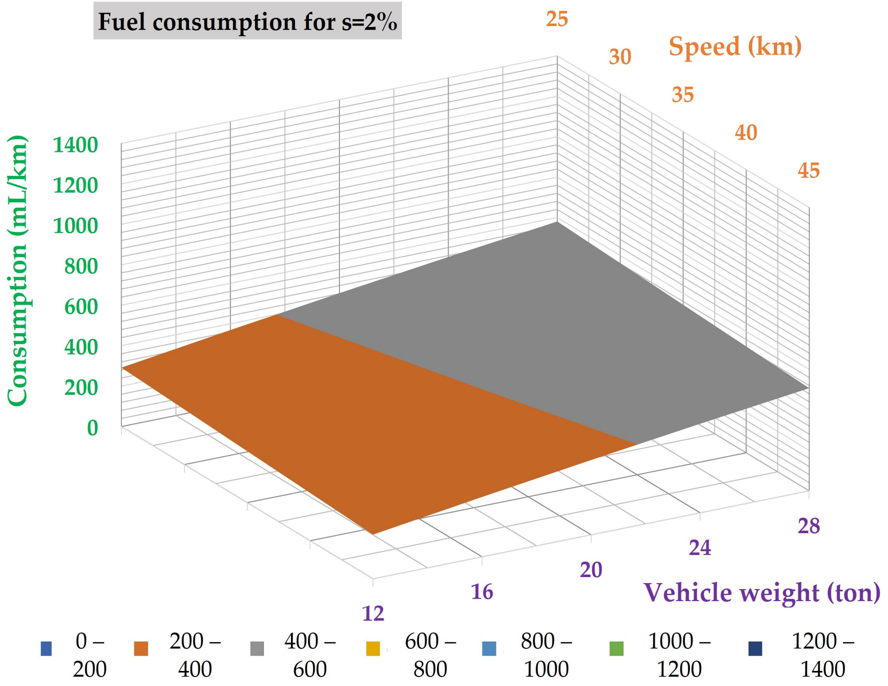

Figure 5. Fuel consumption for the case of mild vertical profile (slope: 2%).

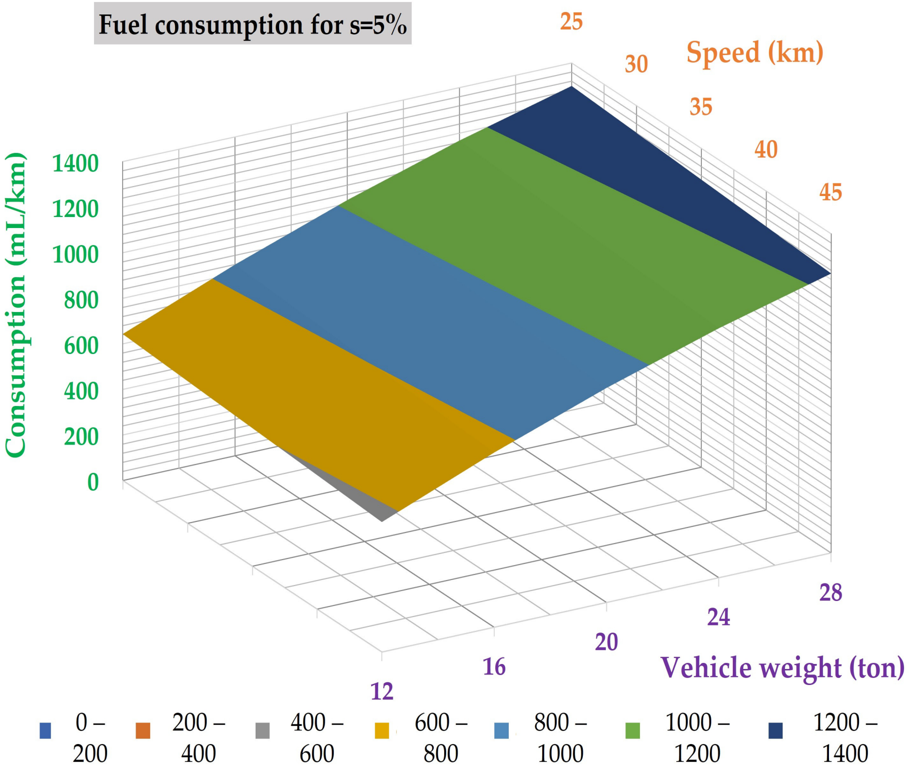

Figure 6. Fuel consumption for the case of moderate vertical profile (slope: 5%).

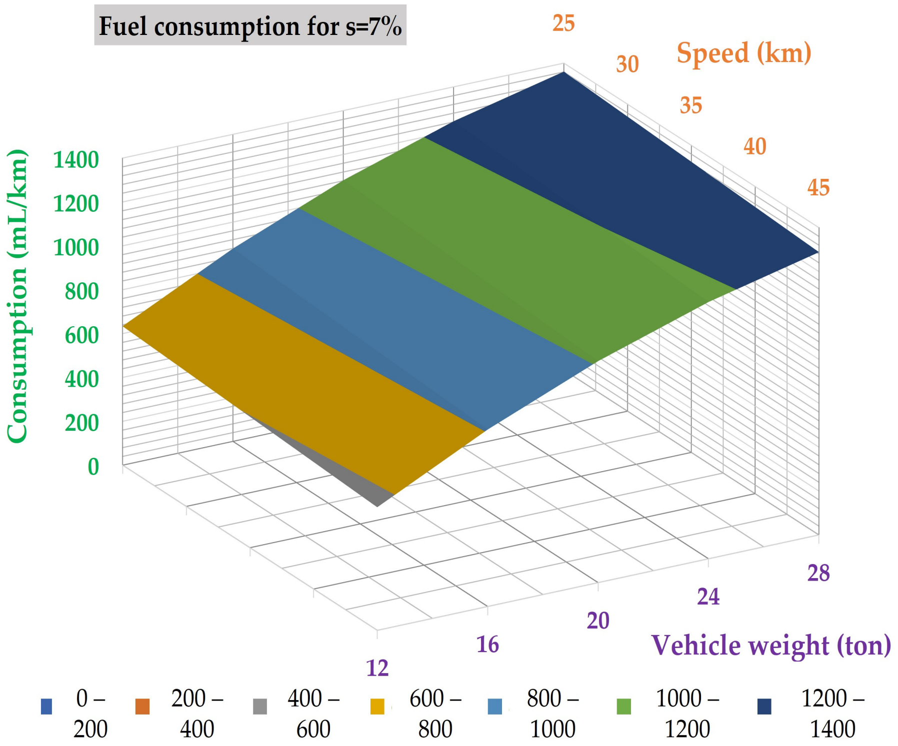

Figure 7. Fuel consumption for the case of intense vertical profile (slope: 7%).

From the above figures, it can be seen that even for the mildest slope considered, the variability in fuel consumption is kept at considerable levels. In particular, it ranges from 218 to 581 mL/km (or else 22–58 L per 100 km). The highest consumption rate is observed for the heavier vehicle weight considered.

For the case of a slope of 5%, a more intense increase rate in consumption is observed. On the contrary, the fuel consumption pattern for the slope of 7% follows a similar trend to the case of 5%. The corresponding ranges for the slopes of 5% and 7% are 561–1299 mL/km and 570–1362 mL/km, respectively. For all the considered cases, the lowest fuel consumption is observed for the lightest vehicle weight and the highest speed, whereas the highest fuel consumption is observed for the heaviest vehicle weight and the lowest speed.

To further assess the impact of longitudinal slope on the fuel consumption reflecting the vertical road profile, the ratio of fuel consumption at each combination of weight and speed at a certain slope to its corresponding value at the slope of 2% (considered as a reference case) is statistically treated.

In addition, the same process is repeated for the assessment of the impact of speed that reflects the horizontal road profile. In that case, the value of 45 km/h is considered as the reference speed. Tables 2 and 3 present descriptive statistics for the consumption rates considering the whole available sample for the cases of the reference slope and the reference speed.

Table 2. Comparison of fuel consumption rates for the individual slopes (the slope of 2% is considered as reference).

Pair of Slopes	2% vs. 3%	2% vs. 4%	2% vs. 5%	2% vs. 6%	2% vs. 7%
Average increase ratio	1.63	2.09	2.39	2.52	2.49
Standard deviation	0.05	0.09	0.11	0.12	0.14
Coefficient of Variation (%)	3.2%	4.2%	4.5%	4.8%	5.6%
Number of values	25	25	25	25	25

Table 3. Comparison of fuel consumption rates for the individual speeds (the speed of 45 km/h is considered as reference).

Pair of Speeds (km/h)	**25 vs. 45**	**30 vs. 45**	**35 vs. 45**	**40 vs. 45**
Average increase ratio	1.12	1.09	1.06	1.03
Standard deviation	0.06	0.05	0.03	0.02
Coefficient of variation (%)	5.6%	4.3%	2.9%	1.5%
Number of values	30	30	30	30

Because of the higher values for the coefficients of variation for the cases of comparing the slopes 2% and 7%, as well as the speeds 45 km/h and 25 km/h, a further statistical analysis is performed to confirm the average ratios shown in Tables 2 and 3. From a distribution fitting analysis of the available values for the fuel increase ratios, the results shown in Figures 8 and 9 are presented.

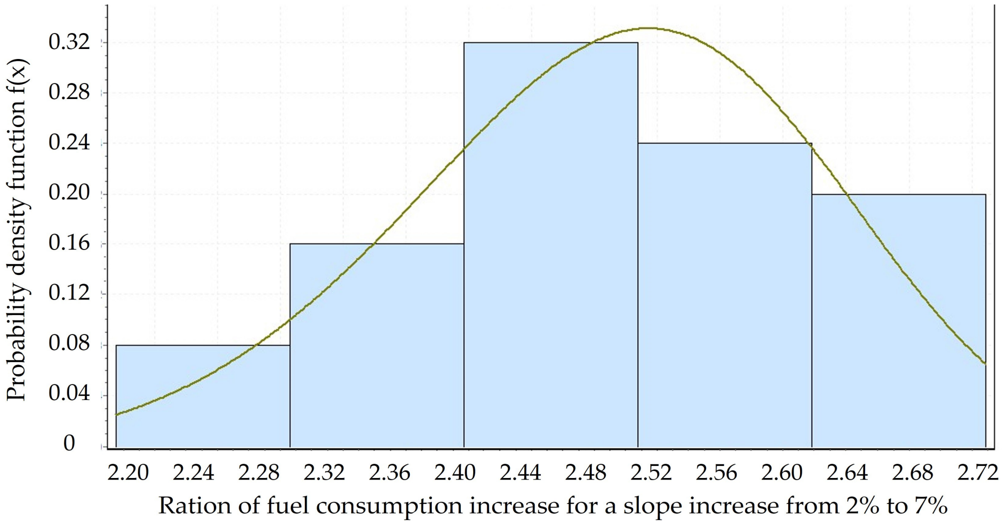

Figure 8. Distribution for the ratio of fuel increase because of a slope increase from 2% to 7%.

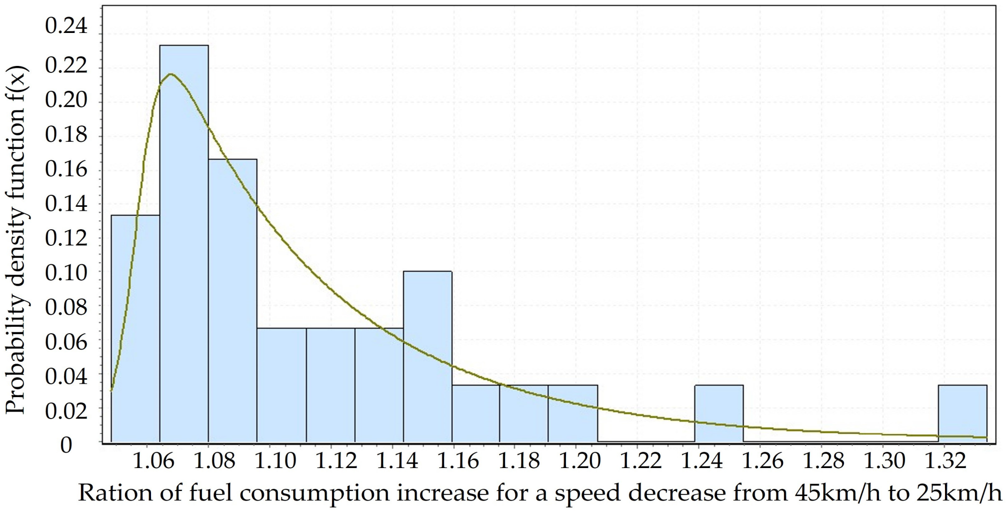

Figure 9. Distribution for the ratio of fuel increase because of a speed decrease from 45 to 25 km/h.

For both cases, the Burr (4P) distribution was found to sufficiently accommodate the available data following the Anderson–Darling evaluation criterion for the assessment of goodness-of-fit. The afore-mentioned distribution has been also used for statistical modelling of other traffic- and road-related data too [31,32]. In Figures 8 and 9, the characteristic values of 2.49 and 1.08 are considered, as their probability density function takes the value of 0.50. These values correspond to the peak area of the fitting curves and were automatically generated from the distribution fitting analysis tool. Therefore, by slightly correcting the values shown in Tables 2 and 3, the evolution trend of fuel consumption increase is shown in Figure 10.

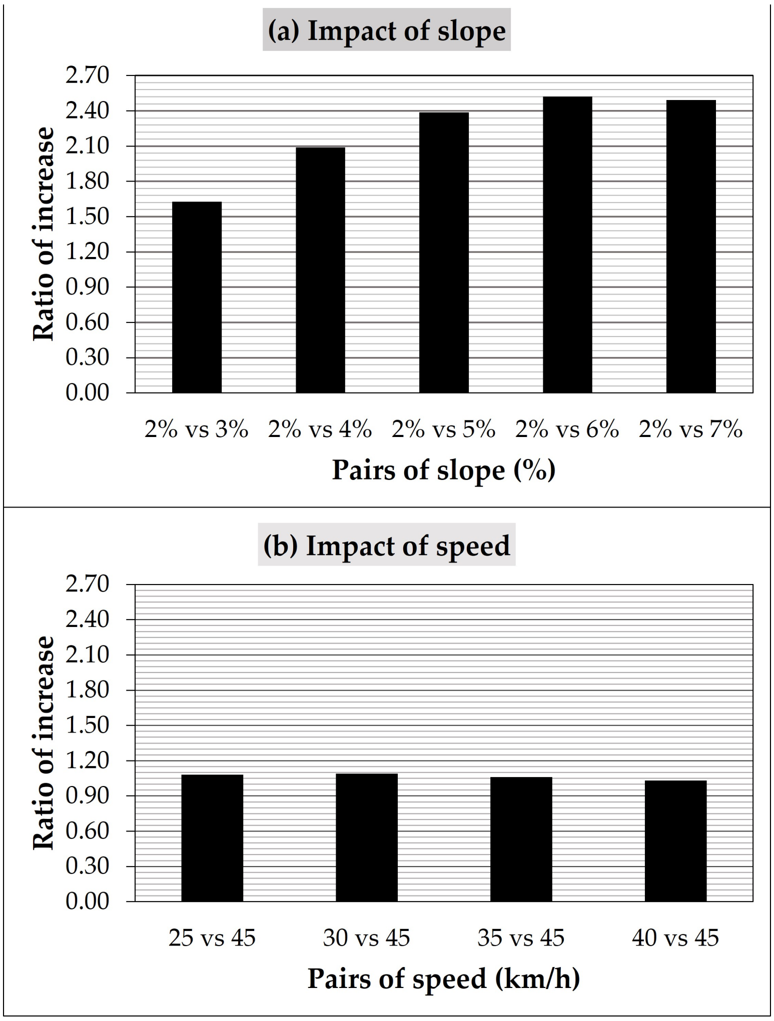

Figure 10. Impact of (**a**) longitudinal slope, and (**b**) vehicle speed on the fuel consumption increase rate (data from all combinations of vehicle weights are considered in each sample).

From the comparison shown in Figure 10, it can be confidently stated that the impact of the longitudinal slope on the increase in fuel consumption is more pronounced compared to the impact of speed. This is in complete agreement with the international literature [10,18,33]. Higher slopes account for the higher power required by the travelling vehicles in order to maintain their speed constant, thereby leading to less energy efficiency, i.e., more fuel consumption. The latter can definitively impose environmental challenges for the citizens of an urban area, thereby affecting their quality of life. Notably, from a relevant investigation, Ko et al. [34] concluded that fuel consumption and carbon emissions on road segments with a slope of 9% were found to be four to five times higher than those in a flat segment. It is to be noted that only the impact of positive slope was considered in the analysis. However, in actual practice the presence of negative slopes implies that fuel consumption can be even reduced and improve the overall energy efficiency of vehicle movement. Indeed, the inability of the investigated model to assess the impact of negative slopes can be considered as a limitation.

In terms of speed, Llopis-Castelló et al. [24] report that if a road design tends to increase the average flow speed and reduce accelerations, then emissions can be minimized. This is something that can be taken into consideration during the road design in urban and suburban areas, provided that limitations from the terrain configuration and the available space are fulfilled.

In particular, considering the results of the present theoretical investigation, the rate of change for the increase in fuel consumption is more intense for the factor of slope, as it ranges from 1.63 to 2.49 for a progressive increase of 1% for the slope (Figure 10a). In addition, for slopes greater than 5%, the impact of slope changes appears to be constant. On the contrary, a progressive decrease of 5 km/h for the speed leads to a constant increase rate of nearly 10% for fuel consumption at all of the considered speeds (Figure 10b). As such, the speed effect is much milder compared to the slope's effect. This is also in accordance with international past studies [35]. Therefore, the impact of the vertical road profile is more pronounced compared to the impact of the horizontal road profile.

5. Discussion and Limitations

Investigating the interaction between road geometric design and environmental quality within urban areas is a privileged domain for current and future research. This comes as a rational result of the growing interest worldwide in an alternative and sustainable perspective applied during urban planning. Aspects of environmental quality, social prosperity and equality, economic viability, and treatment measures for climate change adaptation due to rising CO_2 emissions are becoming part of a consensus of thinking worldwide [36]. The importance of the transportation sector to sustainable urban development must be bolstered by implementing sustainable practices.

From this viewpoint, the present study yielded some useful implications, as follows. First, redesign considerations of existing networks or the new design of roadways and arterial motorways shall require that the criteria of safety and functionality are accompanied by energy perspectives, including prediction modelling of fuel consumption rates. Of course, terrain configuration constraints must be met. The ecological impact should be more drastically accounted for, as carbon emissions play a crucial role for the health and the overall quality of life of human beings in an urban or suburban area. Zheng et al. [37] investigated different classes of roads in an urban environment, e.g., arterial and expressways, and found that carbon emissions in expressways were more than ten times those emitted in arterials. Therefore, once there are indications for increased fuel consumption that are strictly linked to carbon emissions, special countermeasures should be found, like the design and construction of enough green space along urban roadways with high traffic volumes, as proposed in [37], so that a step towards low-carbon cities can be made.

Moreover, carbon dioxide emissions for urban transport come from medium- and heavy-duty trucks and light-duty trucks at rates of 23% and 18%, respectively [24]. Thereafter, when it comes to selecting freight transportation paths from multiple alternative routes, it can be feasible to select the roadway path that can lead to balanced transportation costs because of tolerable fuel consumption costs and thus tolerable carbon emissions. Furthermore, it is recalled that apart from the fuel consumption, an increase longitudinal slope raises sharply the total operational service cost of a heavy truck. And of course, practitioners can benefit from this work based on the fact that a route choice can take into consideration road conditions and traffic conditions, which are predominant factors in determining driving cycle and fuel efficiency [28].

Despite those positive remarks about the contribution of fuel estimation modelling, several limitations are currently present. The lack of experimentally measured data about speed, fuel consumption, etc. appears as a limitation of the present study. A common challenge that can hinder the investment of field measures includes the difficulty of estimating the weight of travelling vehicles, once Weigh-In-Motion (WIM) systems are absent. Despite recent advances in WIM systems, their wide applicability is yet to be achieved because of high installation costs, increased demand on computational resources needed to retrieve meaningful data, calibration problems, etc. [38]. One possible way to access weight data is to consult suppliers from the supply chain management, which is in general considered as a confidential source of information because of competitiveness issues, etc. [39]. This is neither viable nor practical. As such, weight details might remain unknown, thereby limiting the dynamic potential of such models.

In terms of the infrastructure design features, historical records of the initial road design might be absent in general. This can be counterbalanced by the use of crowd-sourced smartphone data for road grade estimations and vehicle driving patterns, including travelling times and speeds [40,41]. Nevertheless, the aim of this paper was not to develop another predictive model for use; it was rather to pinpoint the value of having such models and stimulate the need to invest in experimental research campaigns to achieve this difficult task in favor of society's needs and better freight transportation management in urban areas.

In respect of the latter, rational decision-making on the type and weight of vehicles should consider the trip length, fuel and service costs, delays in loading and unloading operations, as well as the environmental impact from the executed routes (i.e., fuel consumption, energy efficiency, contribution to air pollutants, etc.). In this context, environmental considerations of road geometric features during the initial planning of new urban roads and/or safety interventions in existing parts of the urban road network can act in favor of an optimization of vehicle routing problems and an adoption of a sustainable perspective for freight transportation.

6. Conclusions and Future Prospects

In the present study, an existing fuel estimation model was assessed in terms of its contributing factors, including the vehicle weight and road geometric design features reflecting the horizontal and vertical profile of the road. In particular, two core design features of road design were considered, including vehicle speed and longitudinal slope, following the connection acknowledged in the literature between road design features and carbon dioxide emissions [24].

It was observed that the impact of positive slope is more pronounced for the increase rate of fuel consumption compared to the impact of speed. Based on typically applied slopes during the road design, a ratio of around 2.5 was found for the fuel increase for the two extreme values of slope that were considered (i.e., 2% and 7%). The corresponding ratio for a speed decrease from 45 km/h to 25 km/h was found to be less than 1.10. This practically means that once a vehicle maintains a constant speed, which is preferrable within urban areas in favor of safety, then fuel consumption is mainly controlled by the longitudinal slope that does affect the required power. Of course, in this investigation only the effect of positive slope was considered in the fuel consumption increase. As such, it could be interesting in the future for road planners and engineers to study the aspect of "the negative slope versus fuel reduction" as well, apart from simply considering weighted values for fuel consumption.

While the related analysis reflects the use of conventional thermal cars, related research interests about the impact of more modern vehicle technologies should be considered in the future by fostering research collaboration between different disciplines, those of the vehicle industry and those of the road engineering community. Advanced sensing capabilities of newer vehicles towards the control of acceleration, lateral and forward distance with the surrounding vehicles are, in general, expected to maximize the quality of traffic flow and capacity and improve road safety [42]. In turn, fuel consumption rates and their impact on carbon dioxide emissions for alternative road design features and mobility patterns need to be more systematically explored in favor of a more sustainable urban development and the promotion of both safe and low-carbon roadways. To this end, several roadways with different design features should be explored in the future for more reliable conclusions and contributions to the current state of practice.

Simultaneously, the application of intelligent transportation systems will help the promotion of fuel consumption reduction according to two main strategies [19]. These include: (a) the attempt to reduce congestion and traffic delays thanks to connectivity and the adoption of optimal vehicle speeds, and (b) the ability of drivers to follow a greener route in terms of energy and fuel efficiency. To meet this challenge, information about the impact of road slope and dominant operation speeds will be needed. Thus, in parallel with the advances in the automobile industry and vehicle technology, the connection between road geometric features and the overall energy efficiency in urban and suburban areas (i.e., including fuel consumption rates, electrification vs. fossil-fuel engines, smooth vs. sharp vertical and horizontal profiles, etc.) definitively remains an open issue subject to future investigation.

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