MIRAVEC

Models and methods for the estimation of fuel consumption due to infrastructure parameters

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MIRAVEC

Modelling Infrastructure Influence on RoAd Vehicle Energy Consumption

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Deliverable 2.1: Models and methods for the estimation of fuel consumption due to infrastructure parameters

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Executive summary

CO_2 emissions from road transport represent an important part of the overall greenhouse gas emissions and consequently contribute to the on-going climate change. Efforts to reduce those emissions need to consider all influencing factors on the energy use of road vehicles, where improvement of road infrastructure characteristics related to fuel consumption can contribute to an overall CO_2 reduction in road transport. This requires an understanding of both these interactions and the implementation of results in current pavement and asset management practice. The objective of MIRAVEC is to build on existing knowledge and models in order to achieve a more holistic view considering a broad variety of effects. The project results will be compiled into recommendations to NRAs on how to implement the findings, models and tools in pavement and asset management systems.

This is a report of the findings in Work Package 2 (WP2) in MIRAVEC. The objective of this WP is to describe existing modelling tools and evaluate their capabilities with respect to analysing the effects identified in WP1 "Road infrastructure influence effects on vehicle energy consumption and associated parameters". The variables identified in WP1 and considered to be the most important to take into consideration when estimating the impact of road infrastructure on road traffic energy use are texture (MPD), IRI (unevenness), rut depth (RUT), gradient (RF), crossfall, horizontal curvature (ADC), road width, traffic volume (AADT) and speed (v). In this report, a selection of projects that have evaluated road characteristics and the effect on energy use are described and analysed. The results of these project shows that there can be benefits energy wise in taking the energy aspect into consideration when planning a new road or choosing rehabilitation measure of the pavement.

There are numerous traffic models that can be used to simulate traffic at different aggregating levels. When analysing the influence of road variables on traffic fuel consumption, a microscopic model that simulates individual vehicles is the most appropriate one, since it is possible to describe the input data in great detail. Some models can do this, for example VETO and the coupled FTire/Dymola/Modelica. However, it was decided that generalised fuel use estimates generated by VETO should be used as input to WP3 instead of the model itself, since it was considered to be the most efficient solution. With these estimations it is possible to consider speed, vehicle type and emission concepts, sight class of rural road with ADC and RF and urban roads. There is, though, a need to develop a routine that makes it possible to take changes in IRI and MPD into consideration.

As recommendation for further work, new variables and effects to include in the tool that will be developed it should be investigated if there is a rolling resistance effect due to RUT and if there is a speed effect for MPD. The presence of water, snow or ice on the road surface should be included since this is a reality during a large part of the year, especially concerning water or moisture. Also a well-grounded road deterioration model can contribute additional information since surface defects and road strength can be important for rolling resistance.

The sensitivity analysis, using the available information of the Swedish state road network, shows that there is a close to linear relationship between relative changes in the analysed road variables and the relative change in fuel use. In general, gradients (RF) lead to the largest impact, followed by texture (MPD) and horizontal curvature (ADC). The relative changes are the larger the heavier the vehicle, hence fuel use for trucks with trailer is most affected. The size of the relative change in fuel use is also dependent on the road type. The most important factor and the biggest change varies between road variables and road types. With IRI the speed effect due to less roughness (higher speed) seems to overcompensate the decreased fuel use, leading to increased fuel use for passenger cars and trucks. The same speed effect is present for rut depth (RUT).

When evaluating road characteristics and the effect of changing them one must remember that there is not only an effect on driving resistance but also a direct influence on driving patterns and that it can be expected that there is an influence on the traffic distribution

between links and also on the total number of trips. There is no single model that takes all of the relevant aspects into consideration and is able to perform a complete analysis of the effect of fuel use and traffic emission due to road measures. Therefore, it is necessary to use several different models that describe different aspects such as traffic assignment including induced traffic, driving patterns, driving resistance and fuel consumption. An ideal situation would be if all these types of models could be combined into an integrated model package. This is a very challenging task and demands a substantial effort since the models are not directly compatible with each other. Therefore, it is not possible within the framework of this project to perform this. However, regarding evaluating the prerequisites for energy efficiency measures in the NRA road network it may be sufficient to use comprehensive data and not detailed data. The work performed in MIRAVEC can be used as a basis for developing more integrated tools for evaluating the connection between road characteristics and traffic fuel use.

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1 Introduction

"ERA-NET ROAD – Coordination and Implementation of Road Research in Europe" is a Coordination Action funded by the 6th Framework Programme of the EC. The partners in ERA-NET ROAD (ENR) were United Kingdom, Finland, Netherlands, Sweden, Germany, Norway, Switzerland, Austria, Poland, Slovenia and Denmark (www.road-era.net). Within the framework of ENR this joint research project was initiated. The funding National Road Administrations (NRA) in this joint research project are Germany, Denmark, Ireland, Norway, Sweden and United Kingdom.

CO_2 emissions from road transport represent an important part of the overall greenhouse gas emissions and consequently contribute to the on-going climate change. Efforts to reduce those emissions need to consider all influencing factors on the energy consumption of road vehicles, which is directly linked to their carbon footprint. Besides the 'greening' of vehicle technologies the improvement of road infrastructure characteristics related to fuel consumption can contribute to an overall CO_2 reduction in road transport. This requires both a thorough understanding of those interactions and the implementation of results in current pavement and asset management practice.

The objective of MIRAVEC is to build on existing knowledge and models. In doing so MIRAVEC aims achieve a more holistic view considering a broad variety of effects. Moreover, MIRAVEC will investigate the capabilities of available models and tools and evaluate the relative importance of different road infrastructure characteristics for different settings (e.g. topography or network type). The project results will be compiled into recommendations to NRAs on how to implement the findings, models and tools in pavement and asset management systems. MIRAVEC consist of 5 work packages. WP1 identifies the most important effects contributing to road vehicle energy use; WP2 investigates modelling tools and uncertainties; WP3 compares the relative importance of different effects and parameters; WP4 will form recommendations for implementation in pavement/asset management and WP5 is project management and dissemination. This is the final report in WP2.

1.1 Objective

The main objective of Work Package 2 (WP2) is to provide a description of existing modelling tools and evaluation of their capabilities with respect to analysing the effects identified in WP1. The focus will be on models used in other projects like IERD, ECRPD and MIRIAM, to evaluate these projects and to identify deficiencies and strengths. The objective is also to analyse factors of major importance identified in WP2, quantitatively or qualitatively depending on the information available and to describe methods for the estimation of uncertainties in model estimations. The results of WP2 will be used as input to WP3: Different contexts and WP4: Implementation in pavement and asset management.

1.2 Structure of WP 2

This work package focuses on describing and evaluating other models used in research related to traffic energy use and road infrastructure. WP2 is led by VTI, who bring their experience in modelling road vehicle energy use, assisted by the other project partners. WP2 is divided into 4 tasks, which are described below.

- Task 2.1: Description of models used in other projects like IERD, ECRPD and MIRIAM.
  The work done in IERD and ECRPD includes analysis of the most important factors influencing traffic energy. These results will be examined and judged in relation to the

parameters of main interest, identified in WP1. The MIRIAM I project has been on-going during 2010 to 2012 and has the road surface effects as its main focus.

- Task 2.2: Evaluation of these projects in order to identify deficiencies and strengths.
  Based on the evaluation of different projects it will be possible to examine what parameters (WP1) are included and treated in different models. Parameters not included in the mentioned projects are probably included in other existing simulation models. These models will be identified and qualitatively analysed. One important step will be to make proposals for WP1 parameters not included in existing models in an acceptable way.

- Task 2.3: Evaluation of the most important factors identified in WP1.
  Based on the assessment work and model inventory and depending on the available information, WP1 parameters will be evaluated quantitatively when possible and qualitatively otherwise.

- Task 2.4: Methods for estimation of uncertainties in model estimations.
  One of the most important tasks in model applications is to quantify the uncertainty in estimated values. Such uncertainty estimation will be performed for some examples based on the IERD, ECRPD and MIRIAM projects. In particular, in IERD and ECRPD, the VETO model has been used for estimations of traffic effects. This model will be used for the uncertainty estimations.

2 Projects about infrastructure parameters and the effect on traffic energy

Three projects where the impact the road infrastructure and its characteristics will have on traffic energy use have been included as one aspect to study. These are IERD, ECRPD and MIRIAM. A summary of these projects is compiled below and the models used in these projects for estimating the effect of traffic fuel consumption are described.

2.1 IERD

IERD is an acronym for 'Integration of Energy Usage into Road Design' (IERD 2002). The objective of the project was to support and encourage road design engineers to consider the energy implications when they design new roads with the aim of reducing the total energy used in the construction and use of roads. In the IERD project methods have been developed in order to estimate energy use for road construction and for road traffic. For road traffic the method should manage to estimate the influence of all road-describing variables with more than minor influence on energy use. The project resulted in a software tool called JOULESAVE that was integrated into Bentley MXROAD (www.bentley.com/en-US/Products/Bentley+MXROAD/). MXROAD is a modelling tool that enables the user to create design alternatives of road types and the inclusion of JOULESAVE was meant to enable the road design engineers to evaluate the energy implications automatically.

In the IERD project, a list of all typical activities that are needed to construct roads was compiled, along with a quantification of the energy needed to perform the activities. The construction energy used for a number of routes and types of roads was estimated. The energy use of traffic for a period of 20 years was calculated using the simulation software VETO (Hammarström, Karlsson 1987). The optimal route was identified according to traditional selection using a Route Selection matrix. This was later supplemented with construction and traffic energy to evaluate the effect energy use would have on the process of route selection. Furthermore, the areas where energy use savings could be made were identified.

By using the energy use spreadsheet it was possible to identify the stages during construction which were the most energy-intense. According to the compilation, these were identified to be earthworks, pavement and road structures and it was also in these stages where the main savings could be achieved. For instance, the savings during the construction stage varied between 1 % and 60 % for the different route alternatives used in the country specific studies. To realise the savings this had to be considered during the design stage, for instance when choosing the alignment of the route. The calculations of traffic energy use took into consideration the road geometry, road surface characteristics and conditions, details of the vehicle, driving behaviour and meteorological conditions. The potential energy savings due to modifying the route were estimated to be between 12 % and 34 %.

One aspect of the IERD project was to study if by including energy use as a decision factor in the Route Selection Matrix had an impact on the selection of the best alternative route. This was studied by analysing a number of specific routes in the participating countries. The result showed that for some countries, the most favourable route when energy was excluded as a decision variable was also the one using the least energy, while in another case the one route most favourable in all other aspects was the one that would be the least attractive one in an energy perspective.

One conclusion of the project was that it could be, from an energy use point of view, worthwhile to consider choosing a route design that would lead to higher energy use during the construction stage in case it would mean lower traffic energy. The reason for this is that with a 20 year analysis period, the energy use of traffic was on average 18 times higher than during the construction. This relation will be larger the longer the analysis period.

2.2 ECRPD

Energy Conservation in Road Pavement Design, Maintenance and Utilisation (ECRPD) built on the IERD-project (ECRPD 2010). It was decided that it would be desirable to also incorporate the energy requirements of maintenance works and materials into the JOULESAVE software package. Therefore, the main objective of the ECPRD project was to develop models and methods to minimise the sum of energy use for road construction, road maintenance and traffic. The research resulted in JOULESAVE2. A spread sheet was produced that included material types, material mixes of currently used and new low energy surfacing, density of materials, construction plant, transport of material, placement practices etc. Also, in ECRPD the model VETO was used to calculate the traffic energy. A first attempt was made to incorporate road deterioration and rolling resistance and the impact it would have on vehicle fuel use.

With the contribution of ECRPD it is possible to use JOULESAVE 2 software to evaluate the energy needed for construction, maintenance and traffic on a road over the course of the life of the road. In the evaluation it is possible to take deterioration of the road and rolling resistance into account. The spread sheet has been incorporated into Bentley's MXROAD.

Four different carriageway types have been studied in the project where energy values were calculated for each of them. The various road types are single carriageway, wide single carriageway, dual carriageway and motorway. Five partners made an analysis for road schemes in their own countries where they compared different route options for a particular road scheme. Five sections of motorway, eleven sections of dual carriageways and eight sections of single carriageway roads were studied in total. The analysis showed that energy savings can be achieved in all of the studied stages of a road's life. According to the case studies, energy savings could be achieved with:

- Construction: up to 47 %
- Maintenance: up to 30 %
- Operation: up to 20 %

Another aim of ECRPD was to compare energy used during road maintenance by the more commonly used road pavement materials with new "low energy materials". This comparison showed that it could be possible to achieve average energy savings of 25% to 30% with the "low energy" materials.

As part of ECRPD a life cycle analysis (LCA) of road surfacing during construction and its maintenance was performed, comparing the environmental impact of asphalt road construction and maintenance during a 20 year period. Two maintenance processes were assessed; a hot method of recycling in asphalt plant and a hot-in-place recycling method. It was found that hot-in-place recycling method would need less energy compared to recycling in an asphalt plant, between approximately 27 to 33 %.

2.3 MIRIAM

MIRIAM (Models for rolling resistance In Road Infrastructure Asset Management systems) is a project with twelve partners from Europe and USA that will perform research about rolling resistance and the potential to reduce CO_2 emissions and increase energy efficiency by reducing the rolling resistance. The overall objective of MIRIAM (Schmidt, 2010) is "…to provide a sustainable and more environmentally friendly road infrastructure by developing an integrated methodology for improved control of road transport CO_2-emissions". The first phase of the project is to contribute with investigation of pavement characteristics, energy efficiency and modelling and focus on development and implementation of CO_2 controlling models into the road infrastructure assent management systems

The aim of the project is to establish models for:

- Energy saving through reduced rolling resistance
- Vehicle CO_2 and rolling resistance sources
- Transport infrastructure operation and management

MIRIAM consists of the following five sub-projects (SP) of which SP2 and SP3 are considered to be relevant for MIRAVEC and described in the following paragraphs

MIRIAM-SP2 Investigate influence of pavement characteristics on energy efficiency

The main aim in SP2 was to determine the range of influencing parameters in road characteristics on energy efficiency in road transport and to estimate the saving potentials of various influencing criteria on energy use. The estimations were performed separately by VTI and AIT using different methods and models.

VTI used an approach where the road surface was characterised by unevenness (IRI) and macro texture (MPD). A rolling resistance function based on IRI, MPD and speed was derived and integrated into a larger simulation model to estimate fuel consumption. AIT used another approach with a direct model of unevenness and texture and a vehicle dynamic model to model the reaction of the vehicle. This was integrated in a larger model.

For the calculations made by VTI the model VETO was used to develop fuel consumption (Fc) functions. The fuel consumption data was calculated with the model for a systematic variation of road and speed conditions. A mechanistic function approach was adjusted to these calculated data. The calibrated function had a high degree of explanation, with an R^2 of 0,99.

Calibrated Fc functions were developed for a car, a heavy truck and for a heavy truck with trailer. The function below describes the simulated fuel consumption, Fc_s. The form is equal for the different vehicle categories, i.e passenger car, truck and truck with trailer. However, the parameter values differ depending on category.

$$Fc_s = c1 \times \left(1 + k5 \times (Fr + Fair + d1 \times ADC \times v^2 + d2 \times RF + d3 \times RF^2)\right)^{e1} \times v^{e2-1}$$

Fr: Rolling resistance (N)

Fair: Air resistance (N)

ADC: Average degree of curvature (rad/km)

RF: Rise and fall/gradient (m/km)

*v: V*elocity (km/h)

c1, k5, d1, d2, d3, e1 and e2: Parameters

The variables IRI and MPD are included in the rolling resistance function (*Fr)*.
The fuel consumption function was used in order to estimate saving potentials of fuel use on the paved road network managed by the Swedish Transport Administration. By systematic reductions of IRI and MPD respectively in the network, total fuel use for all vehicle types and for different sight classes[1] (scl) was estimated.

Examples of some of the results are shown below. The estimations are for an average speed of 90 km/h and an alignment standard of scl 1.

The simulated fuel use increases per unit increase of:

- MPD by:
  car: 2.8 %
  heavy truck: 3.4 %
  truck+trailer: 5.3 %.
- IRI by:
  car: 0.8 %
  heavy truck: 1.3 %
  truck+trailer: 1.7 %

It can be seen from these results that the importance of MPD and IRI increases with increasing vehicle weight.

The evaluation model included a description of speed as a function of the road surface condition (IRI and rut depth), since observation on the network has shown that when IRI is reduced the vehicle speed increases. Thus, the actual reduction in fuel consumption when reducing IRI on a road may be less than given in the above example. Road alignment also has an effect on vehicle speed and thus may have an effect on the results. There is no information available about the effect of MPD on speed but a reasonable hypothesis would be there is a speed effect for MPD as well.

In the VTI research fuel consumption functions showing the influence of road surface parameters were derived. However, the road surface parameters were assumed to be constant along a link which is a simplification that may be necessary to make. Further conclusions was that there may be further need for simplifications for a successful integration into pavement management systems, more different tyre models needed and there is still a lack of useful data for validation of the models.

AIT did a simulation using a 3D road surface model based on direct measurements of real road surfaces made by RoadSTAR (a mobile laboratory) as input to a tire model called FTire.

[1] For a description of sight classes see Table 2.

The road variables available via the direct measurements are skid resistance, texture, curve radius, crossfall, gradient or transverse/longitudinal evenness. FTire is a physical tire model that simulates an actual journey of a tire across a road surface model. This model evaluated the information of the 3D model and calculated the contact pressure and frictional forces, and the road surface influence on driving resistance was derived (Haider et al 2012). This was integrated into a vehicle dynamics model called Dymola/Modelica and the fuel consumption was calculated. The included infrastructure parameters into the tire model were curvature, cross fall, slope, longitudinal profile, lateral evenness and texture. Surfaces of 24 real roads were simulated using this method and the resulting effect on fuel use due to driving resistance effect was between 0 and up to app. 3,5 % change in fuel use depending on road and speed (Haider 2012).

MIRIAM-SP3 Investigate importance of rolling resistance on efficiency within LCA framework

The objective of sub project 3 was to investigate the role of rolling resistance on total energy use in a life cycle perspective and if maintenance treatments could be a viable option to reduce total energy use. Two studies were performed, one by VTI and one by UC Davis (USA).

The purpose of the Swedish research was to enable road management to better consider the total energy (traffic and maintenance) used on roads when managing the road network. The objective was to derive meaningful and simple instruments for decision making situations such as when selecting and designing maintenance treatments, in which total energy use is considered in a multiple criteria analysis.

In this sub-project two case studies were made in which the energy use for traffic and pavement manager induced actions was investigated in detail. The two case studies were based on a 1 km motorway and a 1 km 1+1 road. For these two road sections the measurements for the average IRI, MPD and rutting per 20 meter were extracted. According to the measurements three different maintenance strategies for each road section were formulated and the energy use in a life cycle perspective for each treatment was calculated. Furthermore, the influence of the various maintenance strategies on road condition and the following road deterioration was estimated. The resulting measurements of IRI and MPD was then included in the simulation model VETO to estimate the traffic energy. The sum of these two, maintenance treatment and traffic energy, gave the total energy use.

Some general relationships were identified:

- Traffic energy is the main source of total energy use of a road.
- Since a lower rolling resistance saves fuel for each vehicle passing, lowering the rolling resistance on a highly trafficked road will save more energy.
- The larger the influence of rolling resistance is on total fuel consumption, the larger is the influence of a change in rolling resistance.
- Heavy vehicles gain more from lower rolling resistance than cars.
- Rolling resistance is more important at lower speed compared to higher speed when wind forces become more important.

Furthermore, it is more important to have a low rolling resistance where the vehicles are accelerating or maintaining a constant speed, since a decelerating vehicle does not use as much fuel and lowering rolling resistance in this case would not save as much energy. A lower rolling resistance on a downhill slope or before a tight turn will not save as much energy. Altogether, this means that a lane in one direction can require a different maintenance option than the lane in opposite direction.

UC Davis used two case studies of rural and flat freeways, one with an asphalt overlay and one with concrete (Wang et al 2012). In the LCA studies they compare a situation where one chose to do nothing with a situation of a 10 year rehabilitation practise with a smooth or a less smooth rehab. In MIRIAM one part was to study how the rehabilitation, with improvement of smoothness and texture, would affect traffic fuel use. Four road sections were studied; two high volume roads and two low volume roads. The lengths of the roads sections are 16 km for the high volume roads and 8 km for the low volume roads. First, the progressions of IRI and MPD were developed for different pavement types and rehabilitation strategies. To take rolling resistance into consideration in the traffic energy estimations of the LCA, the HDM-4 model (Morosiuk, Riley 2006) was used to calculate rolling resistance based on IRI and MPD. This was included in the vehicle emission model MOVES. (U.S. EPA, 2010) to estimate the fuel use. Traffic situation with 0% and 3% traffic growth, both with fuel economy improvements, was studied. As a worst case, a situation with 3% traffic growth and no fuel economy improvements was also included.

The LCA study showed that energy savings in the use phase (traffic) for a road section with a high traffic volume can outweigh the energy used in the material production and construction phases independent of the material used (hot mixed asphalt or concrete) for the rehabilitation. The energy savings one could reach in a 5-year period and in a situation of no traffic growth, amounted to between 530-540 TJ and 75-78 TJ for the two roads with the largest traffic volume. For the road with lowest traffic volume, there would not be an energy saving by improving the road smoothness.

A conclusion of the UC Davis studies is that there is a great potential to reduce fuel consumption and greenhouse gas emissions by rehabilitating a rough pavement segment with high traffic volume. For road segments with low traffic volumes, the potential benefits will take much longer to achieve, and the benefit due to lower fuel use may never amount to the extra energy use due to materials production and construction.

2.4 Models used in IERD, ECRPD and MIRIAM for estimating fuel use

In all of the three projects, the basic model used for traffic energy estimation is VETO. In the MIRIAM project the models FTire/Dymola/Modelica and MOVES are also used.

VETO

VETO was developed in order to estimate road traffic exhaust emissions and vehicle operating costs, including deterioration of tyres and brakes, repair cost and capital cost (Hammarström and Karlsson 1987). Lately, the model has primarily been used to estimate fuel consumption and exhaust emissions of traffic due to various characteristics of vehicles, roads and driving behaviour. It is a mechanistic model based on physical relationships in which it is possible to describe both vehicles and specific road segments with high precision. A main objective for VETO has been to develop a tool for planning purposes and evaluation of “all” road measures of importance for vehicle operation cost and exhaust emissions.

The basic data in VETO can be divided into the following main parts: Vehicle; Road; Driving behaviour/Traffic situations; Weather conditions.

The vehicle data includes the type of vehicle, masses, vehicle metric dimensions, cross area, air resistance coefficient. Furthermore, one can describe the engine, fuel type, transmission and wheels including rolling resistance. The road characteristics are the geometry, speed limit and surface characteristics. In this part the vertical and horizontal alignment is described, and also the length, width, crossfall and speed limits. The road section can be divided into segments and each segment can be defined with its own values of the variables. Road surface characteristics cover longitudinal roughness (IRI), macrotexture (MPD) and the age of the surface. These parameters cannot be defined per road segment and are therefore defined as an average for the whole road section.

In driving behaviour it is possible to define speed as a function of road width and speed limits for various vehicles and it is also possible to combine this with a description of traffic situations such as free flow, heavy, saturated and “stop and go”. One can also describe retardation level as a function of speed and engine speed limits for gear changes both upwards and downwards, use of max torque and gear change decisions. Data for weather conditions involves wind speed and direction, air temperature and air pressure, snow depth, snow density, and water depth.

The various input parameters can be changed to investigate vehicle energy use under different conditions. The influence of these aspects on energy use for road traffic can be described by the VETO program, and the energy need is describes as: fuel consumption; engine work; engine brake and wheel brake.

Output data is available on different levels: “meter by meter”; per road block and per road object. One more level is per direction or as an average for both directions. Output per road block is of importance on a route including junctions with different traffic link flows.

In Figure 1 there is an example of output showing speed and fuel consumption for a truck with trailer for the Swedish road object in the IERD project (Rv50, Motala), the bridge alternative, for one of the directions of the road.

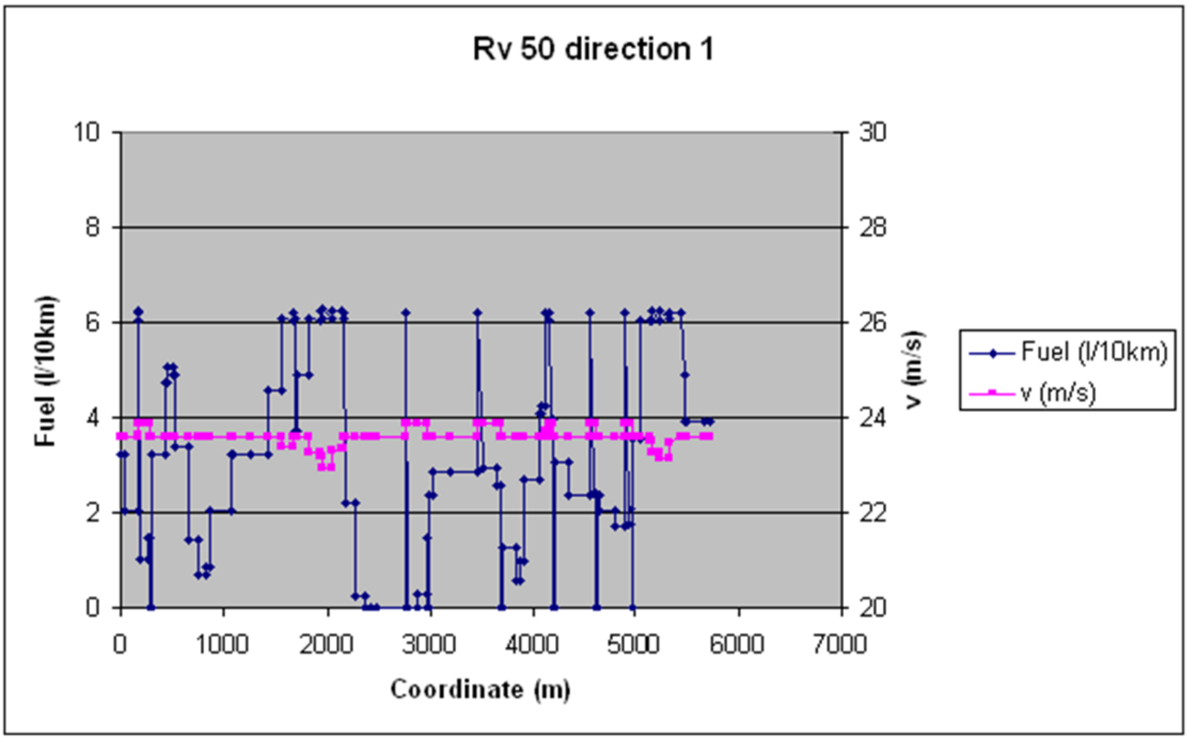

Figure 1 Fuel consumption and speed for a truck with trailer on rv 50, direction 1, in Motala. (“bridge”)

The resulting speed profile, estimated by VETO, is calculated as a function of road conditions, speed limit, vehicle performance and driving behaviour. The effect of junctions on a calculated speed profile can be accounted for by the use of; minimum speed in the junction, stop time and driving behaviour data in junctions. The minimum speed in junctions will be 0 for stopping vehicles and in the interval 20-30 km/h for turning vehicles in junctions. Input data on minimum speed and stop time must be provided by the user.

FTire coupled with Dymola/Modelica

The AIT modelling in MIRIAM phase 1 followed an alternative approach. Due to the availability of the results of measurement campaigns in Austria with the RoadSTAR measuring device three-dimensional road data were available for modelling (Figure 2). This 3D road model could be used as a direct input for a tyre dynamics simulation in FTire coupled to a full vehicle simulation on Dymola/Modelica, yielding directly the driving resistance forces experienced at the rim which are due to the interaction of the tyre with the surface irregularities. In a first-order approximation these forces were converted into the required propulsion power to overcome the driving resistance due to surface irregularities, which can then be used to calculate the increase in fuel consumption. The advantage of this approach is that many effects can be taken into account in a single step. However, this also makes it somewhat more difficult to separate the contributions.

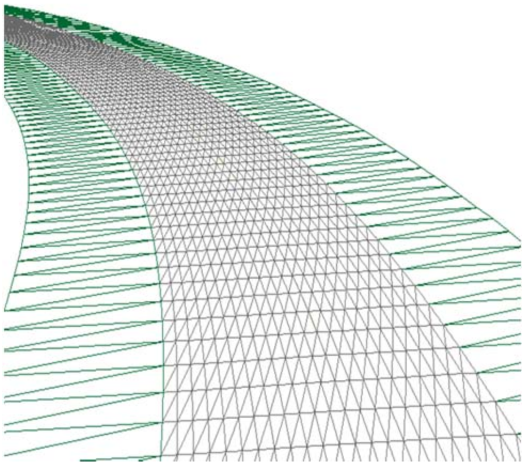

Figure 2 Three-dimensional road model used as basis for simulations.

MOVES

MOVES (Motor Vehicle Emission Simulator) is the official highway vehicle emission model developed by the U.S. Environmental Protection Agency (EPA). It can calculate vehicle fuel consumption and pollutant emissions based on emission factors and traffic fleet composition (EPA, 2010a). MOVES is designed to estimate emissions factors and emissions inventories of VOCs, NOx, CO, PM10, PM2.5 and other pollutants and precursors for vehicles from motor cycles to heavy trucks with trailers. The user starts with modelling geographical areas and road types, specifies vehicle types and vehicle operating characteristics, time periods and pollutants. The user can for example define the vehicle population and age distributions, operating mode distributions, average speed (using default driving cycles), driving cycle (computes operating mode distribution).The model then performs a series of calculations that reflect vehicle operating processes, including cold start or extended idle. Finally it provides estimates of bulk emissions or emission rates. The MOVES model includes a database of emissions relevant for the United States.

The model uses vehicle specific power (VSP), which is the engine power per unit vehicle mass and represents the power demand placed on a vehicle when it operates at various conditions and at various speeds. It is calculated based on the vehicle's speed and the forces that an engine needs to overcome, including rolling resistance, aerodynamic drag, gradient force and engine inertial drag.

$$VSP = (Rolling\ resistance + Air\ resistance + Inertial\ and\ gradient\ resistance) \times \frac{v}{M}$$

Where:

VSP: The vehicle specific power

V: The vehicle speed

M: Vehicle mass

The model contains fine scale information, such as second by second resolution emissions and driving behaviour that can be collected with on-board instrumentation. Thereby any driving pattern can be modelled (Mathey 2012).

Also the energy use is calculated. In MOVES the total activity among emission-relevant operating modes is allocated to running exhaust, start exhaust, extended idle, brakewear, tirewear and evaporative processes. As other output one can get information about distance travelled, hours operating, hours idling, hours parked, number of vehicles and number of starts. One feature is the option to calculate emissions either as inventory estimates (total emissions in units of mass) or as emission rates (emissions per unit of distance for running emissions or per vehicle for starts, extended idle and resting evaporative emissions) in a look-up table format (EPA 2010b).

2.5 Evaluation of models used in IERD, ECRPD and MIRIAM

An analysis was carried out in WP1 that identified the contributing effects and influencing factors for the energy consumption of road vehicles, with a special focus on the effects of road infrastructure. From this analysis, a subset of effects and parameters was identified to take forwards into WP2. A more detailed discussion of this selection can be found in chapter 4.1. The selected parameters were: Macrotexture (MPD), longitudinal unevenness (IRI), transversal unevenness (Rut depth), vertical alignment (gradient), crossfall, horizontal alignment (curvature or ADC), road width and lane layout, traffic volume and composition (AADT) and traffic speed. Table 1 shows which of these variables are included in the models discussed in chapter 2.

Table 1 Inclusion of road variables in models reviewed.

	Variable									
Project / Model	**MPD**	**IRI**	**Rut depth**	**Grad-ient**	**Cross -fall**	**Curve radius**	**Width**	**AADT**	**Traffic com-position**	**Traffic Speed v**
IERD – VETO	X	X		X	X	X	X	x	(x)	X
ECRPD - VETO	X	X		X	X	X	X	x	(x)	X
MIRIAM										
-VETO	X	X	(x)	X	X	X	X	X	(x)	X
-FTire/Dym./Mod.	X	X	X	X	X	X	X			
-MOVES	(x)	(x)		X			(x)	X	X	X

In Table 1 there is a compilation of the projects described in sections 2.1 to 2.3 and the infrastructure variables included in the models used to estimate traffic energy. A large X denotes that the variable is an input to the model used, a small (x) means the variable is indirectly included in the estimation, such as through the use of a predefined rolling resistance function (MPD, IRI), calculated as an additive effect (AADT and vehicle composition) or included via a speed model (RUT).

With VETO there is a high degree of freedom concerning the description of both vehicle and road characteristics making it is possible to take into consideration and analyse the variables defined in WP1. However, the vehicle input data used in MIRIAM was not up to date in order to represent the vehicle data used to develop the EVA fuel consumption model. It is possible to update the model to be able to simulate any road vehicle with manual transmission and Diesel or Otto engine. In the simulation the emissions of HC, CO, NOx and PM are estimated, however, these estimations are not reliable for engines with after treatment of the exhausts.

In MOVES there is a relatively low level of freedom concerning the road description. One has to select from a list of roadway types included in the underlying MOVES database. Thereby, it is not possible to describe specific road sections using the variables identified in WP1. Also, in the driving resistance function the rolling resistance coefficient includes the rolling resistance effect from vehicles. To be able to include and study the effect on fuel consumption due to measures that alter the characteristics on texture and roughness, one needs to alter the driving resistance function parameters for every specific case.

The FTire/Dymola/Modelica model used by AIT in MIRIAM is focused on single vehicles. In order to derive specific results for different vehicle classes, considerable information on representative vehicles and tyres in required. The parameters defined in WP1 are not separate inputs for this model, but most of them, except for speed, should be embodied in the 3D road model which is interacting with the tyre and vehicle. The advantage of this approach is that combined effects and interactions occur naturally and do not have to be modelled in advance. However, the same effect makes it somewhat more difficult to isolate the impact of single parameters. To achieve this it is necessary to vary the properties of the 3D road model systematically in a sensitivity study. Fuel consumption is derived from the resulting driving resistance on a single-vehicle basis and needs to be aggregated for a complete traffic flow using additional information from outside the model.

3 Traffic models

3.1 Models in general

Traffic models can be divided into different categories depending on the level of aggregation such as macroscopic, mesoscopic and microscopic (Burghout 2005). Traffic simulation can also be categorized into network levels, road section and intersection.

Macroscopic models are average speed models that are concerned with the traffic network on a large scale rather than simulating individual vehicles. These types of models are for simulating traffic flow, taking into consideration cumulative traffic stream characteristics such as speed, density and flow and how they relate to each other. Examples of macroscopic models are COPERT and HBEFA 3.1. These types of models have a more aggregated description of the traffic system and are mainly used to estimate fuel use and emissions at the network level ranging from national emissions inventories to small network grids. They include a database of emission factors for different vehicles, traffic situations and road links. However, it is not possible to use these types of models to study effects of changing specific road characteristics variables, such as evenness and texture.

Mesoscopic models are a combination of microscopic and macroscopic simulation models. They describe the individual vehicles at a high level of detail, but their behaviour and interactions are described at a lower level of detail. Examples of mesoscopic traffic models are CONTRAM (Leonard, et al. 1989), Mezzo (Burghout 2004) and DYNASMART (Jayakrishnan, Mahmassani 1994)

Microscopic models simulate individual vehicles and use detailed information of vehicles and calculate fuel use due to the different forces engines need to overcome, for example drag force, inertia, rolling resistance etc. These models are today mainly used to simulate movements of individual vehicles travelling in a road network, using car following, lane changing and gap acceptance rules. The studies focus on the evaluation and development of road traffic management and control systems, and can also examine certain complex traffic problems such as junctions, effects of incidents and intelligent transportation systems. Examples of such models are RuTSim (Tapani, 2005) and Aimsun2 (Barceló et al, 2002).

Another set of microscopic models are used for simulating fuel use and emissions of individual vehicles using a specific driving cycle. These models use detailed information of vehicles, driving behaviour and driving cycles. Two examples of such models are VETO (Hammarström, Karlsson 1987) and PHEM (Hausberger et al 2009; TUG 2013) VETO takes into consideration both detailed vehicle and detailed road characteristics in the estimation of energy need and fuel consumption of vehicles, where the speed and driving cycle for free flow conditions is determined within the simulation and depending on the road description. VETO also includes a tyre wear model based on the forces acting on the tyre. In PHEM one can also describe vehicles in great detail. However there is no possibility to describe the road in the same level of detail, only to define the road gradient when defining the driving cycles used in the simulation and to alter the rolling resistance parameters as input.

In a project like this where the influence of the road infrastructure on traffic fuel use is the main focus there is a need for a model that can describe these effects. In this case the VETO-model is probably the most qualified. However, using the model to study the effects of changes in the infrastructure may not be the most efficient solution since it can be time consuming. Instead, it was decided that generalised fuel consumption estimations from VETO should be used as input to WP3. There were two alternatives to choose between, either the fuel consumption function, Fc_s, derived in the MIRIAM project, see section 2.3, or the energy relations used in the EVA-model. It was decided to use the information included in the EVA-model.

3.2 EVA model

EVA is used by the Swedish transport administration for road planning (object analysis) to calculate effects and socio-economic costs and benefits of individual objects or traffic systems within the road transport system. Several societal aspects are considered such as emission, travel time etc. In EVA there is a fuel consumption model which is split into one urban and one rural part. The rural part is classified into four sight classes (scl 1 – scl 4) by thresholds applied to the road geometry: scl 1 is the best and scl 4 is the worst. In order to classify road links into sight classes one can use definitions in Table 2 (Carlsson 2007).

Table 2 Road alignment for sight class 1–4.

Sight class	Proportion of road with sight>500m	Alignment		Longest gradient		Max gradient (%)
		Horizontal (rad/km)	Vertical (m/km)	Length (m)	Average gradient (%)	
1	>60%	0–0.5	0–10	2 160	0.8	2.1
2	35–60%	0.3–1.0	5–30	2 200	2.0	3.3
3	15–35%	0.7–1.3	>20	2 290	3.2	3.4
4	0–15%	>1.3	>20	2 680	3.4	5.1

A road constitutes a type section (road width) and an alignment. The type section influences the traffic energy use by the desired speed. Increasing road width will increase the desired speed, which in turn will increase the fuel use at least for free flow traffic. In EVA there are separate energy speed related functions per road alignment class for rural roads. Urban roads are described with a straight horizontal road section.

In total there are four road alignment classes. The classes are called sight distance classes and are an indication of how far a user might be able to see ahead. Sight distance class 1 has the longest sight distance. The sight distance will increase when the gradient decreases or the horizontal radius increases. The sight distance classification shall not be regarded as direct indication of how far ahead a user can see. For example road users may be able to see the road long way into the distance, when travelling on a sinuous road in an open landscape but this type of road will not be in sight class 1.

In order to estimate standard fuel use for the four sight classes in EVA, described in Table 2, six road alignment descriptions have been used, see Table 3. The types of roads, named LF_typ11 etc, represent standard road sections characterized by an average degree of curvature (ADC) and average rise and fall (RF). Fuel use in litres per km (L/km) for different vehicle categories, road width and speed limits has been estimated with VETO.

To calculate the standard fuel use per sight class, the following combinations of the fuel use estimated for the six road descriptions has been used:

- scl 1: LF_typ11 only.
- scl 2: 50% of LF_typ12 fuel use and 50% LF_typ21 fuel use.
- scl 3: LF_typ22 only.
- scl 4: 50% LF_typ3x fuel use and 50% LF_typx3 fuel use.

Table 3 Road alignment standard for EVA roads

Type road	**Length (m)**	**Sight class**	***ADC* (°/km)***	***RF* (m/km)****
LF_typ11	22 989	1 (straight, flat)	1,53	5,49
LF_typ12	22 009	2 (straight, rolling)	9,80	15,36
LF_typ21	20 893	2 (sinuous, plane)	29,80	5,00
LF_typ22	21 477	3 (sinuous; rolling)	17,47	17,56
LF_typ3x	25 149	4 (sinuous; rolling)	85,63	18,28
LF_typx3	24 575	4 (sinuous, hilly)	42,43	28,98

* Average degree of curvature; ** Rise and Fall (Gradient)

With the information in EVA it is possible to get a speed and sight class dependant value for fuel consumption. For example, in Figure 3 the fuel use for a passenger car is illustrated per sight class and speed. The estimates are for a dry road surface.

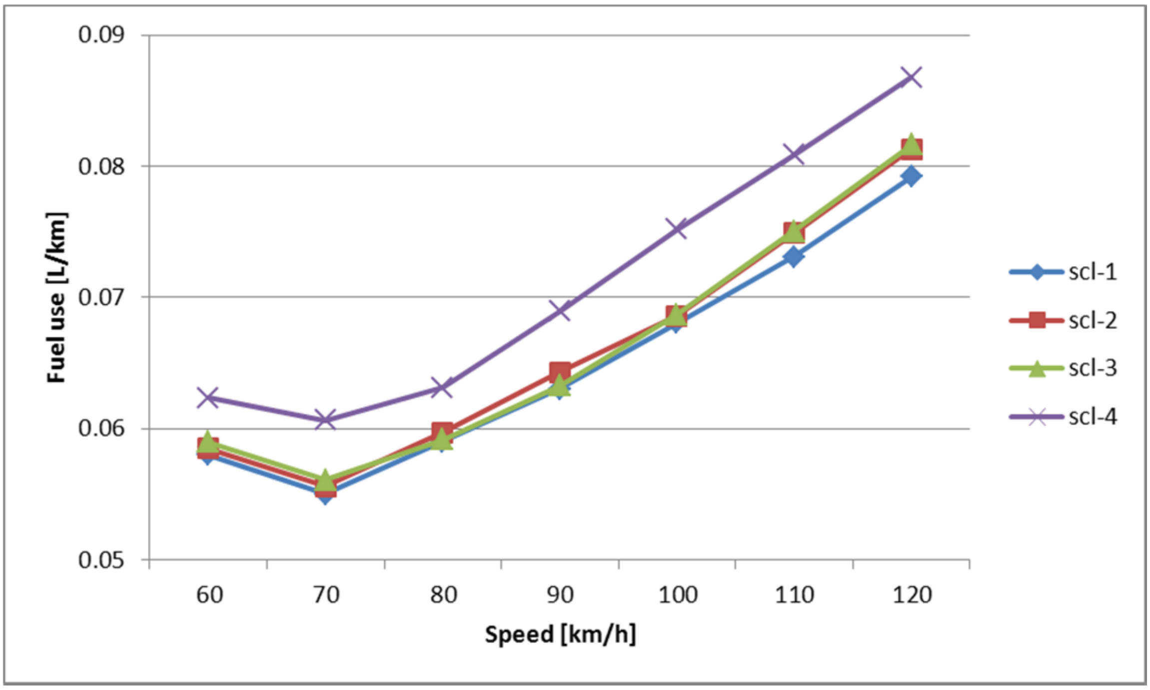

Figure 3 Fuel use for a passenger car (emission class C, petrol), EVA, per sight class (scl 1 – scl 4) and speed.

These "functions" are expressed as table values in EVA. When calculating these values with the VETO model, a series of desired speed values have been selected covering a speed interval big enough for the planning need. The resulting speed cycle per input desired speed only represents interactions between the vehicle and the road alignment. Still these "functions" are used in EVA to also describe interactions between vehicles. One can notice that increasing vehicle weight increases the relative difference in fuel use between sight class functions. There are also possibilities to correct fuel use on rural roads in case of interference in the traffic interactions, such as traffic situations that are not free flow.

In EVA there is a parallel speed model to the fuel consumption model. Speed is calculated as a function of:

- Road width
- Speed limit
- Sight class
- Traffic flow

This speed model is documented in Carlsson (2007). The output speed from this model is used as input to the *Fc* model. Examples describing the influence from road width and alignment standard are presented in Figure 4 and Figure 5.

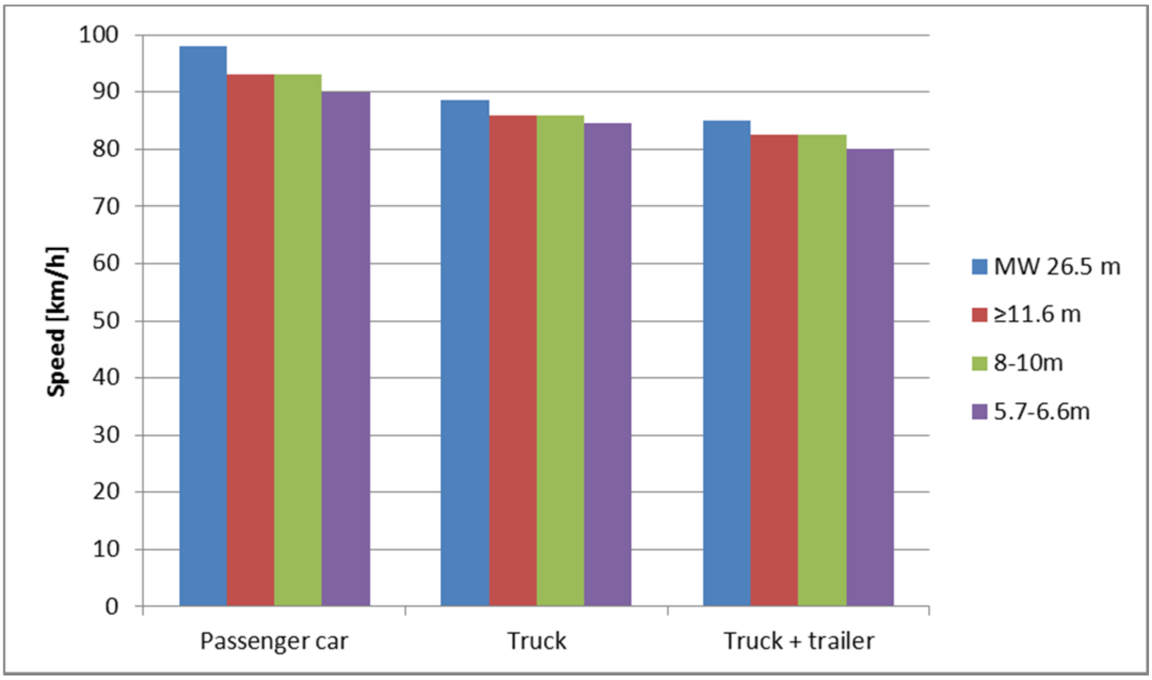

Figure 4 Free flow speed and road width at alignment standard scl 1 and speed limit 90 km/h for different carriageway widths.

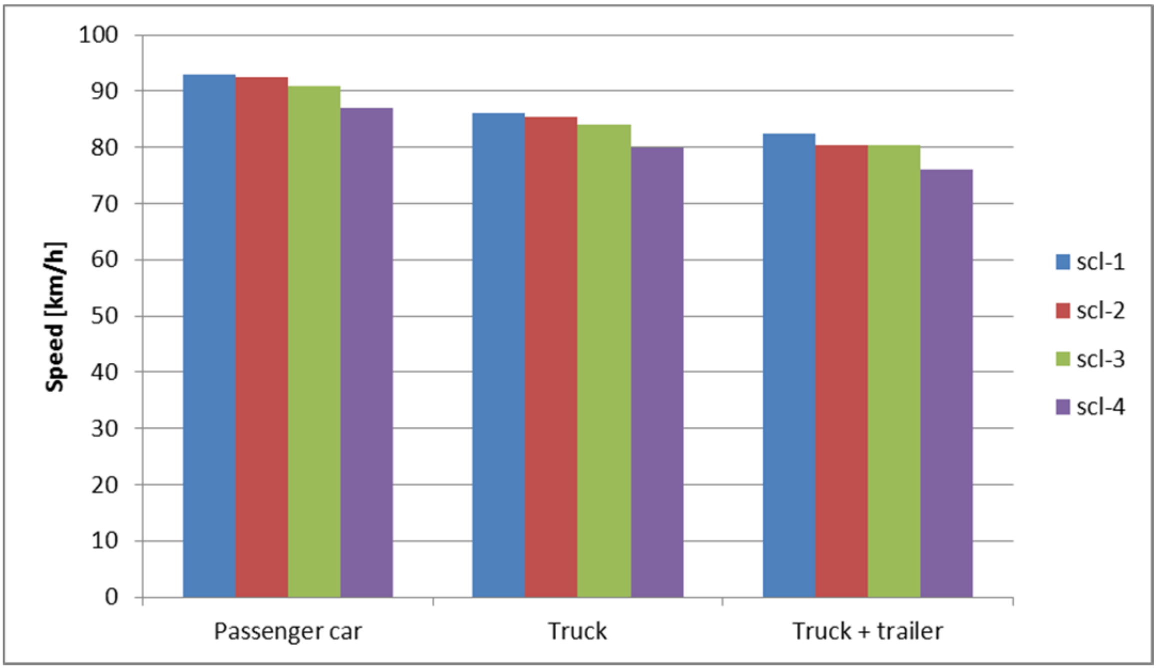

Figure 5 Free flow speed and road alignment standard (scl 1-4) at road width 8–10 m and speed limit 90 km/h.

As can be seen from Figure 4 and Figure 5, the influence of sight class on speed is bigger between scl 3 and scl 4 compared to the differences between scl 1, 2 and 3. For a car and a heavy truck the speed reduction from scl 1 to 2 is just 0.5 km/h. The FC model in EVA also includes some vehicle categories and emission concepts. The vehicle categories included are passenger car (diesel and petrol), truck, truck with trailer urban bus and coach. The emission concepts represent different year model classes or emission concepts. There is no class representing future year models in EVA. However, the future vehicle stock includes both year models existing today and future year models. In this sense EVA includes parts of the future vehicle fleet.

Table 4 Vehicle categories and emission concepts in EVA*

Vehicle category	***Emission concepts*** A	B	C	D	E	F
Car_petrol	*–1987*	*1988–1995 A12*	*1996-2000 (94/12EG)*	2001-2005 (98/69/EG)	2005 98/69/EG+ACEA	2008 98/69/EG+ACEA
Car_diesel	*–1988*	*1989–1995*	1996–2000	2001–2005		
Truck	*–1992*	*1993–1995 A30*	1997 A31	Euro III	Euro IV	Euro V
Truck+trailer	*–1992*	*1993–1995 A30*	1997 A31	Euro III	Euro IV	Euro V
Urban bus	*–1992*	*1993–1995 A30*	1997 A31	Euro III	Euro IV	Euro V
Coach	*–1992*	*1993–1995 A30*	1997 A31	Euro III	Euro IV	Euro V

*At present just concepts with italic letters have separate models in EVA. Other concepts are estimated based on average fuel factors in each concept.

To facilitate taking newer emission concepts into consideration, correction factors has been estimated for vehicle categories described in Table 4. These figures uses EURO3 as reference and EURO1-2 and EURO4-6 are related to that emission concept. The estimations are based on the information in HBEFA 3.1 of Swedish vehicle fleet in 2010 and the result is presented in Table 5. For passenger cars, both petrol and diesel, there are no information about emissions for EURO6 in 2010. For this emission concept information from the prognosis in 2015 has been used instead.

Table 5 Correction factors fuel use different emission concepts, EURO3 = 1.

	PC Petrol	*PC Diesel*	*Trucks*	*Trucks +trailer*	*Urban bus*	*Coach*
Euro-1	1.06	0.94	0.96	1.01	0.93	1.00
Euro-2	1.02	0.92	0.98	1.00	0.96	0.99
Euro-3	1.00	1.00	1.00	1.00	1.00	1.00
Euro-4	0.93	0.86	1.03	0.96	0.84	0.86
Euro-5	0.73	0.73	1.06	0.95	0.93	0.95
Euro-6	0.70	0.68	1.06	0.94	0.92	0.99

4 Evaluation of the factors identified in WP1

Based on the assessment work and model inventory and depending on the available information, the variables identified as the most important were evaluated in a sensitivity analysis.

4.1 Selection of parameters from WP1 for the analysis in WP2

Table 6 shows an overview of the effects and properties analysed in WP1 together with the most important parameters for each effect and the expected level of influence NRAs can exert over it.

Table 6 Overview of effects and properties identified in WP1.

No.	Name of effect or property	Group	NRA influence level (H,M,L)	Variables
1	Rolling resistance (pavement)	A	H	C_R
2	Texture	A	H	MPD, texture spectrum
3	Longitudinal unevenness	A	H	IRI
4	Transversal unevenness	A	H	Rut depth
5	Surface defects	A	H	Defect area density
6	Road strength	A	H	deflection, C_R contribution
7	Vertical alignment (Gradient)	B	H	Angle β or %, RF
8	Crossfall	B	H	Angle γ
9	Horizontal alignment (Curvature)	B	H	R_{Curv}, ADC
10	Road width and lane and carriageway layout	B	H	w_{Road}
11	Intersections and roundabouts	B	H	Level of service
12	Tunnels	B	H	Level of service, $v_{average}$, v_{85}
13	Traffic volume and composition	C	L	AADT, %
14	Traffic flow	C	M	Level of service
15	Traffic speed and speed restriction measures	C	M	$v_{average}$, v_{85}
16	Traffic lights, road signs, road markings and ITS measures	C	M	Level of service, $v_{average}$, v_{85}
17	Driver behaviour	C	M	driving pattern
18	Vehicle type	D	L	vehicle type
19	Tyre type	D	L	tyre type
20	Air resistance	D	M	F_{air}
21	Temperature	E	L	T
22	Wind	E	L	v_{Wind}, α_{Wind}
23	Water	E	M	d_{water}
24	Snow and ice	E	L	d_{snow}, d_{ice}

The analysis in WP2 was focused on a subset of these parameters which was selected according to the following criteria:

- Availability in existing road-infrastructure-oriented models as a numerical model with supporting data.
- Potential NRA influence level.
- Estimation of potential impact on fuel consumption.

The results of this analysis are shown in Table 7.

Table 7 Selections of effects and properties to be analysed in WP2.

No.	Name of effect or property	Model availability (Yes/No/ Partially)	Selected for WP2
1	Rolling resistance (pavement)	N[2]	N
2	Texture	Y	Y
3	Longitudinal unevenness	Y	Y
4	Transversal unevenness	Y	Y
5	Surface defects	N	N
6	Road strength	N	N
7	Vertical alignment (Gradient)	Y	Y
8	Crossfall	Y	Y
9	Horizontal alignment (Curvature)	Y	Y
10	Road width and lane and carriageway layout	Y	Y
11	Intersections and roundabouts	P	N
12	Tunnels	P	N
13	Traffic volume and composition	Y	Y
14	Traffic flow	P	N
15	Traffic speed and speed restriction measures	Y	Y
16	Traffic lights, road signs, road markings and ITS measures	N	N
17	Driver behaviour	P	N
18	Vehicle type	Y	Y
19	Tyre type	P	N
20	Air resistance	P	N
21	Temperature	P	N
22	Wind	P	N
23	Water	P	N
24	Snow and ice	P	N

The following effects were not taken into account for the reasons described below:

- *Rolling resistance* is currently not measured as part of standard monitoring. Therefore it is typically not a primary input to the models, but an intermediate result.

[2] Is not included as a primary parameter

Surface defects and road strength are currently not included in the relevant models, but may be considered in the future. They are, however, influencing the texture and roughness of the road and can be included when there is a suitable road deterioration model available. Also the pavement stiffness can have an influence where a softer pavement can increase the rolling resistance and thereby the fuel use (Hultqvist 2013). Stiffness is not directly considered in the study but, as for surface defects and road strengths, it may be useful to take it into account in the future.

- *Intersections, roundabouts and tunnels as well as traffic lights, road signs, road markings and ITS measures* primarily interact with the traffic flow. The level of service is currently not modelled in detail or given as a general level of service. The potential influence by NRAs is of a more indirect nature, influencing the driving behaviour, i.e. speed, acceleration and deceleration.

- *Driver behaviour* is currently not sufficiently covered in the models.

- *Tyre type* is included in some models, however it was assumed to be determined by the vehicle type as a standard tyre for that vehicle.

- *Air resistance and wind*, whilst these have a substantial effect, and are included in some models, it is difficult for NRAs to influence them.

- *Temperature, water, snow and ice* are currently not sufficiently modelled. However, there is on-going work to improve the accuracy of how these variables may affect fuel use.

Based on these considerations the effects and parameters shown in Table 8 were retained for analysis in WP2.

Table 8: Subset of effects and parameters for analysis and uncertainty modeling in WP2

No.	Name of effect or property	Group	NRA influence level (H,M,L)	Parameters
2	Texture	A	H	MPD, texture spectrum
3	Longitudinal unevenness	A	H	IRI
4	Transversal unevenness	A	H	Rut depth
7	Vertical alignment (Gradient)	B	H	Angle β or %, RF
8	Crossfall	B	H	Angle γ
9	Horizontal alignment	B	H	$R_{Curv,}$ ADC
10	Road width and lane layout	B	H	w_{Road}
13	Traffic volume and composition	C	L	AADT, %
15	Traffic speed and speed restriction measures	C	M	$v_{average}$, v_{85}

4.2 Sensitivity analysis

Material and method

To perform the sensitivity analysis the fuel consumption model described in section 2.3 was used. The fuel consumption per km is calculated using separate functions for cars, trucks and trucks with trailer. For each vehicle type, fuel consumption is calculated as a function of speed limit, road type, road width, rut depth (RUT), roughness (IRI), macro texture (MPD), curvature (ADC) and gradient (RF). The function has, for a given vehicle type, the mathematical structure

$$Fcs = No\_vehicles \times section\_length \times f(speed\ limit, road\ type, road\ width, RUT, IRI, MPD, ADC, RF)$$

Where:

No_vehicles: Number of vehicles

Section_length: Length of the road section [m]

f: A function that can be broken into sub-functions of varying complexity.

The function *f* used within the model is not very complex but because it includes powers and exponential functions it is not linear. However, not being linear does not always mean that it is far from linear. One can try to express this by differentiating the function and inspecting the partial derivatives, or by simply running the model with many different inputs and looking at the functions properties. By doing so, we have found that f is almost linear. It includes squares etc but these have very small coefficients. It also includes cross products but these too have very small coefficients, which results in the overall shape being close to linear.

The sensitivity analysis has used measurement data from the Swedish road network, governed by the Swedish Transport Administration, and the results are based on varying the data around a starting point that resembles the Swedish road network. The data used for this analysis were collected during 2010 and it consists of 144 124 homogeneous road sections with varying length. The total length of the state road network is 98 500 km (www.trafikverket.se). The used data source covers 42 530 km, all Europa roads[3] and state highways (15 400 km), 50% of the primary roads (5 500 km) and 30% of the secondary and tertiary roads (21 630km). The fuel consumption function was used in order to estimate saving potentials of fuel use on the paved road network managed by the Swedish Transport Administration.

[3] Europa road belongs to the Europa road network with E routes numbers.

Information of the road network was compiled using two databases; NVDB and RST. NVDB contains information about:

- road type
- number of lanes
- total width (m)
- speed limit (km/h)
- wearing course
- annual daily traffic (AADT)
- proportion of heavy traffic (%).

The RST includes:

- MPD (mm)
- IRI (m/km)
- Rut depth (mm)
- Cross fall (%)
- Gradient (rad)
- Curvature (10000/radius (m)).

To understand the overall shape of the model and study its properties starting from the situation in Sweden, we altered RUT between seven different levels (0, +/-5%, +/-10%, +/-20%) compared to the current level. For each level we altered IRI according to the same pattern etc. This gave us a grid of 7^5=16 807 scenarios of possible changes in the network. We could thereafter study the shape of the response surface to judge properties such as linearity and additivity. It takes about 1 second to calculate the fuel consumption for the entire network, which provides one point in the grid. All calculations were done in R (http://www.r-project.org/) on a small (8 core) Linux cluster.

Fuel consumption is a function not only of variables but also of a chosen structure and coefficients. It is beyond the scope of MIRAVEC to analyse the suitability of the coefficients used in the model, therefore, the model structure and the coefficients have been considered to be fixed. Sensitivity and uncertainty is thus only discussed in terms of effects of changes to variables.

The results of the sensitivity analysis show that f is an almost linear function of RUT, IRI, MPD, ADC and RF. This is not easy to realise by only studying the model or parts of the model. This result is rather something that was observed from the grid of fuel consumption values generated by varying variables.

Because of the very simple relation to No_vehicles and to section_length, it is obvious that for instance a 1% increase in No_vehicles will give a 1% increase in fuel consumption (FC) or if there is a systematic error in measuring road_length the FC will have the same relative systematic error if all other variables are kept constant. Thus, no further analysis of road length and number of vehicles has been done.

Linear functions have the property that the mean of the function of a variable X equals the function of mean of X and also that the effect of a change in X is the same regardless of the level of X. Therefore a sensitivity can be expressed as a slope.

For the road network, a 1% increase of any of the road variables will cause a relative change (%) in FC, see Table 9.

Table 9 Relative change in % of fuel consumption by 1% increase of the road variables.

	RUT	IRI	MPD	ADC	RF
car	-0.006	-0.003	0.024	0.017	0.039
truck	-0.010	-0.001	0.030	0.008	0.135
truck+trailer	-0.003	0.007	0.042	0.047	0.268

If, for example, rut depth decrease by 1% on average due to road maintenance, then this will result in a fuel consumption increase of only 0.006%. The negative value for trucks fuel use when RUT and IRI is increasing is because the speed of the vehicles is affected by the roughness, i.e. the more rough the road the lower the speed, which outweighs the effect of an increased rolling resistance. This can also be true regarding increasing values in MPD, but there was no information available for this type of speed effect at the time of the MIRIAM project where the fuel consumption function was derived. However, VTI are at the moment in the process of performing such study.

Figure 6 shows the relative differences in fuel use when the road variables are increased separately. For all vehicle categories it is changes in rise and fall that are the most important factor. For example, if RF increases by 20%, fuel use increases by app. 0.8% for passenger cars, 2.7% for trucks and 5.4 % for trucks with trailer. For passenger cars and trucks, RF is followed by MPD and ADC where increases in the values lead to increase fuel use, while there is a slight decrease if IRI or RUT increases. For trucks with trailer the effect due to MPD and ADC are almost equal. Regarding IRI and RUT the development differs compared to passenger cars and trucks since the effect is a small increase in fuel use.

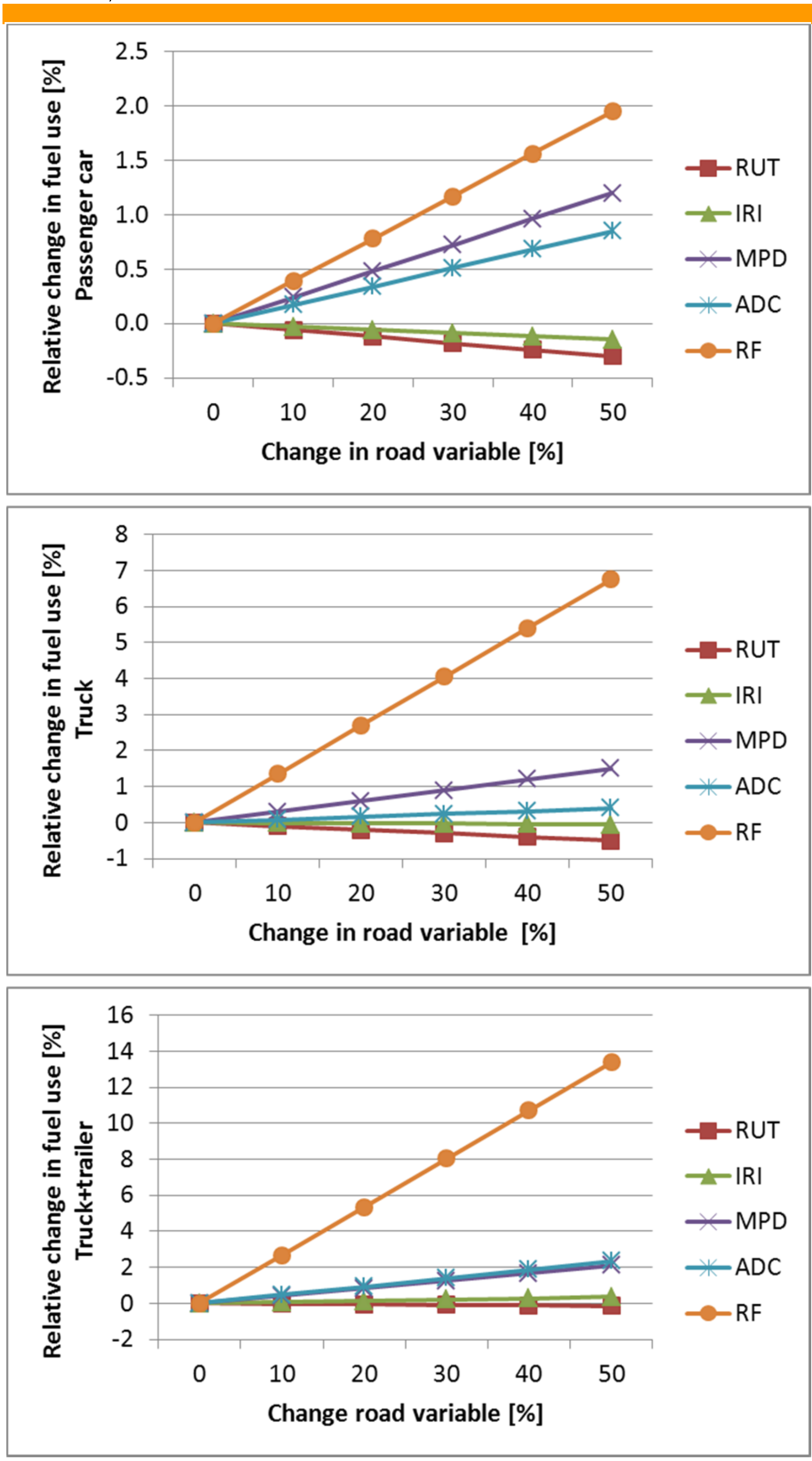

Figure 6 Relative changes in fuel use for different vehicle categories with increasing values of road variables.

These relative differences shown in Figure 6 are estimated for the whole road network. However, the sensitivities vary with road type, , and a separate analysis for road types 1-5 are presented in Table 10, Figure 7 and Figure 8. The road types are:

1. All roads not included in 2, 3, 4 or 5.
2. Wide roads (4 lanes).
3. Freeway with oncoming traffic.
4. Freeway with no oncoming traffic.
5. Regular rural road (2 lanes).

Table 10 Relative change in % of fuel consumption for different road types with a 1% increase of the road variables.

Vehicle category	Road type	Road variable				
		RUT	IRI	MPD	ADC	RF
Car	1	-0.007	-0.002	0.024	0.014	0.027
	2	-0.006	-0.004	0.026	0.022	0.063
	3	-0.006	-0.003	0.026	0.022	0.160
	4	-0.007	-0.002	0.022	0.015	0.023
	5	-0.006	-0.004	0.025	0.018	0.049
Truck	1	-0.011	0.000	0.031	0.008	0.114
	2	-0.010	-0.001	0.033	0.016	0.217
	3	-0.009	0.000	0.030	0.019	0.412
	4	-0.009	0.000	0.028	0.007	0.090
	5	-0.009	-0.001	0.031	0.009	0.167
Truck + trailer	1	-0.003	0.007	0.044	0.037	0.249
	2	-0.003	0.007	0.042	0.061	0.330
	3	-0.002	0.007	0.036	0.066	0.467
	4	-0.003	0.007	0.043	0.035	0.218
	5	-0.003	0.008	0.041	0.055	0.298

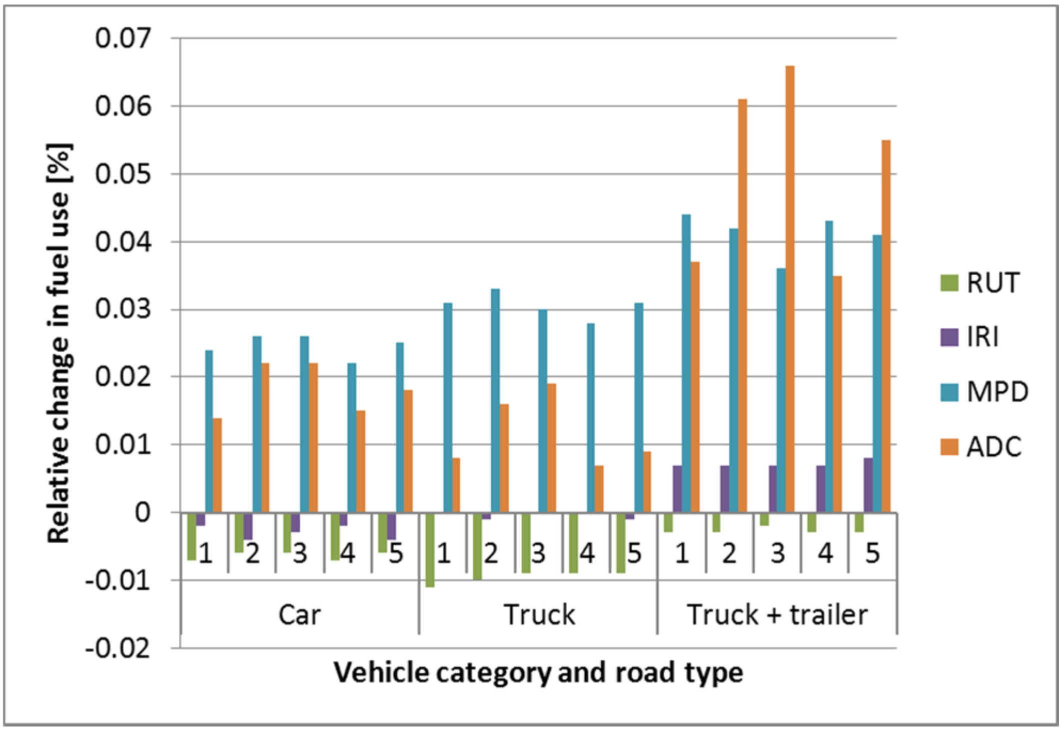

Figure 7 Relative fuel changes for different vehicle categories and road type with a 1% increase in RUT, IRI, MPD and ADC separately.

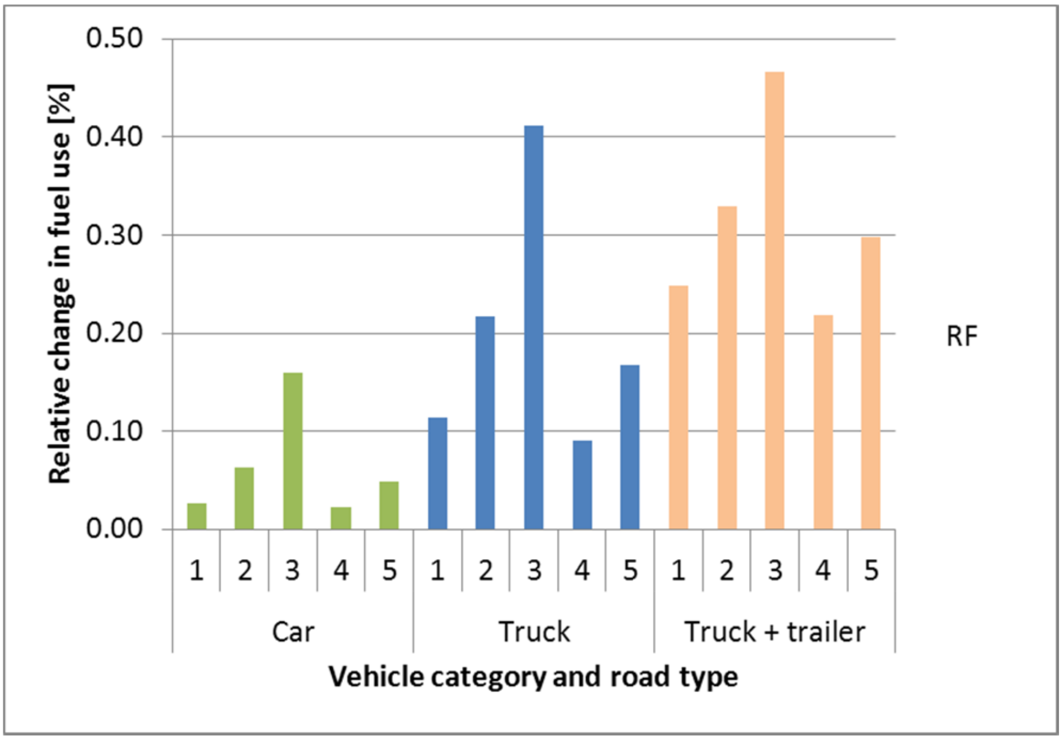

Figure 8 Relative fuel changes for different vehicle categories and road type with a 1% increase in RF.

As can be seen in Table 10, Figure 7 and Figure 8, and for the specific vehicle categories, there is a relatively large difference between road types regarding the resulting impact on fuel use due to changes of the road variables. Also, and as been mentioned before, there is a difference between the vehicle categories where the largest impacts in fuel use are for trucks with trailers. Of the different variables in the analysis, a 1% increase in RF will have the largest effect. Road type 2 and 3 are most affected, while road types 1 and 4 seems to be least affected by a change in RF. This is not the case for the other road variables, RUT, IRI, MPD and ADC, where the road type that is most affected is different depending on the road variable that is changed. An increase in IRI and RUT will according to the calculations lead to a decrease in fuel use for passenger cars and trucks. This is due to the speed effect described earlier. For trucks with trailers only an increase in RUT will have the same effect, while an increase in IRI will lead to an increase fuel use.

According to the sensitivity analysis it can be suggested that it is measures to reduce RF on freeways with oncoming traffic that should be of main interest in order to reduce fuel use. However, it is most likely not a viable option for existing roads, but could be a variable to consider when building new roads. Of the other variables it looks like it is a lower MPD that is a good option to reduce fuel use. Random noise in the input data will give almost no uncertainty in aggregate mean output for a function with a linear nature. This is because the linear nature causes the errors to cancel out on the average. A bias in the input data can cause bias in the output. The sensitivities will help in finding the relative size of any bias in the output caused by bias in the input.

To the Swedish road data, we added random noise with expectation zero to RUT, IRI, MPD, ADC and RF independently and individually in each homogeneous subsection. This simulation was repeated 10 000 times. As expected from the discussion above, this only led to a very small relative variation in total fuel consumption even with standard deviation in the random components as high as 20% of the level. This analysis confirmed the belief that the model is close to linear. If it had not been, another result should have been obtained with this simulation.

The sensitivities tend to be small. Changes in RUT, IRI, MPD, ADC and RF from the current levels only give minor changes in fuel consumption. When evaluating the size of the sensitivities one needs to put them in a context.

RF is smaller on average and less varying in road type 4. A relative change in fuel consumption does not mean that much to a relative change in RF for road type 3 or 5. Also the square of RF is used in parts of the fuel consumption model. This may be an explanation to why the sensitivities against a change in RF differ between road types. It also shows that overall results may not be correct for smaller areas and that there may be reason to do the analysis separate for specific and shorter road segments.

Further discussion of uncertainty could be done on areas small enough, such that random noise does not cancel out. Also, one could try other ways of altering the data like "what happens if the 5% of the roads are repaved, starting with those who have currently deepest ruts and how will this result change if we do not exactly know which roads have the deepest ruts?". This would show the potential traffic energy savings on improving the “worst” roads.

The fuel consumption model uses, for instance, sight class as a function of RF and ADC. This means that a step function is created from continuous data. Sensitivity and uncertainty is easier to discuss for continuous functions of the input. For this use, an improvement of the model could be to try to express a continuous sight value as a function of ADC and RF and to use this sight value instead of sight class in the following calculations.

It is not possible to simply describe the effect on fuel consumption if the speed limit is changed by a small amount because speed limits only have fixed levels. Also road types have only a few levels. A possible analysis could, for instance, be how fuel use would change if the speed change by 10 km/h on 20% of the roads .Road width is continuous but changing it may lead to a road width that is not allowed for that road type. Therefore, it was decided not to discuss sensitivity or uncertainty caused by changes in speed limit, road type, or road width.

5 Discussion and conclusions

Fuel use of vehicles is a function of total driving resistance (F_x) that is the sum of forces:

$$F_x = F_b + F_{air} + F_{acc} + F_{gr} + F_{side} + F_r$$

Where:

F_x: total driving resistance

F_b: wheel bearing resistance (N)

F_{air}: air resistance (N)

F_{acc}: acceleration resistance from vehicle mass (N)

F_{gr}: gradient resistance (N)

F_{side}: resistance caused by the side force (N)

F_r: rolling resistance (N)

In WP1 “Report on the road infrastructure effects contributing to road vehicle energy consumption and their governing parameters”, the variables considered to be important to take into consideration when estimating the effect of traffic energy were identified. These are macrotexture (MPD), roughness (IRI), rut depth (RUT), gradient, crossfall, horizontal curvature (ADC), road width, traffic volume (AADT) and speed (v). MPD and IRI are included in the rolling resistance function; cross fall and longitudinal slope are variables in the side force resistance; road gradient and longitudinal slope are variables in gradient resistance and speed are part of the air resistance, inertial force and side force. AADT is an additive effect which easily can be applied to the estimated fuel consumption. In the case of RUT there is at present no known rolling resistance effect, however, there is a known speed effect which indirectly will affect fuel use via a change in speed. IRI also has a speed effect and it may likewise be true for MPD, but it is a present not known.

In this report, a selection of projects that have evaluated road characteristics and energy use have been described. These are IERD, ECRPD and MIRIAM. IERD primarily evaluated the road alignment and the effect on energy use of different alignment options. The results could be used to include the energy aspect when building a new road. ECRPD complemented IERD in the sense that the operation and maintenance stage of a road life cycle was included in the evaluation. This made it possible to also consider the rehabilitation stages. In MIRIAM, the main focus was on the importance of rolling resistance and how the effect of improvement of road surface characteristics (IRI and MPD) would influence traffic energy, both on a large network and on a specific road section. The evaluation of these models showed that there are possibilities to achieve energy savings in traffic fuel use by taking this into consideration when planning construction of a road or a rehabilitation measure of pavements.

There are numerous traffic models that can be used to simulate traffic in different aggregating levels. When analysing road variables’ influence on traffic fuel consumption, a microscopic model that simulates individual vehicles is the most appropriate since it is possible to describe the input data in great detail. A drawback is that most microscopic traffic simulation models focus on the vehicles, their interaction with other vehicles and the infrastructure, where typical simulations are performed to evaluate road traffic management systems, and complex traffic problems such as junctions, where the traffic flow is of main interest. However, there are some models available where the interaction of the vehicle and road can be described in detail, such as VETO and the coupled FTire/Dymola/Modelica, and where fuel use due to changes in driving resistances can be described. Even though a detailed microscopic simulation model probably is the best choice when investigating the fuel effect due to changes in road variables, it may not be the most practical solution. Therefore, generalised fuel consumption estimations generated by VETO and currently used in the EVA-model will be used in WP3. With these estimations it is possible to consider speed, vehicle type and emission concepts, sight class of rural roads with ADC and RF and urban roads. There is, however, a need to develop a routine that enables to take changes in IRI and MPD into consideration.

The sensitivity analysis, using the available information of the Swedish state road network, showed that there is a close to linear relationship between relative changes in the analysed road variables and the relative change in fuel use. This relationship makes it less complicated to estimate the effect of changes. Another result is that fuel use is insensitive, in that the relative change is less than 1% when the value of a road variable changes by 1%. Generally speaking, RF leads to the largest impact, followed by MPD and ADC. The relative changes are larger the heavier the vehicle, hence fuel use of trucks with trailer is most affected. The majority of vehicles travelling on the roads are passenger cars and these are responsible for the main amount of vehicle kilometres. Therefore passenger cars will most likely be responsible for the largest fuel use reductions, or increase, in case of a change in the road variables. The size of the relative change in fuel use is also dependent on the road type and the most important factor and the biggest change varies between road variable and road type. With IRI the speed effect due to reduced roughness (higher speed with lower IRI) seems to overcompensate the decreased fuel use, leading to increased fuel use for passenger cars and trucks. The same speed effect is present for RUT.

Concerning RUT a possible rolling resistance effect of this parameter should be further investigated and for MPD an analysis should be made to see if there is a speed effect. The aim should be to include these effects, if they exist, in the evaluation of the traffic fuel use. Also, there is an effect on both rolling resistance and to some extent speed, when road surfaces are wet or covered with snow or ice. These effects can be of importance since the roads are moist or wet for a large part of the year. In the more northern countries, the influence of snow and ice on the road surface is also of interest. Another set of variables that are of interest to include are surface defects and road strength. Once there is a suitable and well-founded road deterioration model available these variables should be included.

When evaluating road characteristics and using them as a basis for decision-making for performing road measures one need to keep in mind that road measures not only have an effect on driving resistance but also directly influence driving patterns. Furthermore, when making improvements of one road link, it would be expected that this would not only have an influence on the traffic distribution between links but also on the total number of trips. There is no single model that takes all of the relevant aspects into consideration and is able to perform a complete analysis of the effect of fuel use and traffic emission due to road measures. Therefore, it is necessary to use several different models that describe different aspects such as traffic assignment including induced traffic, driving patterns, driving resistance and fuel consumption. An ideal situation would be if all these types of models could be combined into an integrated model package. While a substantial effort and some simplifications would be needed, this should be the focus for further developments in the future.

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