Paper number ITS-XXXX

# Review of rolling resistance influence on fuel consumption of trucks

**Yue Huang*, Haibo Chen**

Institute for Transport Studies, University of Leeds, UK. *y.huang1@leeds.ac.uk

**Abstract**

Drivers and logistics companies traditionally use GPS for route advice. A two-dimensional route is selected mainly based on the distance and traffic condition. Resistance of road vehicles, namely aerodynamic, grade and rolling resistance, which is strongly related to fuel consumption, also depends on the topographic condition, speed and interface between tyres and road surface. The route optimisation for long distance trucks therefore, needs to consider these. This paper is to review state-of-the-art literature on the modelling of vehicle rolling resistance, and propose a method to integrate the rolling resistance and its influencing factors, e.g. tyre configuration, pavement type, condition (e.g. texture depth, roughness), temperature and dry/wet state, to existing route optimisation framework. The aim is to develop a method to predict fuel consumption more accurately considering a 'third' dimension in vehicle route. The outputs shall help to reduce the fuel consumption of long distance trucks within the European Union.

**Keywords:**

Rolling resistance, fuel consumption, trucks

## 1. Introduction

Drivers and logistics companies currently use GPS for route advice. A two-dimension route is selected mainly based on the distance and traffic condition (e.g. speed). Resistance of road vehicles, namely aerodynamic resistance, gravitational resistance and rolling resistance, is strongly related to fuel consumption. Those resistant forces depend on the topography, speed and friction between tyres and road pavement. The route optimisation for long distance trucks therefore, needs to consider vehicle resistance.

In vehicle dynamics (Mannering et al., 2013), the tractive force (F) of vehicles will overcome these resistances, to gain an acceleration to drive the vehicle forward. A simplified approximation was used for the rolling resistance coefficient by Descornet (Descornet, 1990) in the 1990s, due to being unable to 'single out' the effects of the wide range of influencing factors. In this study, a 'quarter-car' was designed and built at the Belgian Road Research Centre for measuring the rolling resistance of a reference tire on the road. The values provided, between 0.013 and 0.0211 (corresponds to vehicle speed of 48 km/h and 177 km/h, respectively) were derived from a variety of pavement types and conditions on dry state of road surface. The main road-related influencing factor was found to be the surface profile irregularity, in a wavelength range between macro-texture (0.5-50 mm) and unevenness (> 500 mm). However, these values were derived for cars.

## 2. Measurement Standards

The SAE[1] and ISO standards for measurement of rolling resistance of tyres are reviewed in MIRIAM report (Sandberg, 2011). In which,

- SAE J1269 is an industry standard method for determining rolling resistance at four different load and pressure conditions for passenger cars, six test conditions for light trucks, and five test conditions for trucks and buses. It has been extensively used in rating and reporting systems.
- SAE J2452 consists of a coastdown approach. It covers four test conditions for passenger cars and five for light trucks.
- ISO 18164:2005 is similar to SAE J1269, except that this method includes all four-measurement methods, i.e. force, torque, power, and deceleration. It covers four test conditions for passenger cars and five for light trucks.
- ISO 28580:2009 uses all four-measurement methods. It contains a method of laboratory alignment, i.e. the procedure requires two reference tyres for passenger cars and light trucks. The correlation develops an alignment equation for the participating labs to correct their raw data.

Drum, trailer and coastdown are the commonly used methods for measuring rolling resistance. Coastdown measurement (Fig.1a) is performed by letting the vehicle roll freely (clutch down, gear in neutral) between the start- and end-point. The main difficulty in applying this method is eliminating (or compensating for) other resistance, i.e. air and gravity. In some measurements (Fig.1b), the truck drives at a constant speed to avoid wind effects (aerodynamic resistances) on the results.


Fig.1a Coastdown measurement for trucks (Karlsson et al., 2011)

[1] SAE International is a global association of engineers and technical experts in the aerospace, automotive and commercial vehicle industries. SAE develop voluntary consensus standards.

Fig.1b Rolling resistance measured by a truck and trailer. (Sandberg et al., 2011)

## 3. Previous Research

Overall, the following variables are found by literature to be significantly affecting a vehicle' rolling resistance: 1) pavement structure, 2) vehicle mass (tyre pressure), 3) pavement temperature (weather), 4) pavement macro-texture, 5) road roughness (unevenness), and 6) vehicle speed.

### *3.1. Road surface type*

Measurement by Hooghwerff (Hooghwerff et al., 2013) in the Netherlands showed the qualitative relationship between rolling resistance and road surface types. This measurement program was conducted on the Dutch primary (highways) and secondary (provincial) roads, consisting of 69 road sections where the rolling resistance and texture depths were measured simultaneously. The selected road sections vary in both surface type and age (i.e. condition).

Differences in rolling resistance up to 30% due to road surface types were found, whilst no significant differences were found in relation to the age of the road. In general, road surface of the same type but made with fine grading was found to have lower rolling resistance.

Temperature (tyre wall side) had a significant effect on rolling resistance coefficient (RRC), and thus all rolling resistance values were corrected to a reference temperature of 25°C, using a correction of 0.17 kg/t/°C$^3$, see Eq.1. This correction coefficient was obtained by the average of two types of pavement: porous asphalt concrete (PAC) and dual-layer porous asphalt concrete (DLPAC). The influence of tyre temperature is found to be more significant than air temperature (0.11 kg/t/°C$^3$) or road temperature (0.10 kg/t/°C$^3$).

$$RRC_{Temperature\ corrected} = RRC - (0.17 \pm 0.02) \times (25 - T_{Tyre\ wall\ side}) \qquad \text{Eq.1}$$

In addition, the project also found that the relationship between the rolling resistance (kg/t) and tyre pressure of the vehicle (kPa) was almost linear. However, the effect of type pressure on rolling resistance was found to be largely negligible, from the measurements. The report concluded that by varying the road surface type, rolling resistance could be changed by approximately 10%, which will lead to a potential reduction of the fuel consumption by up to 3%.

### *3.2. Pavement type and vehicle speed*

A passenger car and a heavy haul tractor pulling a loaded semi-trailer were driven over three types of pavement (asphalt, concrete and composite) in Canada in 2002-2003, to quantify the fuel consumption and investigate whether fuel savings could be attributed to the pavement type. The tests (Taylor and Patten, 2006) were conducted in four weather conditions (winter, fall and spring, summer cool, summer hot), and at two vehicle speeds: 60 km/h and 100 km/h. In addition, the trailer was loaded at different weights (empty, and fully loaded to 49.4 t), to investigate whether the effect of vehicle load on fuel consumption is different among the three pavement types. The project found:

- At 100 km/h, fuel consumption on concrete roads was less when compared to asphalt and composite roads, except in summer days when driving on composite roads used less fuels.
- At 60 km/h, there were fuel savings for the empty trailer on concrete roads compared to asphalt roads. The fuel savings for the fully loaded trailer on concrete roads were to a less extent.
- At 60 km/h, the fuel savings for both the empty and full trailer on concrete roads, compared to composite roads. However, the summer day data indicated a fuel saving in favour of the composite roads, when compared to concrete roads.

The following surveys were conducted on the tested roads in this project. All tests were carried out on smooth surface (IRI < 2 m/km), whilst the report stated that in the case of higher IRI values, the roughness will be the dominant factor in affecting fuel consumption. In addition, other aspects of pavement functionality, such as noise, skid resistance, maintenance needs and costs, need to be considered.

- International Roughness Index (IRI), to measure irregularities of the road surface
- Precision GPS, to gather information on road curves and grades
- Falling Weight Deflectometer (FWD), to derive the pavement stiffness

### *3.3. Pavement roughness and texture depth*

Research by Zaabar and Chatti (Zaabar and Chatti, 2010) aimed to develop a model to estimate the effects of pavement condition on fuel consumption in USA. The project involved field measurement using both cars and trucks, and it used the site data to calibrate the mechanistic Highway Development and Management software (HDM-4), for predicting fuel consumption of five different vehicle classes under different speed, weather and pavement conditions. Results highlighted the effects of pavement roughness on fuel consumption. For example, a decrease of IRI by 3 m/km would result in a 1.1% to 1.7% reduction in fuel consumption for light and articulated trucks, respectively.

This research was built on the HDM-4 model developed by World Road Association (PIARC). The product includes a software package and associated documentation, for planning, analysis, management and appraisal of road maintenance, improvements and investment decisions. As revealed in the report, the software contains a model for calculating rolling resistance, see Eq.2.

$$F_r = CR2 \times FCLIM \times [b11 \times N_w + CR1 \times (b12 \times M + b13 \times V^2)] \qquad \text{Eq.2}$$

From the above equation, rolling resistance is a function of the following variables:

- Tyre factor, **CR1**
- Surface factor, **CR2**, a function of pavement texture depth (Tdsp, mm), international roughness index (IRI, mm/m), deflection (DEF, mm) and model coefficients (a0, a1, a2, a3)
- Climate factor, **FCLIM**, a function of percent driving in snow condition (PCTDS) and percent driving in wet condition (PCTDW)
- Rolling resistance parameters, **b11, b12, b13**, a function of the number (**Nw**) and diameter (**Dw**, m) of tyres
- Vehicle weight, **M**, kg
- Vehicle speed, **V**, m/s

The rolling resistance (Fr) calculated using the above equation will then feed into a fuel consumption model in the HDM-4, together with other vehicle resistances and traction forces.

### *3.4. Instantaneous modelling*

In the late 1990s, a project (Barth et al., 2000) led by University of California Riverside developed a Comprehensive Modal Emissions Model (CMEM), to estimate emissions from light duty vehicles (e.g. cars and small trucks). The model indicated that the emissions are associated with the vehicle's operating modes and conditions (e.g., properly functioning, deteriorated, malfunctioning). The model is able to predict instantaneous fuel consumption and tailpipe emissions of carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx), and carbon dioxide ($CO_2$). The model and emission database are available for purchase at: https://www.cert.ucr.edu/cmem/model.html. This model was not designed for heavy goods vehicles.

A recent research by Wang and Rakha (Wang and Rakha, 2017) applied the Virginia Tech Comprehensive Power-based Fuel consumption Model (VT-CPFM) framework and developed a new model that was calibrated and validated using field data collected using a mobile emissions research laboratory (MERL). Results demonstrated that the model can accurately predict fuel consumption levels, consistent with field observations, and the model outperformed the comprehensive modal emissions model (CMEM) and the motor vehicle emissions simulator (MOVES) model. The new model consisted of a resistance force model, a vehicle power model and a fuel consumption model. It can be calibrated using GPS data and implemented in traffic simulation software, smartphone apps and eco-freight programmes. In calculating the rolling resistance, this project used the coefficients developed by Rakha (Rakha et al., 2001) and Fitch (Fitch, 1994), shown in Eq.3.

$$R_r = 9.8066 \times C_r \times (C_2 \times V + C_3) \times \frac{m}{1000} \qquad \text{Eq.3}$$

Where:

- Cr - rolling coefficients, a function of the road surface type and condition.
- $C_2$, $C_3$ - constants, a function of the vehicle tyre.
- m - vehicle mass in kg.

*3.5. Research in Sweden*

Research by VTI (Swedish National Road and Transport Research Institute), as part of the ECRPD (Energy Conservation in Road Pavement Design, Maintenance and Utilisation) project funded by Intelligent Energy Europe, used a slightly simplified equation to calculate the rolling resistance, shown in Eq.4 (Hammarström et al., 2009):

$$F_r = mg \times (\alpha_0 + \alpha_1 \times (25 - T) + \mu_0 \times MPD + \mu_1 \times v \times MPD + \beta_0 \times IRI + \beta_1 \times v \times IRI)$$

- MPD: mean profile depth, mm
- IRI is international roughness index, mm/m
- m, V and T are vehicle mass (kg), speed (m/s) and air temperature ($^0$ C), respectively
- α, β, μ are constants

The project used the coastdown method, which indicated the following relationship between rolling resistance coefficient (RRC) and the road surface conditions, i.e. MPD and IRI, for cars (see Eq.5) and trucks (see Eq.6). It concluded that the IRI is much more influential to the RRC for a truck than for a car while the opposite is true for MPD.

- For a car (Volvo 940):

RRC = 0.0148 + 0.0020**x**MPD + 0.00064xIRI + 0.00005xIRIx(V-20) Eq.5

- For a truck (Volvo FH-480 with a total weight of 27t):

RRC = 0.0061 + 0.0014xMPD + 0.00095xIRI + 0.000076xIRIx(V-20) Eq.6

Further work by VTI (Karlsson et al., 2011) developed a similar equation. The main difference is that the air temperature in the above equation was replaced by temperature of the tyre in the new equation. This project developed a general rolling resistance model – with roughness (IRI), macro-texture (MPD), temperature and speed as explanatory variables. Again, the coastdown method was used. The model was applied to a private car and to a heavy goods vehicle (HGV, 14.5t). The coefficients for MPD and IRI were found to be reasonably accurate in cars. The results for HGV were less stable, and thus unable to draw any definitive conclusions.

In another research at VTI (Hammarström et al., 2012) at part of the MIRIAM (Models for rolling resistance In Road Infrastructure Asset Management Systems) project, the rolling resistance model was integrated into a driving resistance-based fuel consumption model. The fuel consumption model also included variables for horizontal curvature (ADC – average degree of curvature, measured by degrees/km) and the road gradient (RF – rise and fall, measured by m/km). A car (1.5t), a heavy truck (12.9t) and a truck with trailer (41.7t) were used in the testing.

Table 2 - Swedish road alignment for sight class (sl) 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 |

The project found that the importance of MPD, IRI and alignment standard (*scl 1 to scl 4, an example see Table 2*) increases with vehicle weight, more specifically:

1) Rolling resistance caused by IRI is dependent on speed. If MPD per road link were reduced by 0.5 mm, the total Fc in the road network would be reduced by 1.1%. By reducing IRI per road link by 0.5 m/km, speed will increase in parallel to reduced rolling resistance and there will be approximately no effect on Fc.

2) At a speed of 90 km/h, rolling resistance increases, per unit increase of IRI and MPD:

- for a heavy truck by 7.1% and 18.4%
- for a heavy truck with trailer by 7.9% and 20.3%

3) At a speed of 90 km/h and an alignment standard *scl 1*, fuel consumption (*Fc)* increases, per unit increase of IRI and MPD*:*

- for a heavy truck: 1.3% and 3.4%
- for a truck with trailer: 1.7% and 5.3%

4) At a speed of 90 km/h, fuel consumption (*Fc)* increases when the alignment standard decreases from *scl 1* to *scl 4*:

- for a heavy truck: 21%
- for a truck with trailer: 60%

It is worth knowing that a good alignment is usually associated with a high design speed which, when at 90 km/h or above, will result in an increase in fuel consumption. Thus, the above finding 4) needs to be dealt with care.

*3.6 MIRIAM project*

The MIRIAM project (http://miriam-co2.net/) investigated how, and to what extent, the rolling resistance is influenced by various road pavement parameters, such as texture, unevenness and stiffness. Results confirmed findings from others that the relationship between rolling resistance coefficients and MPD is rather consistent in different and independent measurement series, and the effect of IRI on rolling resistance is equal to around 1/3 of the effect of MPD (Sandberg et al., 2011). The rolling resistance coefficient with road surface influence, in speed range of 50-110 km/h, is shown in Eq.7:

$$\text{Rolling resistance coefficient (RRC)} = \text{Constant} + 0.0020 \cdot \text{MPD} + X \cdot \text{IRI} \qquad \text{Eq.7}$$

Where:

- MPD is measured in accordance with ISO 13473-1
- X is a constant yet to be determined
- "Constant" is a value unique to a certain tyre and several other circumstances, usually 0.008 to 0.012 for light vehicles and approximately 50-60 % of that for heavy vehicles.

Most of results from the project were based on field measurements of rolling resistance. However, the above model was based on light vehicle data. Another report (Sandberg, 2011) from the MIRIAM project made a comprehensive review of the influencing factors to rolling resistance coefficient (RRC, in unit of kg/t), including tyre, road and temperature. For example, the tyre was found to have the following effects.

- Tyre diameter, $RRC = k \cdot OD^{1/3}$ (OD is tyre outer diameter). For example, if OD is increased by 4%, RRC will decrease by 1.3%.
- Rubber hardness, Two tyres of the same brand, type and dimension but with different stiffness of rubber showed approximately 8% reduction in RRC, when the hardness reduced from 71 to 62.
- Tyre condition. When tyres were worn from 8mm to 2 mm tread depth, the rolling resistance decreased consistently by about 20%, across different tyre brands.
- Inflation pressure. The rolling resistance coefficient decreased by 2.7%, as inflation pressure increased from 15% below recommended tyre inflation (2.7 bar, or 270 KPa) up to the recommended value (3.2 bar, or 320 KPa).

In the MIRAVEC project, vehicle fuel consumption was calculated as a function of road factors, namely the rut depth (RUT), roughness (IRI), macro-texture (MPD), curvature (ADC) and gradient (RF). Sensitivity check was carried out on those factors. Results showed that the RF led to the largest impact, followed by MPD and ADC. The heavier the vehicle, the more influential these factors are to fuel consumption (Carlson et al., 2013).

## 4. Calculation of rolling resistance for trucks

According to the research (Viner et al., 2006) by UK Transport Research Laboratory (TRL), the following relationship exists between the texture depth and MPD, see Eq.8:

$$MPD = 1.42 \times \text{Texture Depth}^{0.840} \qquad \text{Eq.8}$$

If the threshold value of 1.1 mm were used as the texture depth (for Category 1/2 pavement), as defined by UK Design Manual for Roads and Bridges (DMRB, 2008), the MPD can be calculated, using Eq.8, to be 1.538 mm. If the IRI were kept within 2 m/km as suggested by (Zaabar and Chatti, 2010), the rolling resistance coefficient for trucks can be calculated using Eq.6 and the above MPD value, for a range of speeds as in Table 3:

Table 3. Rolling resistance coefficient (RRC) for Category 1/2 pavement

| Speed (km/h) | 50 | 60 | 70 | 85 | 100 |
|---|---|---|---|---|---|
| MPD (mm) | 1.538 | 1.538 | 1.538 | 1.538 | 1.538 |
| IRI (mm/m) | 2 | 2 | 2 | 2 | 2 |
| RRC* | 0.0147 | 0.0162 | 0.0178 | 0.0200 | 0.0223 |

*Results rounded to four decimal places

Similarly, if the threshold value of 0.4 mm were used as the texture depth for Category 3/4 pavement, the MPD will be, calculated using Eq.8, 0.658 mm. Subsequently, the rolling resistance coefficient can be calculated as in Table 4:

Table 4. Rolling resistance coefficient (RRC) for Category 3/4 pavement

| Speed (km/h) | 50 | 60 | 70 | 85 | 100 |
|---|---|---|---|---|---|
| MPD (mm) | 0.658 | 0.658 | 0.658 | 0.658 | 0.658 |
| IRI (mm/m) | 2 | 2 | 2 | 2 | 2 |
| RRC* | 0.0135 | 0.0150 | 0.0165 | 0.0188 | 0.0211 |

*Results rounded to four decimal places

## 5. Conclusion and Future work

In highway engineering, the coefficient of rolling resistance is simplified to have a linear relationship with vehicle speed. However, researches have proved that, in addition to the tyres, the following factors associated with pavement need to be considered for their effects on rolling resistance. Thus, it will be helpful if a model can be developed which is able to predict the rolling resistance.

- Pavement structure (e.g. type, stiffness)
- Roughness or unevenness (e.g. IRI)
- Texture depth (e.g. MPD)

Of all the studies reviewed in the report, the rolling resistance model contained in the HDM-4 looks to be the most comprehensive. This model encompass almost all the influencing factors tested in other research, namely the tyre, the road, vehicle speed and the weather. The work by (Sandberg et al., 2011) investigated the tyre parameters in more details. Unfortunately, that research was only carried out on light vehicles. Research (Hammarström et al., 2009) at the Swedish Road and Transport Research Institute (VTI) established a slightly simpler equation for rolling resistance, as in Eq.6:

RRC = 0.0061 + 0.0014xMPD + 0.00095xIRI + 0.000076xIRIx(V-20)

This equation was developed for a heavy truck (27t). The constant (0.0061), and the coefficients for MPD and IRI, are largely consistent with the key findings from other research (Carlson et al., 2013, Hammarström et al., 2012, Sandberg et al., 2011). Generally:

- The influence of IRI on rolling resistance is affected by vehicle speed.
- Vehicle speed has less influence on the coefficient for MPD.
- The influence of MPD on rolling resistance, and on fuel consumption according to (Hammarström et al., 2012), is about 3 times the influence of IRI.
- The heavier the truck, the more significantly the influencing factors will effect on the rolling resistance, except for the MPD, which is more influential to cars.
- Road geometry, i.e. curvature and gradient, has very significant effect on fuel consumption.

Fuel consumption of trucks is associated with many more factors (see Fig.2). In addition to those that affect rolling resistance, other factors such as vehicle age and driving pattern (Barth et al., 1999). Results from VTI (Hammarström et al., 2012) indicated that the change in fuel consumption is significantly less than the change in rolling resistance. It shows that the effect of rolling resistance on fuel consumption is 'moderated' by the effect of other influencing factors. There are projects that directly measure the relationship between the influencing factors, such as MPD, and vehicle fuel consumption.

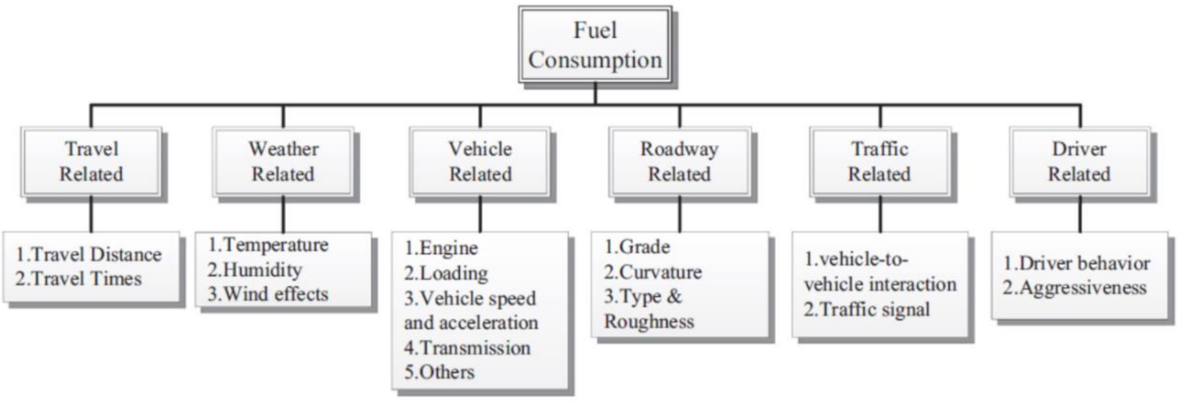


Fig.2 Factors affecting vehicle fuel consumption (Zhou et al., 2016)

In conclusion, three forms of rolling resistance may be used:

A. A fixed value – It is an inaccurate approximation disregarding the internal (vehicle) and external (e.g. road, weather) factors.
B. A variable - a function of vehicle characteristics, road characteristics and traffic conditions. It considers the effects of influencing factors. However, it is difficult to calculate, in that the various coefficients, often a variable in its own, need to be determined.
C. A dynamic model - a model that incorporates the above characteristics, and meanwhile calculate instantaneous rolling resistance for continual inputs of vehicle, road and traffic conditions. This involves a model development, and requires data inputs in a pre-defined format compatible with the model. Undoubtedly, this is the most accurate form.

This study reviewed literature on the modelling of vehicle rolling resistance. The influencing factors include vehicle speed, tyre configuration, pavement type and condition (texture depth, roughness), temperature and dry/wet state of the road surface. Further work will enable more accurate numerical relationship with fuel consumption be developed for rolling resistance. The outputs can help to make accurate prediction of traffic and environment conditions, and quantify their effects on the fuel consumption of long distance trucks. This can be potentially used by the on-board powertrain optimiser, within the European Union.

**Acknowledgement**

The research described in this paper was supported by the EU-funded project optiTruck (grant agreement No 713788) which has the ultimate aim to develop and test a prototype 'global optimizer', capable of achieving a fuel reduction of at least 20% for 40 tonne trucks while still meeting relevant Euro VI emission standards.

**References**

1. BARTH, M., AN, F., YOUNGLOVE, T., SCORA, G. & LEVINE, C. 2000. Development of A Comprehensive Modal Emission Model Final Report - NCHRP Project 25-11. University of California Riverside, Center for Environmental Research and Technology.
2. BARTH, M., SCORA, G. & YOUNGLOVE, T. 1999. Estimating Emissions and Fuel Consumption for Different Levels of Freeway Congestion. *Transportation Research Record: Journal of the Transportation Research Board*, 1664**,** 47-57.
3. CARLSON, A., HAMMARSTRÖM, U. & ERIKSSON, O. 2013. Models and methods for the estimation of fuel consumption due to infrastructure parameters - Deliverable 2.1. MIRAVEC - Modelling Infrastructure Influence on RoAd Vehicle Energy Consumption.
4. DESCORNET, G. 1990. Road-Surface Influence on Tire Rolling Resistance. Centre de Recherches Routieres, Brussels.
5. DMRB 2008. Design Manual for Roads and Bridges. Volume 7. Section 3. Data for Pavement Assessment. HD 29/08 Department for Transport.

6. FITCH, J. W. 1994. Motor truck engineering handbook. *Technology,* 2004**,** 03-08.
7. HAMMARSTRÖM, U., ERIKSSON, J., KARLSSON, R. & YAHYA, M.-R. 2012. Rolling resistance model, fuel consumption model and the traffic energy saving potential from changed road surface conditions. VTI (Swedish National Road and Transport Research Institute).
8. HAMMARSTRÖM, U., KARLSSON, R. & SÖRENSEN, H. 2009. Road surface effects on rolling resistance - coastdown measurements with uncertainty analysis in focus, ECRPD (Energy Conservation in Road Pavement Design, Maintenance and Utlisation) project Deliverable D5(a). VTI (Swedish National Road and Transport Research Institute).
9. HOOGHWERFF, J., VAN-GILS, E. W. & REININK, H. F. 2013. Influence of road surface type on rolling resistance - results of the measurements 2013. M+P, MBBM group.
10. KARLSSON, R., HAMMARSTRÖM, U., SÖRENSEN, H. & ERIKSSON, O. 2011. Road surface influence on rolling resistance - coastdown measurements for a car and an HGV. VTI (Swedish National Road and Transport Research Institute).
11. MANNERING, F., WASHBURN, S. & KILARESKI, W. 2013. *Principles of Highway Engineering and Traffic Analysis*, John Wiley & Sons, Inc.
12. RAKHA, H., LUCIC, I., DEMARCHI, S. H., SETTI, J. R. & AERDE, M. V. 2001. Vehicle Dynamics Model for Predicting Maximum Truck Acceleration Levels. *Journal of Transportation Engineering,* 127**,** 418-425.
13. SANDBERG, U. 2011. Rolling Resistance – Basic Information and State-of-the-Art on Measurement methods. MIRIAM SP1 Measurement methods and source models.
14. SANDBERG, U., BERGIERS, A., EJSMONT, J. A., GOUBERT, L., KARLSSON, R. & ZÖLLER, M. 2011. Road surface influence on tyre/road rolling resistance. MIRIAM SP1 Measurement methods and source models.
15. TAYLOR, G. W. & PATTEN, J. D. 2006. Effects of Pavement Structure on Vehicle Fuel Consumption. Centre for Surface Transportation Technology (CSTT), National Research Council of Canada (NRC).
16. VINER, H., ABBOTT, P., DUNFORD, A., DHILLON, N., PARSLEY, L. & READ, C. 2006. Surface Texture Measurement on Local Roads - Published Project Report 148. Transport Research Laboratory (TRL).
17. WANG, J. & RAKHA, H. A. 2017. Fuel consumption model for heavy duty diesel trucks: Model development and testing. *Transportation Research Part D: Transport and Environment,* 55**,** 127-141.
18. ZAABAR, I. & CHATTI, K. 2010. Calibration of HDM-4 Models for Estimating the Effect of Pavement Roughness on Fuel Consumption for U.S. Conditions. *Transportation Research Record,* 2155**,** 105-116.
19. ZHOU, M., JIN, H. & WANG, W. 2016. A review of vehicle fuel consumption models to evaluate eco-driving and eco-routing. *Transportation Research Part D: Transport and Environment,* 49.