Definition, Analysis and Application of a Simplified Road User Costs Model for Portuguese Trunk Roads

B. Santos & V. Cavaleiro
Department of Civil Engineering, University of Beira Interior, Covilhã, Portugal

L. Picado-Santos
Department of Civil Engineering, University of Coimbra, Coimbra, Portugal

ABSTRACT: A simplified Road User Costs (RUC) model and input data for Portuguese trunk road networks were developed in a research work conducted in two Portuguese Universities (University of Beira Interior and University of Coimbra). This paper describes the main activities that lead to a simplified RUC formulation and the considered input data (from 2006). It also presents a variability study of RUC *versus* changes in parameters values considered likely to vary under specific conditions for road work zones and pavement condition. The goal was to perform a model refinement including these common scenarios and applications to two Portuguese road networks under private concession. The results of the road work zones and pavement conditions scenarios can be taken into account for the choice of the best maintenance strategy, namely allowing approaches as "before *versus* after" and "during construction *versus* after". In this way road user costs computation is used and can be included in cost-benefits evaluation of a certain strategy. This kind of approach could also be included in life cycle costs evaluations. The main goal of the research conducted and ongoing is to provide the needed tool to integrate RUC in Portuguese Pavement Management Systems economic analysis since nowadays no RUC model is being used in Portugal.

KEY WORDS: Costs, user, roads, mathematical models, transportation management.

1 INTRODUCTION

Currently, the Portuguese Road Administration does not consider Road User Costs (RUC) in the evaluation process of road design, maintenance or rehabilitation; therefore estimation of road life cycle costs does not include this important aspect.

However, all over the world, in road management, several RUC models have been used. Some of the most important ones were analysed to provide the conceptual basis for a new general RUC model with application on Portuguese trunk road net. This work was developed in a doctoral thesis (Santos, 2007).

The reviewed models for the definition of the conceptual framework of the model were: the World Bank HDM-RUE – "Modeling Road User and Environmental Effects in HDM-4" (Bennett et al, 2001); the New Zealand Vehicle Operating Cost Model (NZVOC) (Transfund, 2003); the COst Benefit Analysis - COBA (Department for Transport et al., 2002); the Manual "Techniques for Manually Estimating Road User Costs Associated with Construction Projects" used in Texas Department of Transportation (TxDOT) (Daniels et al, 1999); and, the Cost Model integrated in the former Pavement Management System (early 90’s) of the Portuguese Road Administration (designated, at the time, as JAE – Junta Autónoma de Estradas) (GEPA, 1995).

The review shows that beyond the basic methodological approaches, there are three fundamental components of RUC: vehicle operating, accident, and time costs. In general terms, this relationship can be expressed as:

$$RUC = VOC + AC + VOT \tag{1}$$

Where:
RUC is the Road User Cost,
VOC is the Vehicle Operating Cost,
AC is the Accident Cost,
VOT is the Value of Time.

These three main components of road user costs were considered in the proposed model and it can be also added a component related with tolling costs.

The model was developed aiming at simplicity, reduced data requirements (selected data is usually available), easy calibration, easy application and trustworthy results, providing the needed tool to apply RUC in Portuguese Pavement Management Systems economic analysis.

These aspects are the main improvements of the proposed model over the existing ones, such as the World Bank (HDM-4) model. This last model is possible to use in Portugal but would require careful calibration and a high number of data types that, in most cases, are not available.

New developments aim to incorporate in the model formulation the additional costs produced by work zones and pavement conditions. These news considerations will allow a better characterization of RUC values during road life time.

2 METHODOLOGY, GENERAL MODEL DEFINITON AND VARIABILITY STUDY

2.1 Methodology

The proposed Portuguese general RUC model, providing average cost values, is based on simplifications of the HDM-4 equations for the VOC, on the COBA and HDM-4 approach for the AC and the JAE Model and HDM-4 equations for the VOT definition.

The proposed model for Portuguese conditions was developed taking into account the recognized conceptual principles of the mentioned models, application to trunk roads, impact of each component on the total users costs and availability of Portuguese official information. Moreover, four vehicle classes, passenger car (PC), utility (U), heavy truck (HT) and heavy bus (HB) were considered.

The results leaded to a model with three main costs components, as in the great majority of the analyzed models, namely: the VOC, including costs for fuel, tires, vehicle preventive maintenance and depreciation; the AC, considering costs for accident, police and medical assistance by accident type, and casualty costs (fatalities, serious and slight injuries); and the VOT for work and non-work travels. Eventually, a component related to tolling costs may also be added.

In addition to the above factors, during the entire formulation process we constantly aimed at a RUC model easy to understand, use and calibrate.

Several comparative analyses were also made between the reference models and the proposed model, applied to the Portuguese condition. It was found that the contributions of VOT and VOC to the total RUC were similar, as can be seen in Figure 1 for PC and HT vehicles. Differences might be due to the fact that the reference models were developed to other realities.

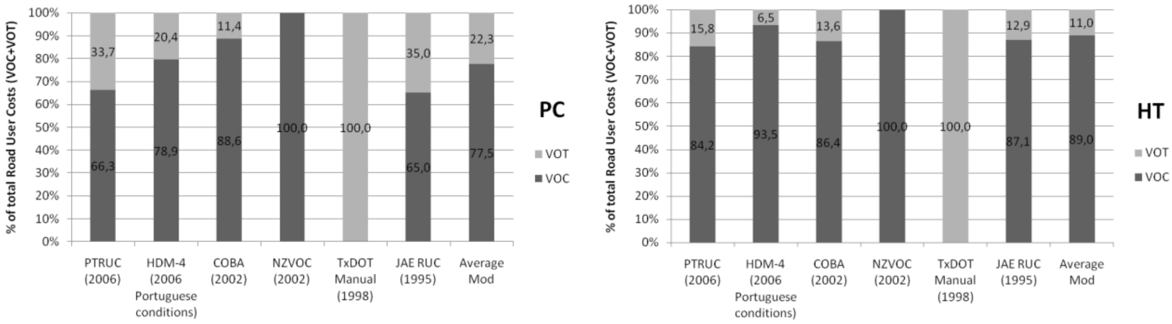

Figure 1: VOC and VOT distribution in RUC models for PC and HT

2.2 Model Formulation

The model developed has the following formulation:

$$RUC = VOC + AC + VOT + Toll \tag{2}$$

$$VOC = AADT \times \sum_{i=1}^{4} \left(VOC_i \times p_i \right) \tag{3}$$

$$AC = AADT \times \left(\sum_{j=1}^{3} AC_j + \sum_{k=1}^{3} CC_k \right) \tag{4}$$

$$VOT = AADT \times \sum_{i=1}^{4} (VOT_i \times p_i) \tag{5}$$

$$Toll = AADT \times \sum_{i=1}^{4} \left(ctoll_i \times p_i \right) \tag{6}$$

Considering by vehicle class:

$$VOC_i = Cf_i + Ct_i + Cm_i + Cd_i \tag{7}$$

$$VOT_i = \frac{1}{s_i} \times \sum_{m=1}^{2} \left(TC_m \times OR_{i,m} \right) \tag{8}$$

And for the set of all vehicle classes (without vehicle class disaggregation):

$$AC_j = AR_j \times ac_j \tag{9}$$

$$CC_k = ANC_k \times cc_k \times \sum_{j=1}^{3} AR_j \tag{10}$$

The list of terms used in the formulation, a brief description of each one and the units to be considered are presented in Table 1.

Table 1: List of terms

Term	Description and Units
AADT	Annual average daily traffic [vehicles/day]
AC	Accident cost [€/km/day]
AC_j	Accident j cost [€/km/vehicle]
ac_j	Accident j cost (police time cost) [€/accident]
ANC_k	Average number of casualties k by accident [casualties/accident]
AR_j	Accident j rate [accidents/vehicle/km]
CC_k	Casualty k cost [€/km/vehicle]
cc_k	Casualty k cost [€/casualty]
Cd_i	Vehicle depreciation cost for vehicle i [€/km]
Cf_i	Fuel cost for vehicle i [€/km]
Cm_i	Maintenance cost for vehicle i [€/km]
Ct_i	Tire cost for vehicle i [€/km]
$ctoll_i$	Toll cost for vehicle i [€/km/vehicle]
i	corresponds to vehicle class: i=1 for Passenger Car; i=2 for Utility; i=3 for Heavy Truck; i=4 for Heavy Bus
j	corresponds to accident class: j=1 for accident with slight injury; j=2 for accident with serious injury; j=3 for accident with fatalities
k	corresponds to casualty class: k=1 for slight injury; k=2 for serious injury; k=3 for fatalities
m	corresponds to travel purpose: m=1 for travel in work time; m=2 for travel in non-work time
$OR_{i,m}$	Occupancy rate for vehicle i and travel purpose m [occupant/vehicle]
p_i	Vehicle proportion of each class i for the AADT considered
RUC	Road user cost [€/km/day]
s_i	Average operating speed for vehicle i [km/h]
TC_m	Time cost for travel purpose m [€/h/occupant]
Toll	Toll cost [€/km/day]
VOC	Vehicle operating cost [€/km/day]
VOC_i	VOC for vehicle i [€/km]
VOT	Value of time [€/km/day]
VOT_i	Value of time for vehicle i [€/km/vehicle]

The complete formulation can be consulted in several papers presented in international conferences, as the ones indicated in the References item (Santos et al, 2008; Santos et al, 2007).

The input model values for average situation were also defined (with 2006 as base year). This definition had into account the values used and recommended by the existing methodologies and, in particular, the values obtained from the Portuguese Haulers Association, companies and official bodies such as the police and emergency services.

Table 2 presents the result of these considerations, showing the input data defined for PC and HT. A similar process was used for the U and HB values definition.

2.3 Variability Study

Several variability studies have been carried out to identify the sensitive parameters of the model. Tables 3 and 4 present some results which show that the model is mainly sensitive to: changes in the average operating speed defined for each class of vehicle and type of road; consumption and fuel cost.

Besides being identified as critical parameters, speed and fuel consumption and cost are also the ones that better reflect the main changes in RUC due to pavements condition and maintenance actions on the network (work zones). The consideration of these scenarios in the RUC formulation will allow a more rigorous characterization.

Thus it is possible to forecast additional RUC in sections where maintenance actions are planned, or compute the benefits associated with a better pavement condition.

Table 2: PC and HT input data values (2006)

<table>
<tr><th>Data</th><th>PC</th><th>HT</th></tr>
<tr><td>Representative vehicle</td><td>Renault Clio III 1.2 16V</td><td>DAF FT 95 430 S 380 with rigid semitrailer</td></tr>
<tr><td>Average operating speed (km/h)</td><td><table><tr><td>EN/ER</td><td>IC</td><td>IP</td><td>AE</td></tr><tr><td>70</td><td>80</td><td>90</td><td>120</td></tr></table></td><td><table><tr><td>EN/ER</td><td>IC</td><td>IP</td><td>AE</td></tr><tr><td>50</td><td>60</td><td>80</td><td>100</td></tr></table></td></tr>
<tr><td>Vehicle service life (years)</td><td>10</td><td>12</td></tr>
<tr><td>Annual average kilometrage (km/year)</td><td>20000</td><td>85000</td></tr>
<tr><td>Occupancy rate (occupants/vehicle)</td><td>2 (1 work driver + 1 non-work passenger)</td><td>1 work driver</td></tr>
<tr><td>Fuel</td><td>Gasoline: 5.9 L/100km
Diesel: 4.8 L/100km
Market price (June/2007):
Gasoline 95: 1.379 €/L
Diesel: 1.059 €/L</td><td>Diesel: 44.0 L/100km
Market price (June/2007):
Diesel: 1.059 €/L</td></tr>
<tr><td>Tires</td><td>nt = 4 tires/vehicle
tsl = 40000 km
Market price: 70 €/tire</td><td>nt = 12 tires/vehicle
tsl = 200000 km
Market price: 455 €/tire</td></tr>
<tr><td>Preventive maintenance</td><td>1515€/10years</td><td>26940€/12years</td></tr>
<tr><td>Depreciation</td><td>16510€/10years</td><td>81172€/12years</td></tr>
<tr><td>Value of time</td><td>6.00€/h (work time)</td><td>9.06€/h (work time)</td></tr>
<tr><td>Accident costs (€/accident)</td><td colspan="2"><table><tr><td>Accident type</td><td>With light injuries</td><td>With serious injuries</td><td>With fatalities</td></tr><tr><td>Police assistance</td><td>53.40</td><td>148.80</td><td>232.80</td></tr><tr><td>Medical assistance</td><td>16.80</td><td>96.40</td><td>96.40</td></tr></table></td></tr>
<tr><td>Casualties costs (€/casualty)</td><td colspan="2">Light injuries:
40000 €/casualty
Serious injuries:
90000 €/casualty
Fatalities:
500000 €/casualty</td></tr>
<tr><td>Toll cost</td><td>0.07€/km</td><td>0.18€/km</td></tr>
</table>

Note to Table 2:
EN/ER – National and Regional Roads with two lanes (one in each direction) and “medium” design standards
IP and IC – Main roads (Principal and Complementary roads) with two lanes (one in each direction) and “high” design standards
AE – Freeways with at least 4 lanes (two in each direction), median and “high” design standards

Table 3: Variability study for operating speed

	PC			HT		
Road Type	**Operating Speed (km/h)**	**2/3 Operating Speed (km/h)**	**Δ VOT (%)**	**Operating Speed (km/h)**	**2/3 Operating Speed (km/h)**	**Δ VOT (%)**
EN, ER	70	46.7	**+50**	50	33.3	**+50**
IC	80	53.3	**+50**	60	40	**+50**
IP	90	60	**+50**	80	53.3	**+50**
AE	120	80	**+50**	100	66.7	**+50**

Table 4: Variability study for vehicle operating parameters

		Δ VOC (%)	
VOC Component	**Parameters Δ**	**PC**	**HT**
Fuel	+20% cf	**+8.0**	**+15.6**
Tire	+25% tsl	-0.9	-0.9
	-25% tsl	+1.4	+1.5
Preventive Maintenance	+20% vsl	+0.07	+0.01
	+25% kma	-0.9	-0.04
	-25% kma	+1.6	+0.06
Depreciation	+20% vsl	**-6.0**	-1.3
	+25% kma	**-7.8**	-2.7
	-25% kma	**+9.0**	**+4.4**

Note to table 4: cf – fuel consumption (L/km); tsl – tire service life (km); vsl – vehicle service life (years); kma – annual average kilometrage (km/year)

3 ADDITIONAL RUC DUE TO WORK ZONES AND PAVEMENT CONDITION

Due to the flexibility of the model, maintenance intervention periods (work zones) and changes in pavement condition can easily be included in RUC formulation by considering specific parameter values defined for a certain maintenance strategy, such as operating speed and fuel consumption values; or for a particular pavement quality index. Research into the definition of these values and adjustments are proposed in this paper.

3.1 Work Zones

The main parameters that can lead to additional RUC in work zones had been identified in several models in use as being the decrease of operating speed, which increases the VOT, and the consequent additional fuel consumption, increasing VOC values.

Data collected, empirical models developed from that information (which usually relate fuel consumption to the operating speed of vehicles) and mechanistic models of fuel consumption (which relates this consumption to the forces opposing motion and allow applications under different conditions) show that maximum fuel consumption occurs for low and high speeds, and minimal fuel consumption for speeds between 40 - 60km/h.

Thus, for trunk roads with high operating speeds (AE's, IP's and IC's with at least two lanes in each direction), taking into account the Portuguese legal framework which limits the road private concessions to guaranty operating speeds greater than or equal to 2/3 of normal operating speed in work zones (up to 10km per set), at day time (7h-21h), there is actually a decrease in fuel consumption.

Lower speeds, up to 1/3 of normal operating speed, are allowed in work zones during the night time. In such cases there is a high probability of frequent stops, resulting in an increased fuel consumption associated with the movement at very low speeds. These cases are more common in two lane roads (one in each direction).

For work zones, the most significant influence on RUC values occurs due to changes in operating speeds. The speed changes and the consequent additional travel time can be easily incorporated into the proposed model formulation by the consideration of lower operating speeds and section length with work zones.

When traffic diversions are needed, changes in operating costs and travel time should be considered in the same manner as described above.

3.2 Pavement Condition

Changes in operating speed due to pavements condition can be easily considered in VOT calculations as described in 3.1 for work zones. However, the most important networks, as the national ones, do not reach in general such degradation level that will influence the values of normal operating speed.

Moreover, pavements in good condition allow vehicles to perform higher speeds with greater comfort and security, reducing travel time and accidents costs. It also allows reductions in operating costs in terms of tires, maintenance and depreciation of the vehicle, but not necessarily in fuel. Opposite situation occurs for pavements in poor conditions.

The pavement conditions can be integrated in RUC formulation through a quality index that represents the functional and structural state of the network pavements. The index adopted in the proposed model was the Present Serviacevility Index (PSI).

Changes in VOC as a function of PSI (or IRI – International Roughness Index) have been obtained from expressions developed by applying regression analysis to real data, resulting in several formulations such as those presented in HDM-4 (World Bank, 2007), TRB (TRB, 1983), ASTM (ASTM, 1983) and by Picado-Santos et al. (Picado-Santos el al, 2006) for Portuguese conditions.

The study of these formulations, as well as the analysis of recent data on Portuguese trunk road pavements condition and average user cost (Santos, 2007) was used to develop an equation that reflects the change of the VOC as a function of PSI (see eq. (17)).

3.3 New RUC Formulation

Having taken into account the performed variability study in model parameters, periods of maintenance interventions in the road network (work zones) and different states of pavements condition, the proposed RUC model is supplemented with the following equations:

$$RUC_{total} = RUC \times L + RUC_{M\&R} \times Y + RUC_{PSI} \times L_{PSI} \tag{11}$$

$$RUC_{M\&R} = dCf + dVOT \tag{12}$$

$$dCf = AADT \times \sum_{i=1}^{4} \left(0.2 \times Cf_i \times p_i\right) \quad \text{for} \quad s_{M\&R_i} \le \frac{1}{3} \times s_i \ \text{ and ER, EN} \tag{13}$$

$$dVOT = AADT \times \sum_{i=1}^{4} \left(VOT_{M\&R_i} \times p_i\right) - VOT \tag{14}$$

$$\mathrm{VOT}_{\mathrm{M\&R}_i} = 1/s_{\mathrm{M\&R}_i} \times \sum_{m=1}^{2} \left(\mathrm{TC}_m \times \mathrm{OR}_{i,m}\right) \quad (15)$$

$$\mathrm{RUC}_{\mathrm{PSI}} = \mathrm{VOC} \times \left(\mathrm{F}_{\mathrm{VOC,PSI}} - 1\right) \quad (16)$$

$$\mathrm{F}_{\mathrm{VOC,PSI}} = -0.0017 \times \mathrm{PSI}^3 + 0.0139 \times \mathrm{PSI}^2 - 0.0712 \times \mathrm{PSI} + 1.15 \quad (17)$$

Considering for the Portuguese trunk road (Picado-Santos et al, 2006):

$$\mathrm{PSI} = 5 \times e^{-0.0002598 \times \mathrm{IRI}/2} - 0.002139 \times \mathrm{R}^2 - 0.03 \times \left(\mathrm{C} + \mathrm{S} + \mathrm{P}\right)^{0.5} \quad (18)$$

Table 5 lists the new terms introduced in the RUC model formulation.

Table 5: List of new terms

Term	Description and Units
C	Total cracked pavement area [$m^2/100m^2$]
dCf	Incremental increase in fuel cost owing to M&R actions [€/km/day]
dVOT	Incremental increase in the value of time owing to M&R actions [€/km/day]
$\mathbf{F_{VOC,PSI}}$	VOC correction factor for a certain PSI value
IRI	International Roughness Index [mm/km]
L	Section length [km]
$\mathbf{L_{PSI}}$	Section length with a certain PSI value [km]
P	Pavement patching area [$m^2/100m^2$]
PSI	Present serviceability index [0-5]
R	Mean rut depth [mm]
$\mathbf{RUC_{M\&R}}$	Road user cost in maintenance and rehabilitation zones (work zones)[€/km/day]
$\mathbf{RUC_{PSI}}$	Incremental increase or decrease in RUC owing to PSI [€/km/day]
$\mathbf{RUC_{total}}$	Total road user cost [€/km/day]
S	Total pavement disintegrated area (with potholes and raveling) [$m^2/100m^2$]
$\mathbf{s_{M\&Ri}}$	Average operating speed in sections with work zones, for vehicle i [km/h]
$\mathbf{VOT_{M\&Ri}}$	Value of time in sections with work zones, for vehicle i [€/km/vehicle]
Y	Maintenance and rehabilitation zones length [km]

4 MODEL APPLICATIONS

The input model values proposed were applied in two Portuguese freeways networks under concession (SCUTVIAS and AENOR) with good results. These results are shown in Table 6.

Table 6: Portuguese RUC model application results (2006 values)

	Scutvias (A23) Average Values		**Scutvias (A23) Work Zone PSI=2**		**Aenor (A7 e A11) Average Values**		**Aenor (A7 e A11) Work Zone PSI=2**	
Costs	**RUC (€/km/day)**	**RUC (%)**	**RUC (€/km/day)**	**RUC (%)**	**RUC (€/km/day)**	**RUC (%)**	**RUC (€/km/day)**	**RUC (%)**
VOC	2267€	60%	**2.379 €**	**56%**	1352€	53%	**1.419 €**	**49%**
AC	83€	2%	83 €	2%	73€	3%	73 €	3%
VOT	703€	19%	**1.055 €**	**25%**	505€	19%	**758 €**	**26%**
Toll	742€	19%	742 €	17%	637€	25%	637 €	22%
RUC	**3795€**	100%	**4.259 €**	**+12%**	**2567€**	100%	**2.887 €**	**+12%**

For the two applications some differences can be found in the values presented for the VOC and toll cost. This disparity is caused essentially by the AADT values of each freeway and by the different toll cost and system of toll charging. Virtual toll charging is adopted by SCUTVIAS (the toll is paid by the taxpayer) and real charging by AENOR (the toll is paid directly by the users).

The road network specific data needed for RUC calculations are the annual average daily traffic (AADT); the traffic distribution by vehicle class; the number of accidents with light, serious and fatal injuries; the number of light, serious and fatal injuries; and the toll cost.

The following table (Table 7) includes the data provided by the private road concessions for RUC calculations.

Table 7: Data provided by road concessions for 2006

Data		**Scutvias (A23)**	**Aenor (A7, A11)**
Network length (km)		177.5	165.4
Total AADT		10290	7769
p_i (1)	PC	0.7987	0.8255
	U	0.0628	0.1337
	HT	0.1295	0.0308
	HB	0.0090	0.0010
Accidents	With slight injury	68	55
	With serious injury	6	9
	With fatalities	2	0
Casualties	Slight injury	89	89
	Serious injury	9	9
	Fatalities	2	0
Approximate toll cost (€/km)		0.20 (virtual toll(2))	0.07 (PC) 0.18 (HT)

Note to Table 7:
(1) Information processed
(2) The approximate toll cost values provided by Scutvias correspond to a uniform rate for all vehicle classes.

The model was also tested in a maintenance/rehabilitation and pavement condition scenario in a section with 1km long, a speed reduction to 2/3 of normal operating speed (to 80km/h), a PSI equal to 2,0 and without deviations. This scenario takes into account the Portuguese legal framework described above for main road network with work zones operating during day time (see Table 6).

Because fuel consumptions associated with high speeds, as the ones practiced in freeways, are high, the occurrence of lower speeds allowed by law for work zones does not increase fuel consumption, thus it was not considered in the analysis. The total RUC obtained considers only additional time costs for work zones and additional non-fuel components costs for the pavement condition, resulting in an increase of 12% when compared to the average values of RUC (about 3% of the additional cost is due to pavement condition and 9% to work zones).

This result demonstrates the importance of taking into account work zones in RUC calculations. For pavements condition similar results were found, however, with less influence when compared to work zones additional cost.

5 CONCLUSIONS

A new RUC model for the Portuguese highway network has been defined and can be used as a tool in road management systems. Currently, no RUC model is being used by the Portuguese Road Administration.

From the observation of the results obtained from the reference and proposed models we can confirm the main role of the VOC component in the total RUC. However, the VOT and Toll costs obtained also represent significant contributions (approximately 20%) and must be considered in the calculations. Moreover, despite the small contribution of the AC component in the RUC results obtained for the analyzed networks, this component will be more significant in low-medium design standard roads, and for that reason must be also considered in the RUC calculations.

The influence of work zones and pavements condition on RUC values through sensitive model parameters identified is also very important and will allow the consideration of more accurate RUC calculations for total service life road economic analysis. Thus, it will be possible to reach optimal solutions with good benefits/cost relations, contributing to sustainable infrastructures through an extended transport costs consideration (construction, maintenance and user costs).

Simulations on work zones RUC calculation already show the importance of their consideration. Similar analysis performed for pavements condition show that this aspect, in trunk roads, has less influence when compared to work zones additional cost.

REFERENCES

ASTM, 1983. *Measuring Road Roughness and Its Effects on User Costs and Comfort.* ASTM-STP 884, p. 127-142.

Bennett, C., Greenwood, I., 2001. *Modelling road user and environmental effects in HDM-4, Volume 7*. The Highway Development and Management Series, PIARC, Paris, France.

Daniels, G., Ellis, D., Stockton, Wm., 1999. *Techniques for manually estimating road user costs associated with construction projects*. Texas Transportation Institute, USA.

Department for Transport, Scottish Executive Development Department, Welsh Assembly Government / Llywodraeth Cynulliad Cymru, The Department for Regional Development / Northern Ireland, 2002. *Design Manual for Roads and Bridges, Volume 13: Economic Assessment of Road Schemes, Section 1: The COBA Manual*. UK.

GEPA – Gestão de Pavimentos, Lda., 1995. *Sistema de Gestão da Conservação. Sistema de Custos dos Utentes*. JAE – Contrato 4915, Lisboa.

Picado-Santos, L., Ferreira, A., Pereira, P., 2006. *Estruturação de um Sistema de Gestão de Pavimentos para uma Rede Rodoviária de Carácter Nacional* (in portuguese). CEC – Revista Engenharia Civil, N.º 26, p. 45-59.

Santos, B., 2007. *Modelação dos Custos dos Utentes na Gestão da Estrada* (in portuguese). PhD Thesis, Covilhã, Portugal.

Santos, B., Picado-Santos, L., Cavaleiro, V., 2007. *Vehicle Operating, Accident and User Time Costs in Pavement Management Systems: Approach for Portuguese Conditions*. The Fifth International Conference on Maintenance and Rehabilitation of Pavements and Technological Control, Utah, USA.

Santos, B., Picado-Santos, L., Cavaleiro, V., 2008. *A Road User Costs Model for Portuguese Trunk Roads.* Proceedings of the 3rd European Pavement and Asset Management Conference, CD edition –1027, Portugal.

Transfund., 2003. Using the NZVOC Model To Prepare PEM Vehicle Operating Costs. Data Collection Ltd., New Zealand.

The World Bank, 2007. HDM-4 *Road User Costs Model.* Version 1.20, Washington D. C.

Zaniewski, J., 1983. *Fuel consumption related to roadway characteristics.* TRB.