Comparison of truck fuel consumption measurements with results of existing models and implications for road pavement LCA

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ABSTRACT: Life Cycle Assessment (LCA) is increasingly used to evaluate the impact of all lifecycle phases of road pavements on the environment. From the late '90s, this technique has continuously evolved and improved, however, there are still limitations and uncertainties in the framework. In this regard, Santero et al (2011) showed that gaps still exist in the road pavement LCA methodology. More recently, Trupia et al (2016) highlighted how existing models of the impact of the road pavement condition on vehicle rolling resistance and hence, fuel consumption, can lead to very different results. This study presents a comparison between real measurements of truck fuel consumption from fleet manager's databases, and results of existing pavement models, MIRAVEC, a model recently developed within an ERA-NET ROAD action, funded by the 6th framework programme of the EU, and HDM-4, one of the most widely used models for estimating vehicle operating costs in road asset management. The paper shows how far results of the considered models can be from reality and opens a discussion of the implications of these differences on pavement LCA and strategic decisions of managers of the road infrastructure.

1 INTRODUCTION

In road pavement life cycle assessment (LCA), several studies have pointed out lack of a standard methodology (e.g. Santero et al. 2011; Trupia et al. 2016). Different models and methodologies are applied meaning the results of existing studies cannot be compared (Trupia et al. 2016). In particular, one of the main concerns of engineers in the field is regarding the high level of uncertainty in the assumptions and parameters included, which have an effect on the final results. This is the case for vehicle fuel consumption and related greenhouse gas (GHG) emissions during the road pavement use phase. In pavement LCA it is important to estimate the impact on road vehicle fuel consumption of the condition of the road. Several studies have claimed that the impact of the conditions of the road pavement on vehicle fuel consumption can be significant (e.g. Sandberg et al. 2011; Karlsson et al. 2011; Haider & Conter 2012; Chatti & Zaabar 2012). Road maintenance strategies could, therefore, be designed to reduce fuel costs and GHG emissions from the road transport industry.

Assessing and improving the reliability of existing models to estimate the relationship between pavement condition and fuel consumption is critical.

Several models are available and used by road managers for estimating the fuel consumption and environmental effects of road vehicles. In Europe, the most commonly used tool for this purpose is the Highway Development and Management (HDM-4) model, developed by PIARC (the World Road Association) (Kerali et al. 2006). In addition, a model was recently developed within an ERA-NET ROAD action, funded by the 6th framework programme of the EU, known as MIRAVEC (Modelling Infrastructure influence on RoAd Vehicle Energy Consumption) (Benbow et al. 2013).

Although these models are based on a physical approach and are easy to understand they are only validated or updated infrequently.

For example, in the United States, calibration of HDM-4 has been performed recently showing a good level of accuracy (Zaabar & Chatti 2010; Chatti & Zaabar 2012; Jiao & Bienvenu 2015).
However, a recent study (Perrotta et al. 2018) showed that, for the case of the United Kingdom, although HDM-4 was recently calibrated by Odoki et al. (2013), it does not give an accurate estimate of the fuel consumption of modern trucks. MIRAVEC has never been calibrated or validated using real data.

Modern trucks have standard sensors installed to constantly monitor their performance and inform fleet managers regarding the maintenance of the vehicles or training of drivers. This is mainly to optimize the operational costs of large truck fleets.

However, the same data may be used to validate, calibrate or update models like HDM-4 (Perrotta et al. 2018) and MIRAVEC.

In this study, the HDM-4 model calibrated for the UK (Odoki et al. 2013) and the MIRAVEC model (Benbow et al. 2013) are adopted to estimate the fuel consumption trucks. This is then compared to direct measurements from the field. Conclusions include considerations on the validation and calibration process of models like HDM-4 and MIRAVEC and consequences of their use in road asset management. The paper also discusses the possibility of using fleet managers' databases to develop new models based on data that reflect real driving conditions.

2 THE MODELS

HDM-4 and MIRAVEC are two fuel consumption models developed with similar aims but with substantial technical differences.

2.1 *HDM-4*

HDM-4 is used for supporting decisions of road agencies at a strategic level and to evaluate the investments needed in road infrastructure, worldwide. It incorporates various tools that help road managers in e.g. programming road works, performing economic analysis, and to estimate the long term impact of the introduction of new policies.

One of the facilities that HDM-4 implements, is a fuel consumption model that is used in road pavement LCA studies to calculate the road user effects on the environment. The model is physical/mechanistic based and thanks to correction factors it can be adapted for estimating the fuel consumption of different types of vehicles. The model used is:

$$IFC = f(P_{tr}, P_{accs} + P_{eng}) \quad (1)$$

where, IFC is the instantaneous fuel consumption (ml/s), P_{tr} the power required for traction (kW), P_{accs} the power required by accessories in the vehicle (kW), and P_{eng} the power required to overcome the internal friction in the engine (kW). From the computation of the power required to overcome the resistance that acts against the movement of the vehicle, HDM-4 then computes the fuel consumption by applying different correction factors that depend on the characteristics of the considered vehicle, size of engine, etc. (Bennett & Greenwood 2000).

However, in order to obtain accurate and reliable estimates, HDM-4 needs calibration to local conditions (Bennett & Paterson 2000). This is important as in asset management small errors can lead to wrong decisions in terms of budget allocation.

In fact, the HDM-4 model comes from an update of the HDM-III and ARFCOM models that have been developed by performing tests in India, Brazil and the Caribe (Kerali et al. 2006) and these countries have different infrastructures and climates compared to those of some parts of Europe or the United States for example. For this reason, the model needs re-calibration each time it needs to be applied to new situations In UK the HDM-4 fuel consumption model has been calibrated at the University of Birmingham (2011) by Odoki et al. (2013) and road managers refer to this study to perform their analyses.

2.2 *MIRAVEC*

MIRAVEC was a European project under the ERA-NET Road action. The main goal of MIRAVEC was to build on existing knowledge and models to develop tools able to effectively support the decisions of road agencies in the reduction of GHG emissions from the road transport industry.

One of the main outputs of the project is the MIRAVEC spreadsheet, an Excel file that incorporates models for estimating the fuel consumption of road vehicles based on a number of parameters (Benbow et al. 2013). The fuel consumption model implemented in MIRAVEC is based on the VETO model developed in MIRIAM (Models for rolling resistance In Road Infrastructure Asset Management Systems) another European project that focused on estimating the effect of rolling resistance on the fuel consumption of road vehicles (Hammarström et al. 2012).

The model implemented in MIRAVEC takes the form:

$$F = F_{roll} + F_{air} + F_{int} + F_g + F_{side} \quad (2)$$

where, F is the total force acting on the vehicle, F_{roll} is the fraction of the total force due to rolling resistance, F_{air} is the part of total force due to the aerodynamics, F_{int} is the portion of the total force due to the inertia of the components of the vehicle, F_g is the component of the total force due to the road gradient, and F_{side} is the fraction of the total force due to the side force resistance.

From the calculation of the forces the model then computes the power required by the engine to overcome F and finally computes the fuel consumption.

Similarly to HDM-4, MIRAVEC adopts a theoretical approach that is to relate the fuel consumption to the power spent by the engine of the considered vehicle. This represents a complex problem to solve in non-stationary conditions that requires the solution of multiple differential equations that is simplified in VETO and MIRAVEC with the introduction of correction factors (similar to what happens in HDM-4); see Carlson et al. (2013) for more details.

3 DATA

Anonymized data, from standard sensors (SAE International 2016) installed in trucks, have been provided by Microlise, a company based in Nottinghamshire, UK, that specializes in the optimization of costs of large vehicle fleets. The data contain, for example, the GPS location, the vehicle speed and fuel consumption, among many other measurements. The data are recorded by default every 1 minute or 1 mile (approximately 1.6km). For this reason, in order to make sure that the vehicle remains on the same road, only data from motorways and from trucks driving at a constant speed have been considered in this study.

The data include 19,991 records in total from three types of trucks; light, medium and heavy trucks driving at a constant speed (86 +/- 2.5 km/h) on part of the M1 and the M18, two major motorways in England. In particular the study considers 14,281 records from 1,110 heavy trucks, 5,423 records from 473 medium trucks, and 286 records from 61 light trucks. Classification of vehicles is based on the HDM-4 manuals (Kerali et al. 2006; Bennett & Paterson 2000).

Table 1. Characteristics of the considered fleet of trucks.

Type of truck*	Avg fuel consumption [l/100km]
Light	16.04
Medium	24.73
Heavy	27.64

*defined in (University of Birmingham 2011)

4 METHODOLOGY

Following the guidelines given by Bennett & Paterson (2000) and using the parameters published in the WSP report from the University of Birmingham (2011) and by Odoki et al. (2013), the HDM-4 model has been calibrated for the conditions of the UK. However, several of the parameters that are meant to be specified in HDM-4 for adapting it to local conditions are not publicly available. In this case, the default value of the parameter has been used. This represents a level 1 calibration of the HDM-4 model (Bennett & Paterson 2000).

Because MIRAVEC is more recent than HDM-4 and due to the fact that MIRAVEC was developed to fit the conditions of Europe (Benbow et al. 2013), no calibration has been performed in this case.

Then, fuel consumption estimates have been computed using the two models. The calculation has been made for a straight and flat road in good condition, which is representative of a motorway in UK. Table 2 reports the characteristics input to HDM-4 and MIRAVEC for the characterization of the road pavement.

Table 2. Summary of the average characteristics of the considered road.

Gradient [°]	Radius of curvature [rad/km]	Roughness [IRI]	Macro-texture [MPD]	Rutting [mm]
0.00	0.50	1.60	1.10	2.50

Finally, the study compares the estimates made by HDM-4 and MIRAVEC with the average fuel consumption of the considered fleet of trucks.

5 RESULTS

Table 3 and Figure 1 summarise the estimates made by HDM-4 and MIRAVEC for each of the considered types of truck and makes comparison with the real measurements from the field.

Table 3. Summary of the results of the study.

Type of truck	Real FC [l/100km]	HDM-4 [l/100km]	MIRAVEC [l/100km]
Light	16.04	13.35	10.74
Medium	24.73	33.79	31.69
Heavy	27.64	69.67	37.00

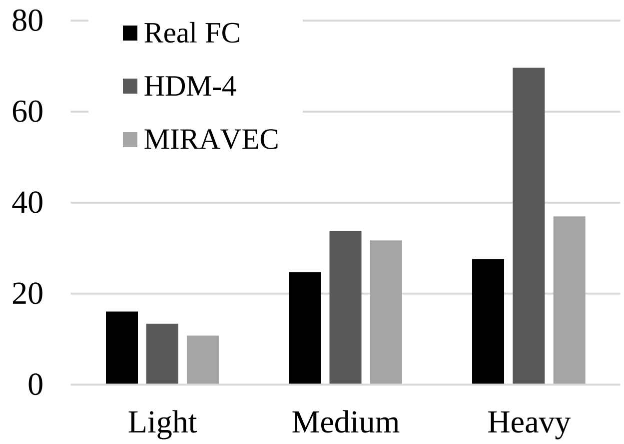

Figure 1. Comparison of fuel consumption estimates made by HDM-4 and MIRAVEC with real measurements for three types of trucks.

6 CONCLUSIONS

The study shows that estimates of physical-mechanistic based models like HDM-4 and MIRAVEC that can be used for the estimation of fuel consumption and related GHG emissions in road asset management and LCA studies of road pavements can be far from reality. This should raise discussion in the community regarding the approach used to develop these models and the calibration process.

In particular, results show that the models tend to underestimate the fuel consumption of light trucks while they tend to overestimate the fuel consumption of medium and heavy trucks.

By comparing the two models it is possible to say that MIRAVEC tends to perform slightly better than HDM-4, which may be reasonable since HDM-4 derives from models developed several years ago and is a model that can be recalibrated to any condition worldwide, while MIRAVEC is more recent and has been specifically designed for European conditions.

The results strongly suggest that this type of model should not be used without validation. As specified in the HDM-4 manual (Bennett & Paterson 2000), continuous re-calibration should be performed in order to minimize uncertainties and improve accuracy. However, this may be expensive in terms of experimental setup. For this reason, the authors suggest the data from fleet management systems could be used in the validation and calibration process.

As an alternative to the classical approach used to develop HDM-4 and MIRAVEC, the authors also suggest that regression techniques may be used to develop new models, based on the data available. In fact, recent studies showed the feasibility of this new approach of using existing data, from a fleet management database, combined with information in the road asset management system for fuel consumption modeling (e.g. Perrotta et al. 2017b; Perrotta et al. 2017a). This represents an opportunity for road asset managers to develop models that give estimates closer to reality and reduce uncertainties produced by the existing tools in the field of road pavement LCA.

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REFERENCES

Benbow, E., Brittain, S. & Viner, H., 2013. *Potential for NRAs to provide energy reducing road infrastructure*, Deliverable D3.1.

Bennett, C.R. & Greenwood, I.D., 2000. Modelling Road User and Environmental Effects in HDM-4, Volume 7. *The Highway Development and Management Series, International Study of Highway Development and Management (ISOHDM).*

Bennett, C.R. & Paterson, W.D.O., 2000. HDM 4: A Guide to Calibration and Adaption, Volume 5. *The Highway Development and Management Series, International Study of Highway Development and Management (ISOHDM).*

Carlson, A., Hammarström, U. & Eriksson, O., 2013. *Models and methods for the estimation of fuel consumption due to infrastructure parameters Modelling Infrastructure Influence on RoAd Vehicle Energy Consumption*, Deliverable D2.1.

Chatti, K. & Zaabar, I., 2012. Estimating the Effects of Pavement Condition on Vehicle Operating Costs. *NCHRP Report 720*.

Haider, M. & Conter, M., 2012. *Report on the road infrastructure effects contributing to road vehicle energy consumption and their governing parameters Modelling Infrastructure Influence on RoAd Vehicle Energy Consumption*, Deliverable D1.1.

Hammarström, U., Eriksson, J. & Karlsson, R., 2012. *Rolling resistance model, fuel consumption model and the traffic energy saving potential from changed road surface conditions*, Linkoping. Available at: http://miriam-co2.net/Publications/modeller_for_rullmotstand_och_bra nsleforbrukning_samt_energisparpotential_som_foljd_av _andrade_vagyteforhallanden.pdf.

Jiao, X. & Bienvenu, M., 2015. Field Measurement and Calibration of HDM-4 Fuel Consumption Model on Interstate Highway in Florida. *International Journal of Transportation Science and Technology*, 4(1), pp.29–46.

Karlsson, R. et al., 2011. *Road surface influence on rolling resistance Coastdown measurements for a car and an HGV*,

Kerali, H.R., Odoki, J.B. & Stannard, E.E., 2006. Overview of HDM-4, Volume 1. *The Highway Development and Management Series, International Study of Highway Development and Management (ISOHDM).*

Odoki, J.B., Anyala, M. & Bunting, E., 2013. HDM-4 adaptation for strategic analysis of UK local roads. *Proceedings of the Institution of Civil Engineers - Transport*, 166(2), pp.65–78. Available at: http://www.icevirtuallibrary.com/doi/10.1680/tran.9.0002 6.

Perrotta, F. et al., 2018. Comparison of HDM-4 fuel consumption estimates with real measurements from trucks on motorways: a UK case study. *Transportation Research Board 97th Annual Meeting. January 7-11, Washington, D.C.*

Perrotta, F., Parry, T. & Neves, L.C., 2017a. Application of Machine Learning for Fuel Consumption Modelling of Trucks. *2017 IEEE International Conference on Big Data*.

Perrotta, F., Parry, T. & Neves, L.C., 2017b. Using truck sensors for road pavement performance investigation. In M. Čepin & R. Briš, eds. *Safety and Reliability – Theory and Applications, Proceedings of 27th annual European Safety and Reliability Conference, ESREL 2017*. Portoroz, Slovenia: CRC Press Taylor & Francis Group, pp. 392–396.

SAE International, 2016. SAE J1939-71, Vehicle Application Layer - Surface Vehicle Recommended Practice. *SAE International Standards*. Available at: http://standards.sae.org/j1939/71_201610/.

Sandberg, U. et al., 2011. *Road surface influence on tyre/road rolling resistance*, Available at: http://miriam-co2.net/Publications/MIRIAM_SP1_Road-Surf-Infl_Report 111231.pdf.

Santero, N.J., Masanet, E. & Horvath, A., 2011. Life-cycle assessment of pavements. Part I: Critical review. *Resources, Conservation and Recycling*, 55(9–10), pp.801–809.

Trupia, L. et al., 2016. Rolling resistance contribution to a road pavement life cycle carbon footprint analysis. *International Journal of Life Cycle Assessment*, pp.972–985.

University of Birmingham, 2011. Development of socio-economic models for highway maintenance, Analysis of DfT Road Network Using HDM-4. *WSP*, (March).

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), pp.105–116. Available at: http://dx.doi.org/10.3141/2155-12.