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IMPACT OF ROAD GEOMETRY ON VEHICLE ENERGY CONSUMPTION

Summary. It has been shown that road geometry has a great impact on overall energy consumption and emissions. Some roads connect traffic origins and destinations directly. On the other hand, some use winding, indirect routes. Indirect connections result in longer distances driven and increased fuel consumption. A similar effect is observed on congested roads and mountain roads with many changes in altitude. Therefore, we propose a framework to assess road networks based on energy consumption. This framework should take into consideration traffic volume, shares of vehicle classes, road geometry and energy needed for road operation and construction. It can be used to optimize energy consumption with efficient traffic management and to choose an optimum new road in the design phase. This is especially important as the energy consumed by the vehicles soon supersedes the energy needed for road construction.

1. INTRODUCTION

The European Union focuses a great deal on policies for energy efficiency and to decrease emissions in transport [1]. The transport sector contributes nearly a third of CO_2 emissions and energy consumption within the EU [2]. Most efforts to combat this problem are directed towards traffic mode shift, use of energy-efficient vehicles and alternative fuels [3]. As a result, there was a decline in overall emissions by 3% in 2012 and by 2014 average light vehicle emissions were below the targets set for 2015. These values were obtained in part as the EU requires member states to record data on registering new vehicles [4]. Similar policies are being practiced elsewhere in the world, such as in the USA and in China [5, 6]. Such transport policies also focus on limiting road traffic in cities, increasing the use of public transport and on shifting from road to other modes of transport. Such approaches work well in densely populated areas, but in sparsely populated areas road traffic is still, necessarily, the transportation mode of choice. An example of a study on reducing emissions in a densely populated area is the article [7], where a case study from London is described. An alternative to such approaches can be better traffic management that could result in less congestion and lower emissions.

When roads are preferred and necessary, some focus should be put on the relation between greenhouse emissions and traffic management. Traffic simulation and emission models are tools that can be applied for such an analysis. This paper will include a review of traffic simulation models that may be used for developing a microscopic emissions model that can be used to calculate emissions.

1.1. Traffic simulation models

Traffic simulation models can be divided into microscopic, mesoscopic and macroscopic models. Microscopic models are models that simulate the highest level of detail. On the other hand, the least detailed models are macroscopic, which simulate traffic conditions by representing the road network with pipe equations. Microscopic models consist of vehicle-following and lane-changing models.

Among the most popular are the Fritzsche [8], Wiedemann [9], IDM (Intelligent Driver Model) [10–12] and the Gipps [13] models. The common factors among them are that they consider speed, acceleration and longitudinal distance to be continuous variables, and lateral position (lane) to be a discrete variable. Nearly all of the microscopic vehicle-following models output acceleration, which is later integrated by the simulation software in order to obtain speed and longitudinal position. In contrast, some models are formulated to update from speed data, and acceleration data are obtained by differentiating them. Such examples are the Gipps model and its derivatives such as the Krauss model.

Most of the traffic microsimulation software use a single vehicle-following model, for example, VISSIM uses the Wiedemann model, Paramics uses the Fritzsche model etc… In the area of research, the SUMO (Simulation of Urban Mobility) tool is becoming increasingly popular as it is open source and allows modifications to be made to any part of the code. Even without modifications of the code, it provides many configuration options not usually found in other packages such as choice of vehicle-following, lane-changing and emission models. It uses the Krauss vehicle-following model by default [34].

1.2. Overview of emission models

Traffic microsimulation models need to be coupled with emission models in order to obtain individual and aggregated vehicle emissions. Vehicle emission models can also be divided into microscopic and macroscopic. Macroscopic emission models are used to estimate emissions based on traffic volume and average speed, ignoring instantaneous accelerations. More detailed are the microscopic emission models that rely on inputs such as speed, acceleration, vehicle weight and road grade.

Regardless of whether the model is microscopic or macroscopic, most models provide no direct physical model of fuel consumption, rather, they provide tables or functions that are based on statistical analysis of different variables that have an impact on emissions [15, 16]. One example of a macroscopic model is the ARTEMIS study that involves CO_2 and NO_X emissions dependent on vehicle speed and driving cycles [17, 18]. A statistical analysis of the dependence of truck fuel consumption on speed and road grade was conducted in an experimental study by [19] conducted on highways in realistic traffic conditions. Fuel volume flow was measured using the vehicles' CAN (Controller Area Network) bus interface. Such results can be used for comparative purposes and for model tuning, but not for the direct estimation of instantaneous fuel consumption for different types of vehicles that is required for microsimulation. For general energy demand, forecasting models with a lower level of detail are used. In [20], where a long-term forecasting was simulated, a simple model based on mileage travelled and average fuel economy was used.

Notable microsimulation models are Versit+, PHEM, CMEM and VT-Micro. Versit+ is a model that is based on vehicle type, velocity and acceleration [21], which was developed by the TNO from Netherlands. It has an interface with the AIMSUN traffic microsimulation software. AIMSUN is based on the Gipps model; therefore, velocity must be differentiated to obtain acceleration [22]. PHEM is an emissions model that was developed by the University of Graz and has an interface for the SUMO microscopic traffic simulator [23, 24]. CMEM and VT are models that were developed in the USA. CMEM was developed during the 90s, whereas the VT (Virginia Tech) is a newer model. Both of them are based on velocity, acceleration and factors that depend on vehicle types.

1.3. VSP (Vehicle Specific Power) model

Since new fuels and electric vehicles are becoming increasingly popular, calculating the energy impact of traffic can be difficult. A more straight-forward approach would be to rely on the energy required by the vehicle directly. Among all approaches, the VSP (vehicle specific power) model was the only one that was directly based on power required by the vehicle [25, 26]. Vehicle specific power is based on energy conversions and on changes of potential and kinetic energy. The power needed for acceleration results in a change of kinetic energy and is therefore affected by congestion; road grade, too, has an impact on potential energy change. Apart from the energies, air and rolling resistances are also modeled. There are two frequently mentioned formulas for VSP in the literature. The first was developed by Jimenez and is based directly on changes of energy, and further derived to include drag and rolling resistance coefficients and accelerations [25]. Another formula was developed by Zhai; this also introduces several coefficients [26]. The main difference between the two is that Jimenez uses wind velocity as an independent variable, which is the reason this formula is preferred; in case of unidirectional tunnels the air velocity is usually in the direction of travel, which results in lower air resistance as opposed to the open road.

The downside of the VSP model is that it does not account for engine idling, which can be significant in case of congested traffic. According to [27] and [28], fuel consumption during engine idling is between 0.5 and 1.5 l/h for light vehicles and a bit over 3 l/h for heavy vehicles. The VSP is also suitable for adaptation to analysis of alternative drive-trains as it is based on energy consumption with a clear physical background. It is not a regressive model of fuel use. It merely estimates power at the wheels. The power at the engine should be higher as transmission and engine efficiencies should be considered as well. The relationship between the vehicle-specific power and fuel consumption rate (flow) was determined by [29, 30].

An exhaustive study involving vehicle efficiency defines separate ratios for powertrain, vehicle and primary energy efficiency [31]. It can be deduced that due to many different fuels that are being used, it is more feasible to have a model that is based on energy, and then to calculate primary energy use from the energy at the wheels.

1.4. Energy for road construction

Results on the energy consumed by traffic would be more valuable if they are compared with the energy needed to build a more efficient road. A useful source for the amount of energy required for construction is a report covering embodied energy in construction materials, which also includes an estimate for square meters of a road [35]. But construction energy greatly depends on terrain, especially when tunnels have to be drilled and viaducts have to be built. In such cases a more in-depth analysis is required, which will include drilling energy, ground works and energy needed to build road support [36].

2. ROAD GEOMETRY DATA SOURCES

The energy footprint of vehicles that pass along a road network can be estimated when geometrical and traffic data are available. Road geometry can be obtained from road management companies or any map provider. Useful map data with worldwide coverage is available free of charge from OpenStreetMap [32]. Although elevation and road grade have a significant impact on energy consumption, most traffic maps do not include elevation data, which therefore have to be obtained elsewhere. It is possible to augment traffic maps using high-resolution elevation data measured by remote sensing from satellites. One such example is datasets from the USGS Earth Explorer [33], which can be used to estimate road grade.

Road grade is an important input variable for energy consumption analysis, including the estimate of how much energy is consumed by the traffic in comparison with an ideal, direct road with sufficient capacity to handle traffic without congestions. The most precise way to obtain road grade data is from road project documentation. It is often inconvenient to obtain and sometimes has to be sourced from different authorities, especially when a road crosses several states or countries. As GIS road maps such as OpenStreetMap do not include elevation data, the GMTED2010 database was used to augment it. It is stored in the GeoTIFF format, which provides exact geographic coordinates of the samples. Accuracy of road grade calculations based on the GMTED2010 satellite data [33] was analyzed, finding that if raw satellite data is used, a problem with extremely high gradients arises due to the limitations of the data. The highest resolution available for GMTED2010 is 7.5 arc-seconds, where the

RMSE range is between 26 and 30 meters. Every measured area has mean, median, minimum, maximum and standard deviation data available.

A solution was proposed to filter the GMTED2010 data in order to obtain a better estimate of the gradients. Filtering was carried out using a variant of the weighted moving average filter over a distance of 250 m. The reason for this is that the horizontal resolution for GMTED2010 of 7.5 arc seconds is 160 m by longitude and 231 m by latitude. By providing a large enough filter and by using long distances for gradient calculation we ensured that every segment for gradient calculation was long enough to include at least 2 different elevation measurements. In this manner, we obtained a smoother elevation profile and more realistic gradient results. The roads in mountain areas are not as steep as the surrounding terrain and therefore smoothing was carried out along the direction of the road. A weighted moving average filter was applied along points that define the route.

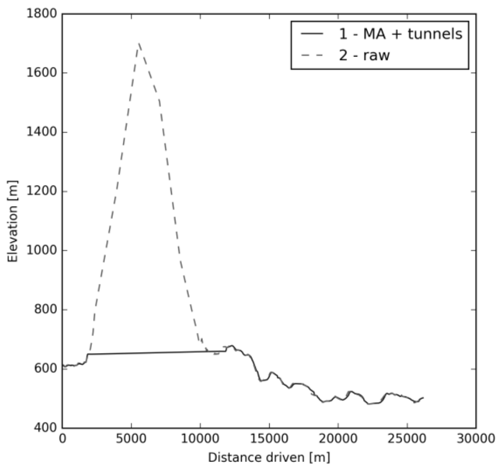

Fig. 1. Processed and raw elevation data

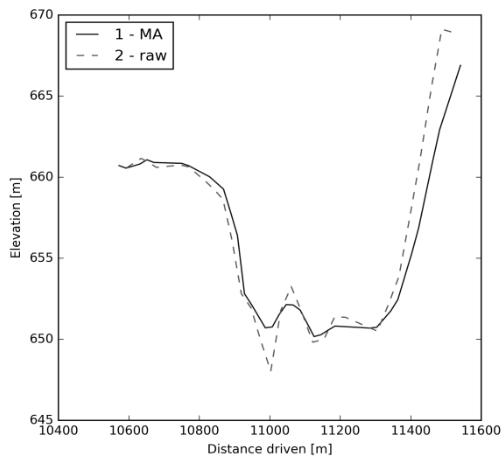

Fig. 2. Processed and raw elevation data (closeup)

The elevation values of each point were weighted by the variance reading from the database. In this manner, points with more stable elevations had a stronger influence on the results. Weights can be calculated as

$$w_i = \frac{1}{\sigma_i^2}. \quad (1)$$

The moving average for elevation at point Z_i along the path is obtained from

$$Z_i = \frac{1}{W_i} \sum_{j=i-N}^{i+N} w_j \, Z_j, \quad (2)$$

where the sum of weights W_i for the point Z_i is

$$W_i = \sum_{j=i-N}^{i+N} w_j. \quad (3)$$

In fig. 1 and 2, the processing of elevation is shown. It should be noted that in certain types of terrain, especially in place of viaducts and tunnels, manual corrections are required (fig. 1).

3. TRAFFIC AND EMISSION MODELS IN SUMO

SUMO uses the Krauss vehicle-following model by default [34]. It is based on the maximum safe speed, v_{safe}, that a following vehicle can maintain considering the gap to the leading vehicle, and its speed. Every vehicle sets its desired speed v_d to

$$v_d = min\big(v_{safe}(t), v(t-1) + aT, v_{max}\big), \tag{4}$$

where v_{max} is the maximum allowed or possible speed on a road section, T is the time step and reaction time and the maximum safe speed, v_{safe}, is calculated as

$$v_{safe}(t) = v_l(t) + \frac{g(t) - v_l(t)T}{(v_l + v)/b + T}, \tag{5}$$

where v_l is the leading vehicle speed, g is the gap and b is the desired maximum deceleration.

The emission model in SUMO can be HBEFA, which is basically a macroscopic emission model that does not consider instantaneous acceleration directly and is therefore a function of

$$CO_2 = f(v, m, k), \tag{6}$$

where *v* is the vehicle velocity, *m* is the vehicle mass and *k* is the road grade.

3.1. Adaptation of VSP for use in sumo simulator

The VSP model, which was developed by Jimenez [25], was slightly modified to consider not only vehicle power while vehicles are moving, but to penalize idling as well. It was estimated from

$$VSP = 2 + 1.1va + gkv + 0.213v + 0.000305(v + v_w)^2 v, \tag{7}$$

where *v* is vehicle speed, *a* is acceleration, *g* gravity and v_w wind velocity. The constant power of 2 kw per ton is an additional term to consider energy lost during idling . The estimate is based on data from [27, 28].

The vehicle trajectories were exported from SUMO and later processed for calculation of the VSP that has to be integrated to obtain the energy consumed by a certain vehicle

$$E_v = m_v \int_0^T VSP(t)dt \quad . \tag{8}$$

4. THE KARAWANKS TUNNEL CASE STUDY

We conducted an analysis of the Karawanks road tunnel connecting northern Slovenia with southern Austria. The tunnel itself is a single tube tunnel with bidirectional traffic connecting motorways on both sides of the border. It is located under the Karawanks mountain ridge, which is approximately 2500m high. We chose this route for the analysis as all alternative routes are much longer and include many serpentine segments and changes in elevation (as can be seen in fig. 3 and 4). In fig. 4, the axis represents the geographical longitude and latitude. The road XY coordinates were obtained from OpenStreetMap, while the elevation data are from the GMTED 2010 database [33]. It is evident that the tunnel route (black) is a lot shorter than the alternative route because that one crosses the mountain ridge (the white route in fig. 4). It is, however, still longer than the hypothetical ideal route (dashed line). Length and elevation comparison of the routes are shown in table 1.

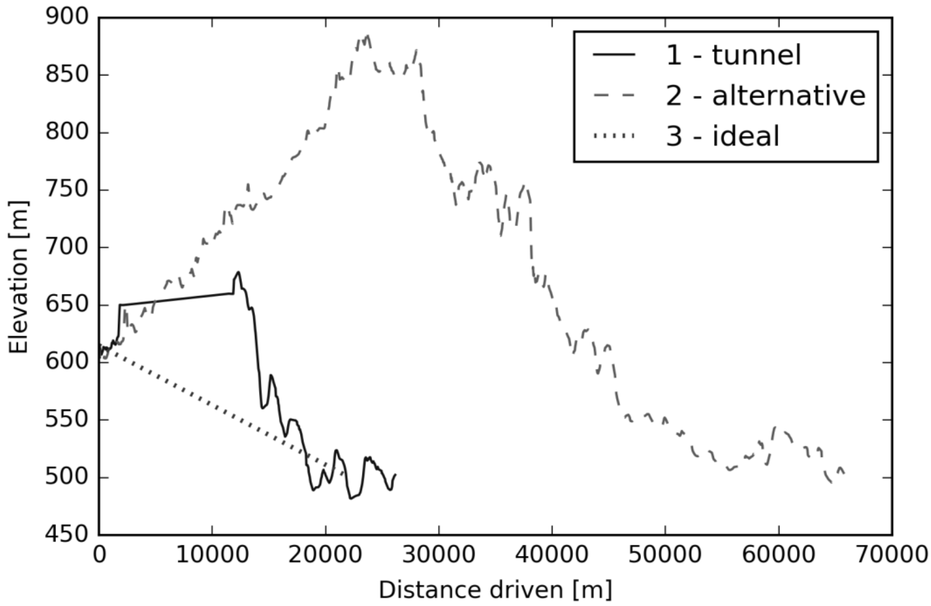

Fig. 3. Elevation profile of the routes

Table 1

Basic route characteristics

	Tunnel Route	Alternative Route	Ideal Route
Minimum Elevation	481 m	495 m	510 m
Maximum Elevation	679 m	890 m	622 m
Route Length	26.2 km	66.2 km	21.7 km
Tunnel Length	8019 m	-	-

It would be possible to split traffic data into several time periods, but since detailed traffic data were not available, analysis using an average number of vehicles per day was conducted: separating them into personal vehicles, busses, light commercial vehicles and heavy goods vehicles. Vehicle weight for each class was approximated. An overview of traffic data can be seen in the table 2. As can be seen, the traffic volume is relatively low with a high share of personal vehicles. The vehicle types that were used in simulation are shown in the table 3. The HBEFA emission classes were used merely for comparison of obtained energy consumed by the vehicles with increase of emissions.

After obtaining the traffic data, we assigned each vehicle class an approximate weight and length. The vehicle length is needed for microsimulation as well.

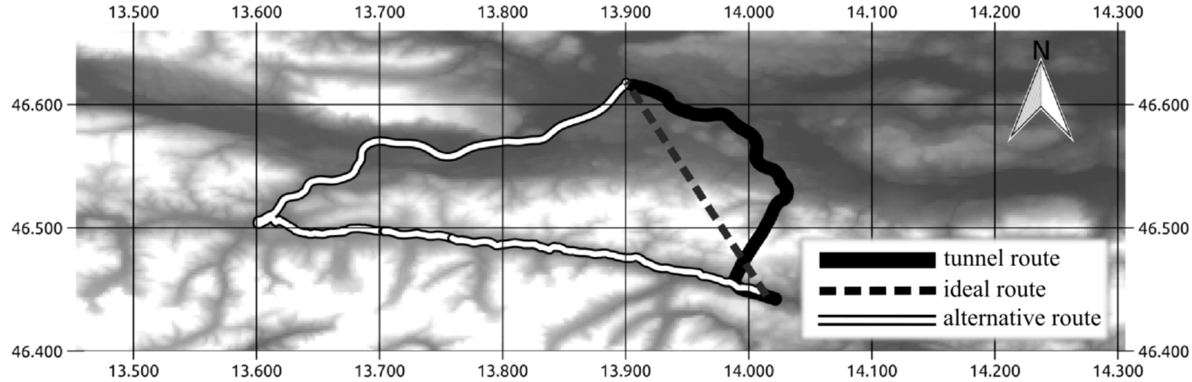

Fig. 4. Tunnel, alternative and ideal routes

Table 2

Traffic data

	Daily traffic	Approximate weight [t]	Vehicle length [m]
Personal vehicles	7144	1.5	5
Busses	96	20	11
Light goods vehicles (up to 7t)	884	4	7
Heavy goods vehicles (over 7t)	1164	40	12

Table 3

Vehicle types in simulation

	Acceleration [m/s^2]		Maximum speed [km/h]	HBEFA emission class
	min	max		
Personal vehicles	6.0	1.0	130	HBEFA3/PC
Busses	4.5	0.7	100	HBEFA3/Bus
Light goods vehicles (up to 7t)	4.5	0.8	110	HBEFA3/LDV
Heavy goods vehicles (over 7t)	4.5	0.9	100	HBEFA3/HDV

After applying the VSP calculation along the route, the dependence between VSP and elevation time can be seen in the fig. 5. VSP is highly dependent on road grade. Changes in road grade have many peaks that are not evident in reality because of the resolution of satellite elevation data and the very steep changes in elevation in these narrow Alpine valleys. These peaks will not necessarily yield wrong results as there are significant changes in elevation on the actual road which are spread over longer distances compared with those of the satellite-based elevation data. If the analysed road was on a flat area, such irregularities would be minimized.

Calculated average values for energy consumption that were obtained by preprocessing microsimulation vehicle trajectories of each vehicle in a class are shown in table 4, where route 1 is the tunnel route, 2 is the alternative route and 3 is the ideal route.

Table 4

Mean energy consumption per trip for each vehicle class in MJ/t

Route	1	2	3
Personal vehicles	14.5	39.3	13.3
Busses	13.6	37.4	12.5
Light goods vehicles (up to 7t)	13.6	37.4	12.5
Heavy goods vehicles (over 7t)	13.1	36.3	11.3

On the basis of data from table 4, the daily amount of energy consumed by all vehicles on all 3 routes can be calculated according to eq. 7. The results can be seen in table 5, which shows that the tunnel route is about 3 times more efficient than the alternative route (230% more energy is consumed). An interesting overview is the average daily power needed to drive all the vehicles that pass on the route for all three options. The difference between the tunnel and alternative routes is 18 MW which is an order of magnitude of a smaller electrical power station. This means that the impact of road geometry on fuel consumption is far from negligible. If the obtained results are compared with HBEFA results from table 6, it can be concluded that estimated fuel consumption and CO_2 emissions are about 3 times higher on the alternative route; therefore, both models show similar sensitivity to road geometry and traffic parameters.

Table 5

Total energy consumption per route

Route	1	2	3
Total Energy[GJ]	893	2431	736
Increase over ideal road [%]	21	230	0
P [MW]	10.3	28.13	8.5

Table 6

Daily fuel consumption and CO2 emissions (HBEFA3.1)

Route	1	2
Total fuel [m^3]	18.8	47.8
CO2 [t]	43.5	110.5

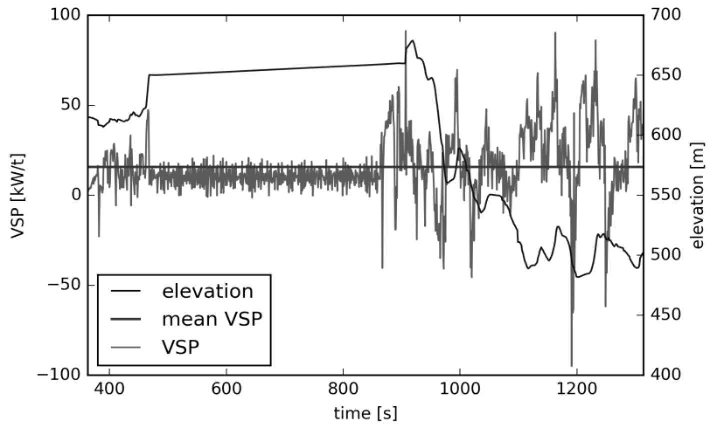

Fig. 5. VSP elevation and time on tunnel route

If the amounts of energy that are saved on the tunnel route are compared with estimates for road construction it can be concluded that the energy invested in construction of the tunnel route is saved by the traffic in roughly less than 5 years [35,36]. To provide exact details a more detailed analysis would have to be carried out.

5. CONCLUSIONS

Use of a traffic microsimulation for analysis of how vehicle emissions are affected by different routes and traffic management regimes was presented. Analysis was carried out on a simple case of traffic light cycle adjustment. It has been shown that it is possible to save enormous amounts of energy by making road networks more energy efficient, by building more direct, shorter routes without significant changes in road grade. This is especially evident in mountainous areas where open roads must pass through significant variations in elevation. This results in longer routes with higher road grades, causing higher energy consumption.

We modelled traffic with an assumption that no braking energy is recovered, as electric and plug-in hybrid vehicles are very rare. With simple modifications, simulation of electric vehicles would be possible.

In the future more research regarding accuracy of the VSP model should be carried out as it is better suited to assess the energy used by vehicles powered by electricity and other emerging drive-trains. It is then possible to calculate emissions based on the energy obtained from VSP for different drive-train types.

Other emission models that are better suited to estimating the impact of a stop and go traffic, such as the PHEMLight, should also be evaluated.

It would also be beneficial to conduct an in-depth analysis of the energy consumed by the traffic with the energy that is needed to build a more efficient road. A rough estimate showed that all energy invested in the road would probably be saved in less than 5 years in extreme cases such as the Karawanks tunnel, where the traffic through the tunnel route requires a lot less energy.

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