Analysis of the technical parameters for the determination of Road User Costs for planning and management of road infrastructures

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Synopsis

Road user costs are one of the components of the total road transport costs, which have a primary importance when carrying out an economic appraisal of investments in road construction or rehabilitation projects.
Road investment appraisal models simulate the interrelationships between the environment, construction standards, maintenance standards, geometric standards and road user costs. Modification to road condition or to the geometric standards of the road have a direct effect on vehicle speeds and the costs of vehicle operations, as well as accident rates on the road. The costs that the community has to bear because of these modifications can be evaluated through road user costs models.
The models used in the HDM-4 (Highway Development & Management, World Bank, 2001) seem to better represent the relationships existing between road condition and geometric standards of the road and road user costs. A mechanistic/behavioural model is used to calculate the *average vehicle operating speed* of a section of the road as a function of road characteristics, vehicle characteristics and traffic flow levels
The aim of the present study is to provide an expression to calculate the *average vehicle operating speed* as a function of a reduced number of factors such as road curvature, surface roughness, gradient, etc. and that refers to the Italian reality.
The equations the HDM-4 provides to calculate the *average vehicle operating speed* have been calibrated to reflect the Italian trends. These equations have then been combined together, also using statistical tools, to obtain a single expression for the *average vehicle operating speed*. This expression is valid as long as the independent variables that had been chosen as such are included in set intervals.
Travel time can then be easily calculated once the *average vehicle operating speed* is known. Its definition and value is decisive to determine travel time costs that are probably the most consistent part of road user costs and they play a significant role in road investment appraisals. Therefore, an approximate estimation of road user costs could be easily achieved and may be used as an indication to assist with the selection of the appropriate projects when a wide range of alternatives is available.

Analysis of the technical parameters for the determination of Road User Costs for planning and management of road infrastructures

The purpose of an economic appraisal of road projects is to determine how much to invest, in which project and what economic returns to expect. The size of the investment is determined by the costs of construction and annual road maintenance. The economic returns are mainly in the form of savings in road user costs due to the provision of a better road facility. All these costs are the components of the total road transport cost or the whole life cycle cost. A road investment appraisal model may be used to assist with the selection of appropriate road design and maintenance standards which minimise the total transport cost. The function of a road investment appraisal model is therefore to calculate the costs of road construction, road maintenance and road user costs for a specified analysis period. This is accomplished by modelling the interrelationships between the environment, construction standards, maintenance standards, geometric standards and road user costs.
The HDM-4 is a mechanistic/behavioural model that mathematically represents the existing relationships between road users, vehicles and the road characteristics. The HDM-4 uses a large number of factors and of coefficients that need to be calibrated for each case. In this study, the system of models used to determine the average vehicle operating speed has been investigated. The default values provided by the HDM-4 in these models in some cases are not appropriate to represent the local conditions in Italy. Therefore the HDM-4 models have been calibrated to match local data. The calibrated models have then been elaborated and a set of equations has been provided to estimate the average vehicle operating speed as a function of a few main variables.
A road investment appraisal model in Italy should be able to reflect the benefits/costs that the requalification projects may bring although minor modifications to the road are made. The main variables have been chosen to satisfy this requirement as far as possible.
In fact, the major developments of the Italian road network have taken place mainly in the 70s and 80s. In the last years there has been a little increase of the extension of the road network. At present, the infrastructural density in Italy is about 0.6 km/km^2, one of the highest among the developed countries. At the same time there has been a significant increase of traffic volumes. The Italian roads were then designed to meet different capacity requirements. In most cases the Italian network suffers from a lack of quality rather than from quantity. It is therefore more likely that future road investments will be focused on the requalification of the existing roads.

ROAD USER COSTS

When planning investments in the road sector, it is necessary to evaluate all costs associated with the proposed project. These include construction costs, maintenance and rehabilitation costs, road user costs, external and exogenous costs or benefits that can be directly attributed to the road project. Road user costs are borne by the community at large in the form of vehicle operating costs (VOC), travel time costs, accident costs and other indirect costs. A road investment model simulates the interaction between the pavement construction standards, maintenance standards and the effects of the environment and traffic loading in order to predict the annual trend in road condition. This together with the geometric standards of the road has a direct effect on vehicle speeds and on the costs of vehicle operation and accident rates on the road.
The equations the HDM-4 model is based on to calculate the average vehicle operating speed mathematically represent the existing relationships between road users, vehicles and the road characteristics.
Most of the road user costs components depend on the vehicle operating speed. Vehicle operating speed in turn depends on vehicle characteristics, road characteristics, road environment and users driving behaviour (figure 1). Whichever project that modifies one of these factors will have effect on the vehicle operating speed and thus on the road user components that depend on it. These components will vary with the different alternatives that are proposed and will determine the difference in road user costs. Determining the most accurate value of vehicle operating speed will have great importance then.
Travel times strictly depend on vehicle operating speed. To obtain the costs related to travel time this has to be multiplied by the unit cost of the resource. The unit cost of the resource will depend on the type of vehicle, the user category and the reason of the journey (work or other).

Because travel time costs are one of the major components of road user costs it is of crucial importance to achieve the correct estimation of the vehicle operating speed. Therefore, the HDM-4 model used to calculate the vehicle operating speed has to be calibrated and validated against available data so to reflect local conditions.

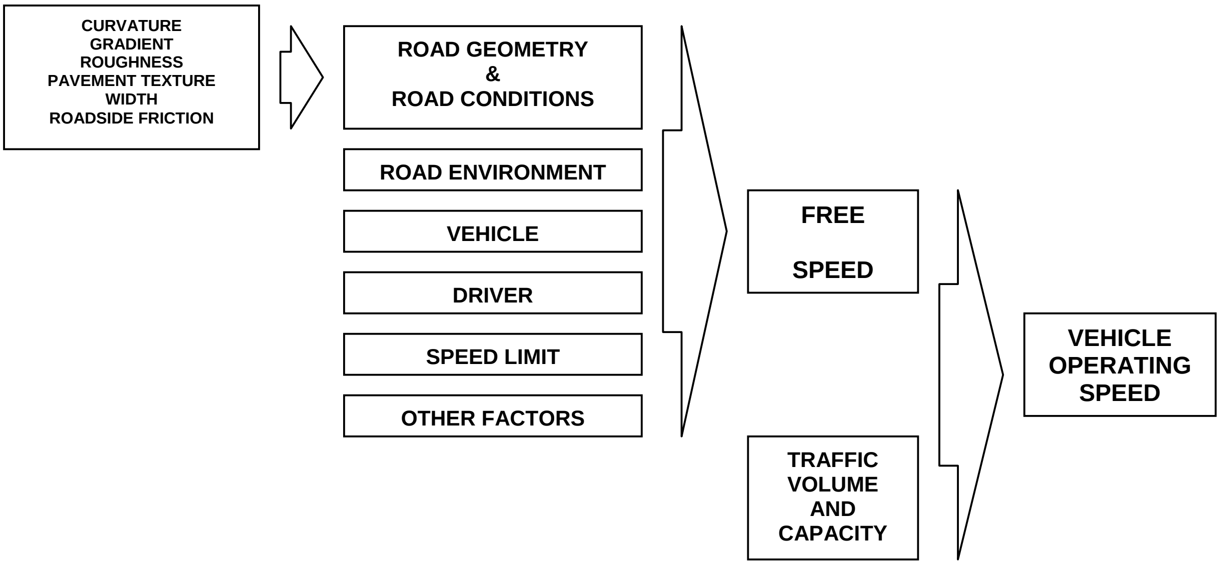

Figure 1: Factors influencing the vehicle operating speed

THE HDM-4 SPEED MODEL

At first, the HDM-4 model determines the free speed of each vehicle type, for each road section. The free speed of a vehicle is defined as the speed which the vehicle travels at on uncongested wide sections of the road that is being analysed.
Free speeds are used to determine the vehicle operating speeds once the speed-flow relationship is defined. As traffic flows increase, the interactions between vehicles increase too causing a reduction in speed. The model adopted in HDM-4 assumes that drivers maintain the free speed as long as the traffic flow is below a certain level. When traffic flows increase over this level vehicle speeds decrease at a linear rate until when the nominal capacity of the road is reached. At that point all the vehicles will travel at the same speed. Whether the nominal capacity of the road is exceeded, all vehicles will travel at the speed that corresponds to the ultimate capacity, also referred to as jam speed.
Vehicle operating speed are determined for each traffic flow period. Traffic flow levels are different at different hours of the day, at different days of the week and of the year. The flow-frequency distribution, or traffic flow pattern, specifies the number of hours per year that the traffic volume is at a certain percentage of the annual average daily traffic. The total number of hours in a year is divided in a number of flow periods, each of which is characterised by a percentage of the annual average daily traffic. For each of these periods is calculated a steady-state congested speed for vehicle type k during period p. The annual average vehicle operating speed is then obtained as the weighted average of the vehicle operating speed of each period.

The Free Speed

The free speed of the vehicles on the road is determined, at all times, by a series of speed constraints that have been identified in the HDM-4 model as the driving power, the braking capacity, the curvature, the surface condition and the desired speed. The interaction between road severity factors and the relevant characteristics of the vehicle limits the speed at which the vehicles travel on the road. Each of these factors considered separately, has its own influence on the speed of the vehicle. The free speed at which the vehicle will travel is given by the probabilistic minimum of the five constraining speeds that result from the limiting action of each constraining factor considered on its own.
The Probabilistic Limiting Velocity Model used in HDM-4 to determine the free speed of vehicles, considers each constraining speed as a random variable that has a probability to influence the driver's perception and therefore to limit the free speed. The driver will drive at, or slower than, the minimum of the constraining speeds, depending on the number of speed constraints that have a dominant influence on him/her.
The equations used in the HDM-4 are the following[1]:

$$V_{FL,u,k} = \exp(\sigma^2/2) \;/\; \left[(1/V_{P,u})^{(1/\beta)} + (1/V_{B,u})^{(1/\beta)} + (1/V_C)^{(1/\beta)} + (1/V_R)^{(1/\beta)} + (1/V_D)^{(1/\beta)} \right]^{\beta}$$

[1] All the symbols used in the document are listed and explained in the Appendix A.

$V_{FL,d,k} = \exp(\sigma^2/2) \ / \ [(1/V_{P,d})^{(1/\beta)} + (1/V_{B,d})^{(1/\beta)} + (1/V_C)^{(1/\beta)} + (1/V_R)^{(1/\beta)} + (1/V_D)^{(1/\beta)}]^\beta$

In the above equations (and in all the equations that will follow) the indexes u and d refer to the uphill and the downhill section of the road.

The model parameter β is an overall measure of the degree of interaction between the constraining speeds. It also can be considered as a measure of the behavioural reaction to the different combination of operating conditions (i.e. constraining speeds). For lower values of the parameter β, the free speed is in greater part affected only by the minimum of the constraining speeds. The higher is the value of the parameter β, much lower than the constraining speed is the free speed. When two or more constraining speeds become equally dominant the free speed drops below the minimum constraining speed of an amount that is larger with higher values of β.

The model parameter σ is a measure of possible errors in the observed values of speeds. The parameters σ and β have been set equal to the default values suggested by the HDM-4.

The constraining speeds are quantified using mechanistic and/or behavioural models which are described in the following paragraphs.

The Constraining Speeds V_P and V_B

The mechanistic model used to calculate the constraining speed due to driving power and road gradient (V_P) and the constraining speed due to braking capacity and road gradient (V_B) is based on the balance of forces acting on the vehicle in absence of acceleration. The forces that act on the vehicle are the tractive power, or the braking power, and the forces opposing motion, such as the aerodynamic resistance, the rolling resistance and the gradient resistance.

$V_{P,u}$ is obtained as the only real positive solution of the following equation:

$1000 \cdot P_T = z_0 \cdot (V_{P,u})^3 + z_1 \cdot V_{P,u}$

z_0 and z_1 are functions of the factors that characterise the resistances: gradient, mass density of air, aerodynamic drag coefficient, projected frontal area, rolling resistance coefficients, number of wheels, rolling resistance parameters, average sand patch texture depth, average roughness, wheel characteristics and climatic factor.

$V_{P,d}$ is obtained solving the same equation, in which the gradient this time is negative[2].

The constraining speed V_B, does not affect vehicle speed on upgrades since the braking capacity does not represent a limit for the vehicle performance. So, it is:

$V_{B,u} = INF$

On the contrary, when vehicles travel on downgrades their speed is influenced by the gradient and the length of the slope, because of the braking requirements that need to be satisfied. If the average gradient length of the road section does not exceed a critical value, then the braking capacity of the vehicles does not affect their speed. In this case, it is:

$V_{B,d} = INF$ if $L_G < L_{CR}$

L_G is the average gradient length and is estimated as the inverse of the number of rise and fall per kilometre (N_{RF}); L_{CR} is the critical gradient length and depends on the gradient. If $L_G > L_{CR}$ then $V_{B,d}$ is calculated using the following equation:

$-1000 \cdot P_B = z_0 \cdot (V_{B,d})^3 + z_1 \cdot V_{B,d}$

This equation has real solutions only for particular combinations of braking power and vehicle operating weight and when gradient is smaller than -6%. $V_{B,d}$ is a real value (i.e. acts as a constraining speed) only for some types of heavy vehicles assuming that $L_G > L_{CR}$ and GR<-6%.

The Constraining Speed V_C

The constraining speed due to road curvature depends on the average curvature radius and is based on the balance of forces acting on the vehicle when it travels on a curve. The equation used is the following:

$V_C = a \cdot R^b$

a and b are coefficients of the model that depend on the type of vehicle; R is given by the following expression:

$R = 180'000 / [\pi \cdot \max(18/\pi, C)]$

The Constraining Speed V_R

The constraining speed due to the road roughness does not appear to be significantly limiting. In fact, it lowers enough to be compared with all the other constraining speeds only when IRI > 3.5 m/km, as it is shown in the graph in figure 2. An IRI index of more than 3.5 m/km is not likely to be observed on paved roads that have a low level of roughness such are the ones usually found in developed countries. It is:

$V_R = V_{OM,max} / (a_0 \cdot IRI)$

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[2] The average gradient of the road section is estimated in HDM-4 from the following expression:
GR = ± RF/1000

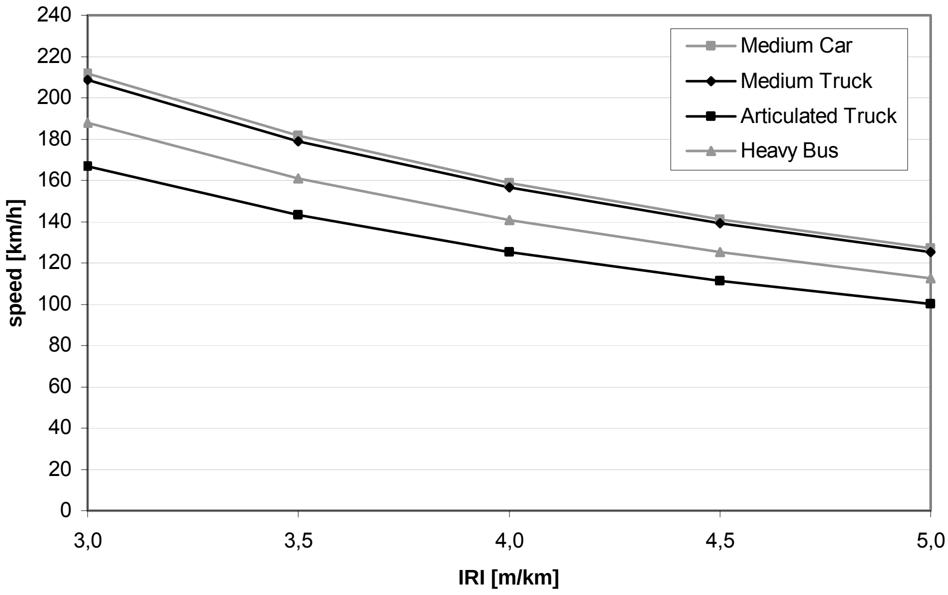

Figure 2: The constraining speed V_R

The Constraining Speed V_D

The desired speed is the speed that the driver chooses when traffic is free flowing and there are no other factors, such as gradient or curvature, influencing the driving behaviour. The desired speed depends on factors such as speed limits and enforcement, the carriageway width, the roadside friction and the presence of non motorised transport other than on the driver's behaviour. In the HDM-4 model, the desired speed is calculated using the following expressions:

$V_D = \min[\ V_{D0}\ ,\ (V_{LIM} \cdot K_{LIM})/3.6\ ]$

and

$V_{D0} = V_{DC} \cdot K_{VD} \cdot \max(0.36,\ X_F \cdot X_{NM})$

V_{DC} is the desired speed that is influenced only by the carriageway width and is a function of the minimum desired speed for two lane roads, the minimum carriageway width for a single lane road, the minimum carriageway width for a two lane road and the rate of increase in desired speed (m/s per meters of road width). The desired speed in the HDM-4 model has a linear increase with width up to 6.8 m, then it increases at a higher rate for cars and light vehicles while it increases at a lower rate for the heavy vehicles. K_{VD} is a factor used to adapt the model to the different types of roads (0.85÷1.30). K_{LIM} is the speed enforcement factor and in the HDM-4 is suggested a default value of 1.10.

ANALYSIS AND CALIBRATION OF THE HDM-4 EQUATIONS

To calibrate the HDM-4 speed models a research in the available technical literature was carried out to find data and relationships that could give indications on the average speeds that are typical in Italy, depending on different key factors. Among the available data it has been chosen to use the data that better represented the context of application of the model. Changing in an appropriate way the default values of the HDM-4 coefficients it can be determined a set of equations that represent the relationships between road users, vehicles and the road characteristics based on the Italian local conditions.

The Constraining Speed V_P and V_B

The effects that the parameters variations had on the constraining speeds were analysed to determine which of the factors had a significant influence. To analyse these effects it has been considered a bituminous surface, being the most common type of surface of the Italian roads. In addition, the roads which is more likely that an economic appraisal will be carried out, are all characterised by a bituminous surface.

A variation of 5m/km of the average roughness (IRI) produces a 2.5% variation of the constraining speeds, while a variation of 0.5mm of the average sand patch texture depth produces a 0.3% variation of the constraining speeds. The climatic factor depends on the percentage of time travelled on water covered or snow covered roads. The percentages can be estimated observing the number of days per year that rains or snows in Italy. Considering the territory divided in 3 major areas (north, central, south and islands) the average percentage of raining days per year varies between 26% and 28.5%. Assuming a maximum variation of the percentage between 0% and 30%, the climatic factor varies by 6% producing a 1% variation of the constraining speeds. The average days of snow in Italy are even less, that means that the percentage of time travelled on snow covered roads has very little influence on the constraining speeds. Overall, this analysis indicates that none of the above factors is worth an accurate estimation, since they do not have a significant influence on the constraining speeds. The road factor that mainly influences the constraining speeds is the average road gradient.

The Constraining Speed V_C

In Italy an official formulation on speed variation due to the road curvature is missing. Two empirical relationships have been found by researchers at Naples and Trieste universities. The expression given by Capaldo and Grossi from the Department of Transport Engineering of the University of Naples is the result of data collection on roads with high geometric standards (i.e. radius not less than 200 meters, carriageway width not less than 7m and gradient less than 6%). Instead, the road sections on which data was collected to provide the expression by the University of Trieste (IASPIS project), were mostly characterized by small radius, below 150 meters.
As shown in figure 3 the HDM-4 model, for small values of the average curvature radius, is very close to the relation given by the University of Trieste, which is more relevant for these values. As the average curvature radius increases the HDM-4 model is intermediate between the two formulations, getting closer to the Capaldo-Grossi formulation for higher values of the average curvature radius. When the average curvature radius is bigger than 477 meters, the HDM-4 model estimates a higher value of the constraining speed than the Capaldo-Grossi formulation. The difference should not affect the free speed; other factors such as speed limits or desired speed should be limiting the speed of vehicle when travels on a road that is characterized by an average curvature of 120deg/km or less (i.e. an average curvature radius of 477 meters or more).
IASPIS researchers have carried out updated research. The new equation provided is close to the one that was used in first place (represented in figure 3), thus the HDM-4 model is still very close to the relation given by the University of Trieste for small values of the average curvature radius.

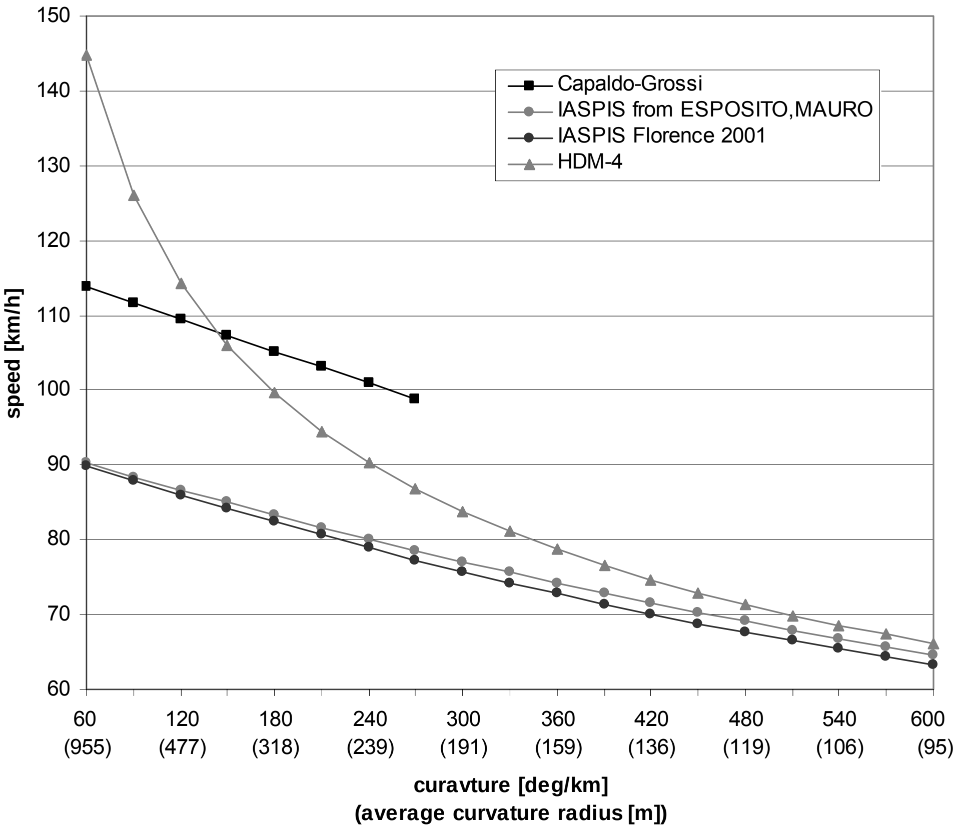

Figure 3: The comparison between the HDM-4 constraining speed V_C and the Italian empirical expressions

The Constraining Speed V_D

The desired speeds provided by the HDM-4 model applied using the default values for the coefficients (X_F=1.0, X_{NM}=1.0, K_{VD}=1.0) and assuming a lane width of 3.75 meters, were compared with the desired speeds of the Italian road network. Some evident differences resulted from the comparison, so the HDM-4 model for the desired speed had to be calibrated using the Italian data and the guidelines provided by the HCM (Highway Capacity Manual 2000) for the estimation of free flow speed. The HCM only gives indication on the reductions to apply to cars depending on the type of road and the carriageway width. The following methodology was applied to calibrate the HDM-4 desired speed for the vehicle type medium cars. The calibration of the desired speed of light, medium and heavy trucks, articulated trucks and coaches was achieved using a similar methodology but having to make some assumptions that will be explained in detail further on.

Data collected on Italian 6-lane freeways (3 lanes for each direction) in free flowing traffic conditions, shows that speeds are normally distributed. The 85^{th} percentile of the distribution associated with the data collected has been chosen as representative of the 6-lane freeways desired speed. For the 4-lane freeways it has been considered a desired speed resulting from the desired speed of 6-lane freeways reduced of the amount suggested in HCM when passing from 3 lanes to 2 lanes per direction on freeways. For the 4-lane highways it has been assumed a desired speed that is 10% lower than the desired speed of 4-lane freeways. For the 2-lane highways it has been considered the average speed between the two speeds obtained from empirical relations of Capaldo-Grossi and the University of Trieste, having assumed in them the curvature and the gradient equal to zero.

Table 1: The HDM-4 desired speed and the desired speeds on the Italian roads (for the vehicle type medium car)

Type of road	Desired Speed in Italy [km/h]	HDM-4		
		V_{D0} [km/h]	K_{VD}	$K_{LIM} \cdot V_{LIM}$ [km/h]
2-lane highway	106.0	106.7	0.999	99
4-lane highway	131.0	106.7	1.228	121
4-lane freeway	145.6	106.7	1.365	143
4-lane freeway	148.1	145.8	1.016	143

As it is shown in table 1 there is a good correspondence between the HDM-4 model and the Italian data only for 2-lane highways, while there is a fair correspondence for 6-lane freeways. In the table are also shown the values that should be assigned to the coefficient K_{VD} to make the HDM-4 model match the Italian desired speeds on the different types of roads. In addition, in the table is reported the value of the factor $K_{LIM} \cdot V_{LIM}$ if it is assumed K_{LIM}=1.10 as suggested in HDM-4. Given these values and the value of V_{D0} (which is equal to V_{DC} when coefficients are set to the default values) the constraining speed V_D of HDM-4 is going to be always equal to the factor $K_{LIM} \cdot V_{LIM}$ that is much less than the desired speeds on the Italian network. That means that probably the speed limits in Italy do not have the same limiting action as in other countries and thus the enforcement factor K_{LIM} should be raised to take into account the drivers' behaviour.

So, K_{LIM} has been set equal to 1.20 for the 2-lane highways and 2-lane freeways, to 1.30 for the 4-lane highways and to 1.25 for the 6-lane freeways. K_{VD} has been set to the values shown in table 1 for each type of road. Figure 4 shows the comparison between the HDM-4 desired speeds and the Italian desired speeds if the only coefficients to be changed were K_{VD} and K_{LIM}.

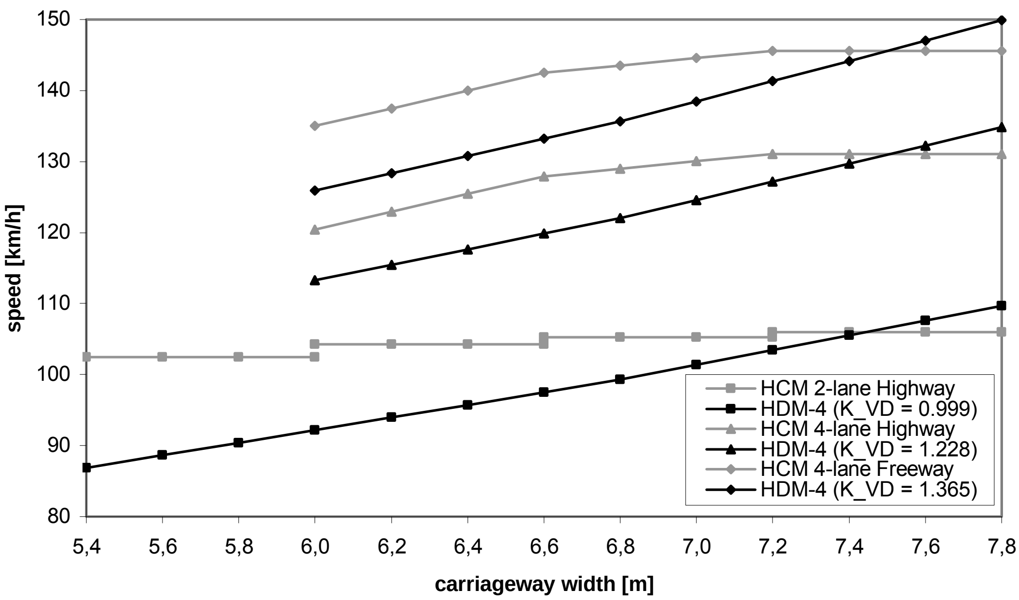

Figure 4: The HDM-4 desired speed V_D and the desired speed in Italy for different types of road (for the vehicle type medium car)

Then, a new set of coefficients V_{D2}, a_1 and a_2 for each type of road were determined. These coefficients are respectively, the minimum desired speed for a two lane road, the increase rate of the desired speed with road width for a single lane or a two-lane road, and the fraction between the minimum desired speed for a single lane road and the minimum desired speed for a two lane road. To calculate the coefficients the following condition had to be satisfied for three different values of the road width (L_1, L_2, L_3):

$V_{DC}(L_i)=V_{HCM}(L_i)$

L_1=minimum carriageway width assumed by HCM;

L_2=carriageway width where the rate of increase of speed with road width changes in HDM-4 (L_2=6.8 m);

L_3= maximum carriageway width.

In the case of 6-lane freeways only two values (L_1, L_3) must satisfy the above condition, being the carriageway width always greater than 6.8 meters.

Figures 5, 6, 7 and 8 show the comparison between the Italian desired speed according to the observed data and the HCM theory and the desired speed calculated with the HDM-4 model using the new set of coefficients for each type of road[3].

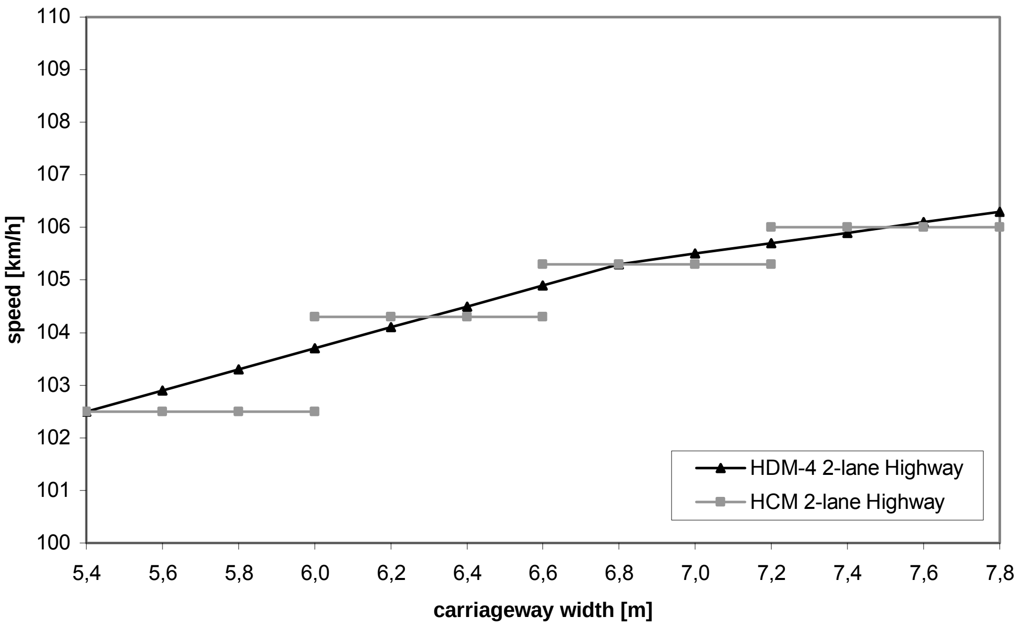

Figure 5: The calibration of the HDM-4 constraining speed V_D for 2-lane highways (for the vehicle type medium car)

[3] The new coefficients are reported in Appendix B.

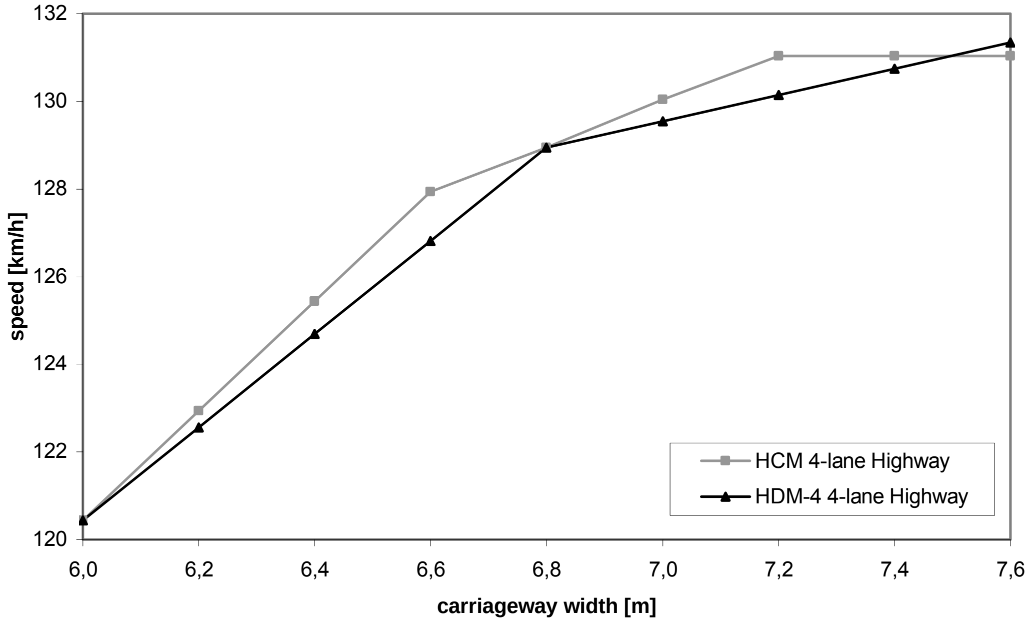

Figure 6: The calibration of the HDM-4 constraining speed V_D for 4-lane highways (for the vehicle type medium car)

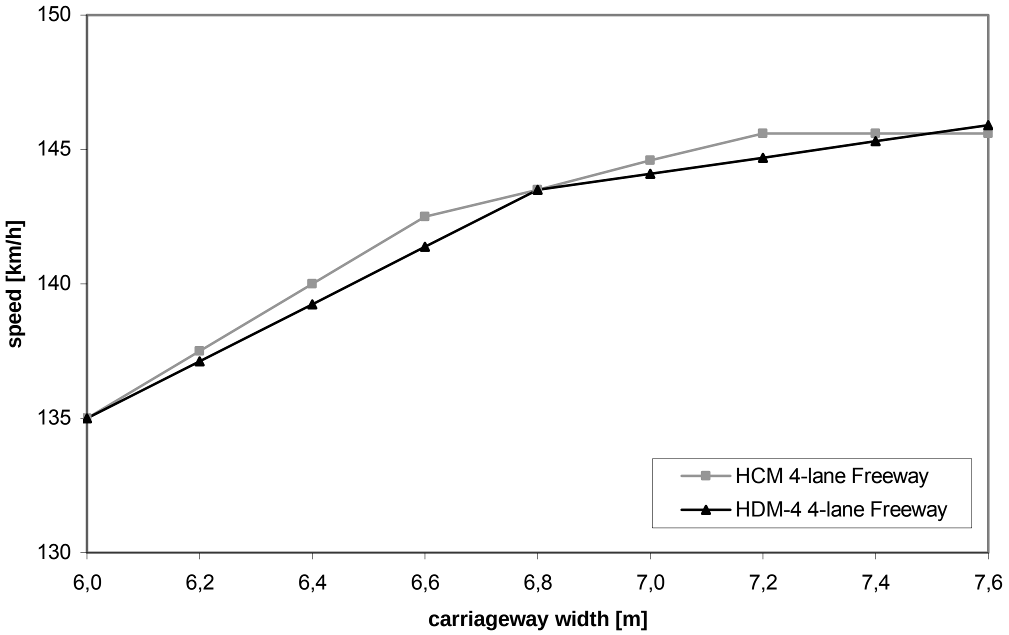

Figure 7: The calibration of the HDM-4 constraining speed V_D for 4-lane freeways (for the vehicle type medium car)

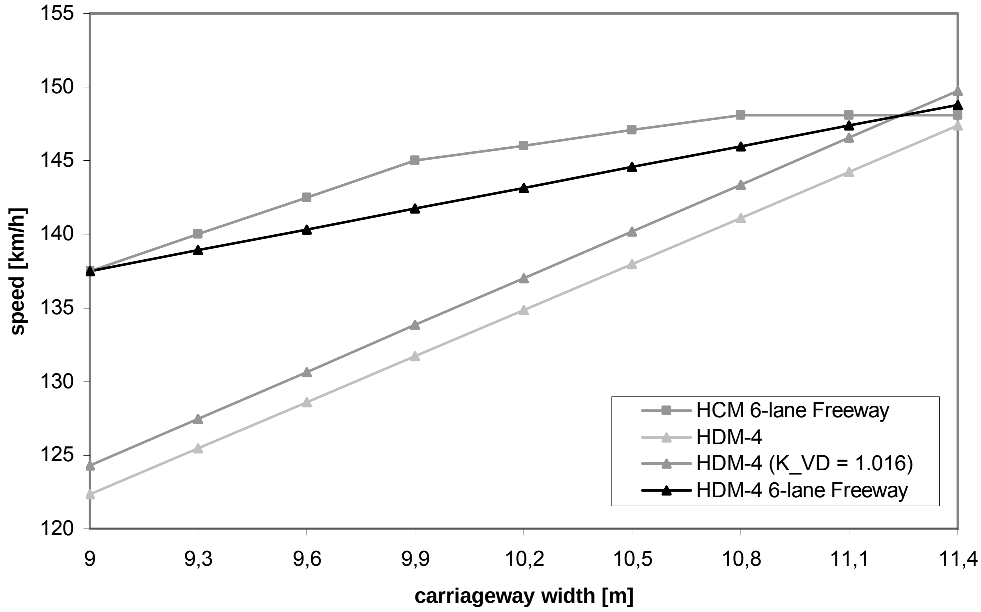

Figure 8: The calibration of the HDM-4 constraining speed V_D for 6-lane freeways (for the vehicle type medium car)

Also in the case of light, medium and heavy trucks, articulated trucks and coaches the 85th percentile of the distribution associated with the data collected on Italian 6-lane freeways has been chosen as representative of the 6-lane freeways desired speed. The HCM does not give any indication on the reduction of speed of these types of vehicles when the number of lanes and the type of road are changing. Therefore, the desired speed for the above types of vehicles has been determined assuming that the desired speed is proportionally reduced, on each type of road when passing from cars to heavy vehicles, as it is on a 6-lane freeway. The HCM also does not give any indication on the reduction of speed with road width. In this case, the indications given by the HDM-4 default values were used. So, the coefficient a_2 has been set the same as cars, while to the coefficient a_1 were assigned values that are proportional to the new coefficients determined for cars, as set by HDM-4 when comparing the default values. Finally V_{D2} has been determined using the following relationship, where L has been considered equal to the maximum carriageway width and V_{DC} has been set equal to the assumed desired speed for each type of road:

$V_{DC} = V_{D2} + a_1 \cdot (L-6.8)$

A graphical estimation of the speed reduction factor X_F

When considering requalification road investments a crucial role can be played by the modification of the shoulder width and/or the access points. These road characteristics are taken into account in the HDM-4 by the speed reduction factor X_F due to the roadside friction. The HDM-4 does not give any strict correspondence between the factor and the roadside conditions; it simply gives a sample of typical situations with an associated roadside friction coefficient value. The estimation of the coefficient X_F is therefore up to one's own judgement.

The HCM provides speed reductions depending on the shoulder width and the access point density or the interchange density. Figures 9, 10, 11 and 12 show the graphs that have been elaborated using the HCM indications, which can be used to determine the speed reduction factor due to roadside friction for the different types of roads.

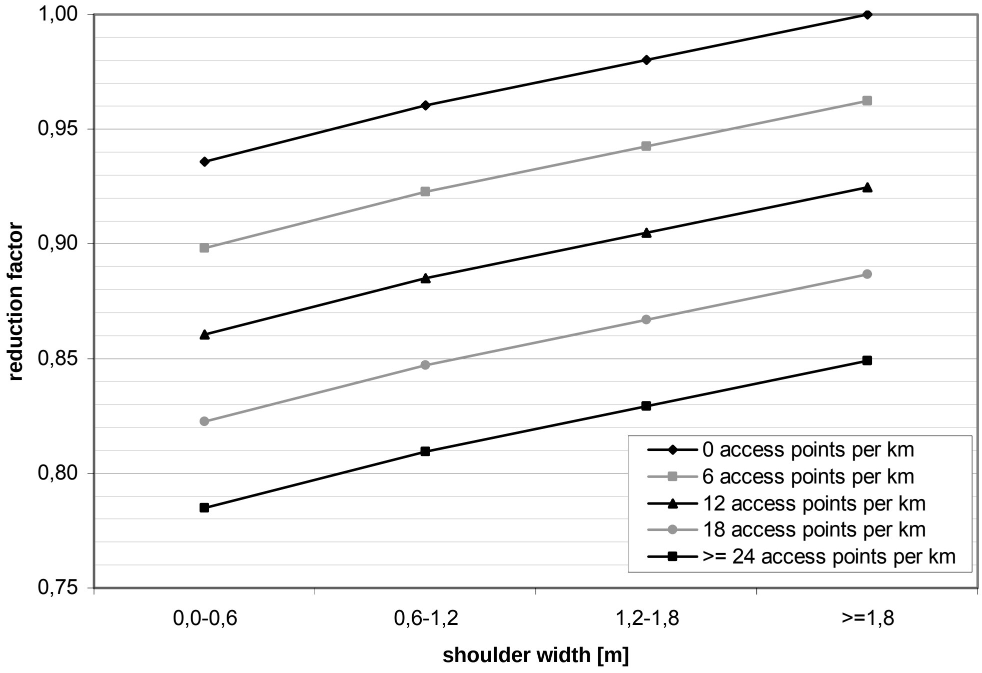

Figure 9: The speed reduction factor X_F due to roadside friction for 2-lane highways

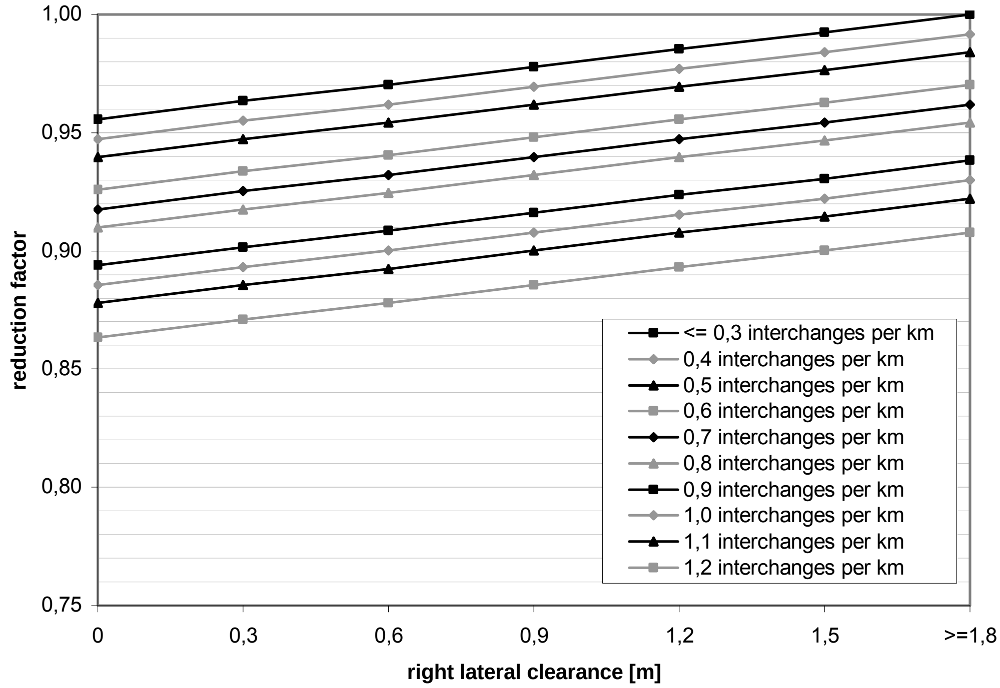

Figure 10: The speed reduction factor X_F due to roadside friction for 4-lane highways

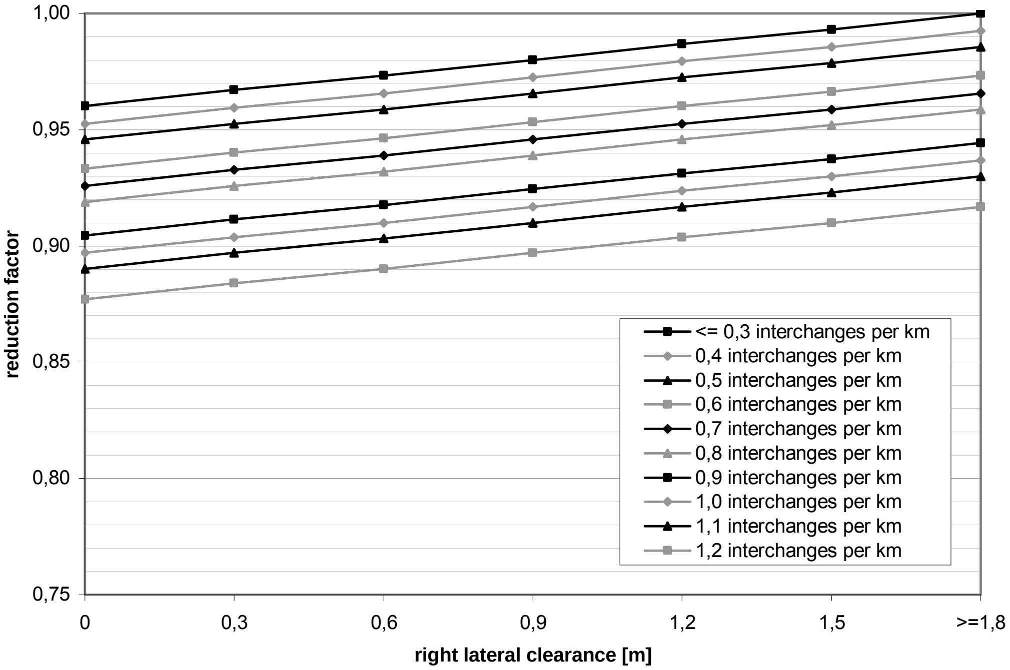

Figure 11: The speed reduction factor X_F due to roadside friction for 4-lane freeways

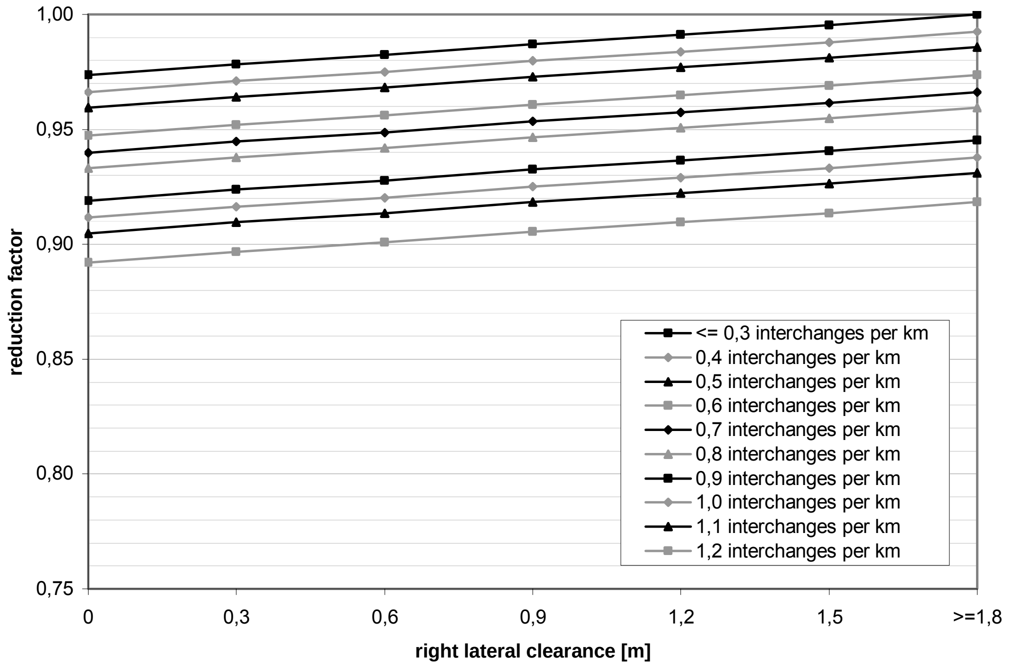

Figure 12: The speed reduction factor X_F due to roadside friction for 6-lane freeways

THE GENERAL EQUATIONS TO CALCULATE VEHICLE OPERATING SPEED

Once the HDM-4 free speed model has been calibrated and the new set of coefficients has been provided, the new equations have been used to produce general equations which estimate the average vehicle operating speed as a function of a few main variables that can be easily achieved.
Known the average operating speed, travel time, and therefore the travel time costs, can be easily determined.

The methodology and the equations

In the HDM-4 model equations the less significant parameters have been set to medium values in order to calculate the free speed as a function of the following, chosen independent variables:

- average road rise and fall RF,
- average horizontal curvature of the road C,

- carriageway width L,
- average number of rise and fall per kilometer N_{RF},
- speed reduction factor due to roadside friction X_F.

The HDM-4 equations have been input in an excel worksheet. A visual basic program has been used to generate all the 74’088 values of the free flow speed depending on the different combinations of the values of the independent variables. The intervals in which the independent variables vary and the step chosen for each of them are indicated in table 2. These variations have been applied for all the types of road that have been considered in the present study, except for the 6 lanes motorways. On this type of roads the carriageway width varies between 9 m and 11.25 m, with a step of 0.75 m.

Table 2: Variation intervals of the most significant parameters used to calculate the free speed

Parameter	Unit	Interval	Step	Number of values
RF	m/km	-100÷100	10	21
C	deg/km	0÷600	30	21
L	m	6.0÷7.5	0.5	4
N_{RF}	n°/km	0.05÷0.35	0.05	7
X_F	-	0.75÷1.00	0.05	6
Total combinations				74'088

The 74’088 values have been analyzed with statistical software (SPSS) to achieve a linear regression. The equations that have been produced are used to determine the free speed, by using the appropriate regression coefficients for each type of road[4].

$V_{FL,u,k} = cost_1+B_{11}\cdot RF+B_{12}\cdot C+B_{13}\cdot L+B_{14}\cdot N_{RF}+B_{15}\cdot X_F$

$V_{FL,d,k} = cost_2+B_{21}\cdot RF+B_{22}\cdot C+B_{23}\cdot L+B_{24}\cdot N_{RF}+B_{25}\cdot X_F$

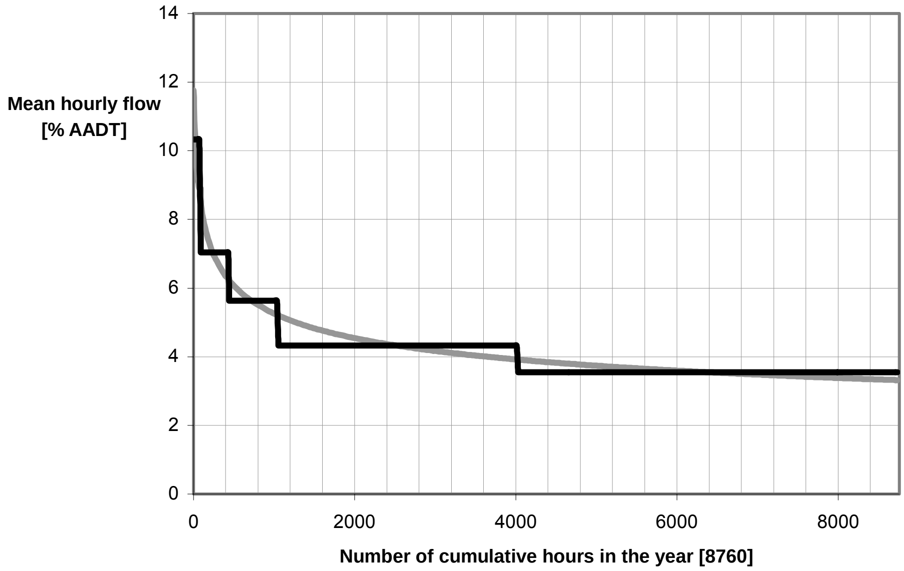

Figure 13: The traffic flow pattern

The vehicle operating speed depends on the free speed, the speed-flow relationship and the traffic distribution. Each flow period p in which the traffic flow distribution is divided is characterised by an hourly flow (Q_p) that is expressed in PCSE/h (passenger car space equivalents per hour) and that depends on the annual average daily traffic and on the percentage of heavy vehicles. The vehicle operating speed of each vehicle type, for every flow period p, is calculated with a different expression depending on which interval the hourly flow (Q_p) belongs to. If $Q_p<Q_0$ then the vehicle operating speed is equal to the free speed. If $Q_p>Q_0$ then the vehicle operating speed is reduced according to the speed-flow relationship.

The vehicle operating speed can be expressed as a function of the following variables:

- free speed,
- speed at the nominal capacity of the road,
- annual average daily traffic,
- percentage of heavy vehicles.

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[4] The regression coefficients for each type of road are reported in Appendix B.

The speed at the nominal capacity is estimated as the 85% of the free speed of the slowest vehicle in the traffic stream.
$V_{nom,u} = 0.85 \cdot \min_k(V_{FL,u,k})$
$V_{nom,d} = 0.85 \cdot \min_k(V_{FL,d,k})$
The flow-frequency distribution shown in figure 13 has been assumed, regardless of the type of road to be considered. The parameters in table 3 identify the flow-frequency distribution.

Table 3: The traffic flow distribution in traffic periods

Period	q_p	H_p
1	0.1034	87.6
2	0.0703	350.4
3	0.0563	613.2
4	0.0433	2978.4
5	0.0355	4730.4

It has been then assumed that each type of road of the Italian network is characterised by the same heavy vehicle distribution as the one specified in the CNR official document “Catalogo delle Pavimentazioni Stradali” for each type of road.
The equations to calculate the vehicle operating speed have been input in an excel worksheet. A visual basic program similar to the previous one has been used to generate all the values of the vehicle operating speed depending on the different combinations of the values of the variables. The intervals of variation and the step chosen for each of them are shown in table 4.

Table 4: Variation intervals of the variables used to calculate the vehicle operating speed

Variable	Unit	Interval	Step
Free speed	m/s	0÷50	5
Nominal speed	m/s	0÷42.5	3.5
AADT (2-lane highways)	veh/day	5’000÷30’000	1’000
AADT (other roads)	veh/day	20’000÷80’000	5’000
% Heavy Vehicles	%	0÷30	1

Linear regression equations and the corresponding coefficients have been determined, as follows:
$V_{u,kp} = cost_3 + B_{31} \cdot V_{FL,u,k} + B_{32} \cdot V_{nom,u} + B_{33} \cdot AADT + B_{34} \cdot p_{HV}$
$V_{d,kp} = cost_3 + B_{31} \cdot V_{FL,d,k} + B_{32} \cdot V_{nom,d} + B_{33} \cdot AADT + B_{34} \cdot p_{HV}$
The average vehicle operating speed for each flow period p, is given by the average of the uphill and downhill vehicle operating speed:
$V_{kp} = \beta_V \cdot \{ 7.2 / [(1 / V_{u,kp}) + (1 / V_{d,kp})] \}$
The annual average operating speed is:
$V_k = (\Sigma_p H_p \cdot q_p \cdot V_{kp}) / (\Sigma_p H_p \cdot q_p)$
Because the traffic flow pattern is assumed and fixed, then all the factors $H_i \cdot q_i$ are constant, so the annual average vehicle operating speed can be written in the following way:
$V_k = A_1 \cdot V_{k1} + A_2 \cdot V_{k2} + A_3 \cdot V_{k3} + A_4 \cdot V_{k4} + A_5 \cdot V_{k5}$
and
$A_i = (H_i \cdot q_i) / (\Sigma_p H_p \cdot q_p)$
The whole process that brings to the estimation of the annual average vehicle operating speed is represented graphically in figure 14.

Table 5: Constants A_i for each flow period

Period	A_i
1	0.0248
2	0.0676
3	0.0946
4	0.3530
5	0.4600

Travel time costs

Once the annual average operating speed is known, the annual average travel time for each vehicle type can be easily determined, knowing the length of the section that is being considered in the analysis. To determine the travel time costs the appropriate value of time must be assigned to ever vehicle type depending on the user category and the reason of the journey (work or other).

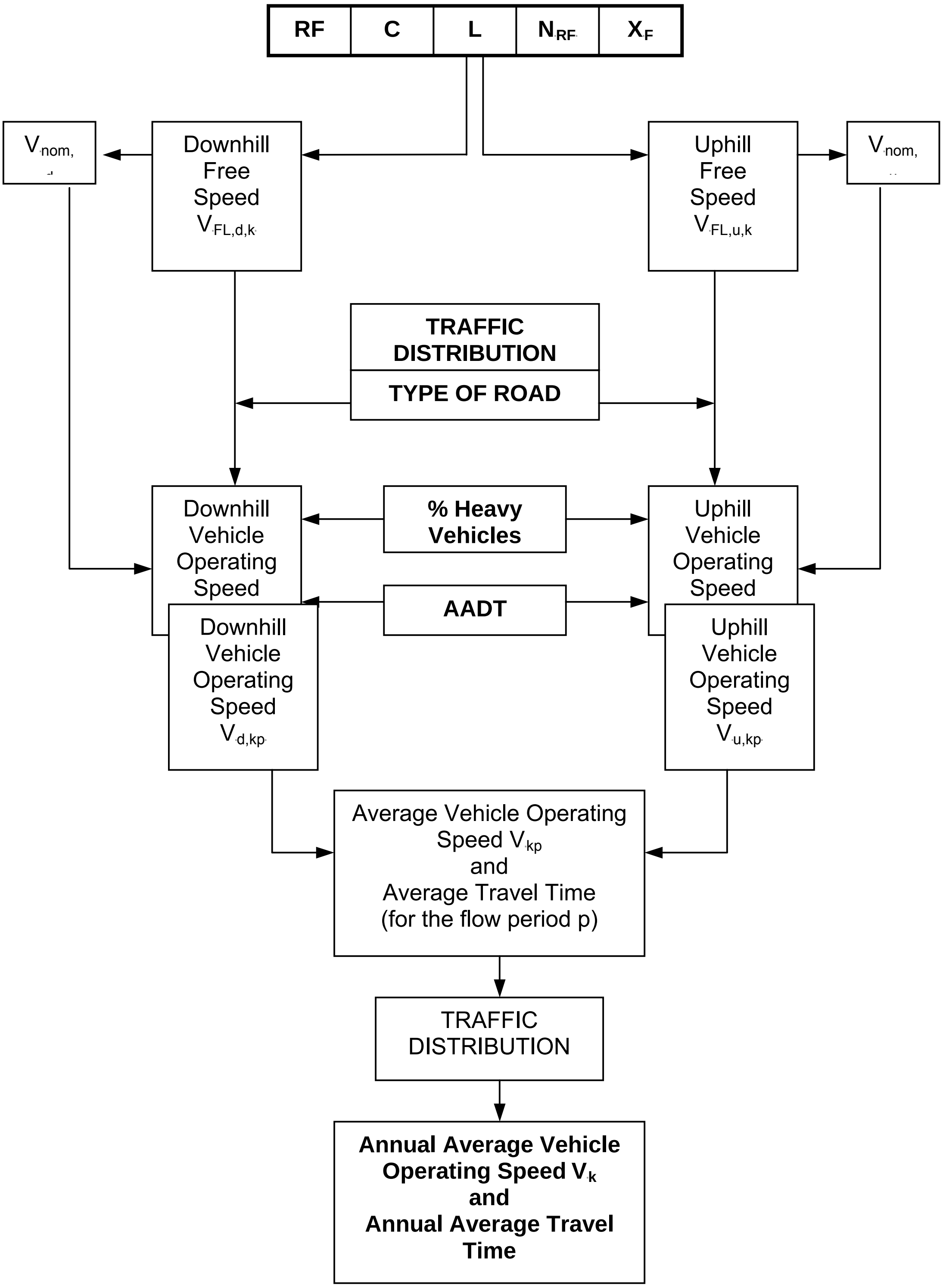

Figure 14: The process to estimate the annual average vehicle operating speed

CONCLUSION

The equations provided in the study estimate the average vehicle operating speed as a function of a few main variables. The equations can be considered as a first step towards the production of a set of relationships that can be used to estimate road user costs when the economic appraisal of alternative road projects is still at an early stage. When a strategic assessment of the local road network is carried out, the decisional process involves a large number of alternative projects. Then, a simple and quick estimation of the possible benefits, in terms of road user costs savings, would assist with the selection of the project alternatives which would be more appropriate for further investigation with an in depth investment appraisal.
At this stage a thorough application of the HDM-4 model would require an amount of data collection and resources that would consistently raise the budget expenditures. The equations provided in the study are based on the mechanistic/behavioral models used in the HDM-4 but use only a few variables. The

independent variables to be used in the equations can be readily achieved without need for large amount of data to be collected. Also, the models used in the HDM-4 have been calibrated referring to available Italian data and to the theory that has a valid application in Italy.
Finally, travel time costs can be estimated from the average vehicle operating speed and thus using only a few number of variables. Travel time costs are a major component of road user costs and usually represent the bigger part of savings of vehicle operating costs. A good estimation of the travel time costs could already provide for an indication on the possible benefits of a road project.

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APPENDIX A

Symbols

β free speed model parameter,
β_V correction factor for speed, β_V=f(C_V),
σ free speed model parameter,
AADT annual average daily traffic,
C average horizontal curvature of the road [deg/km],
C_V coefficient of speed variation within the traffic stream [default value=0.15],
GR average road section gradient [fraction],
H_p number of hours per year in flow period p,
IRI international roughness index [m/km],
L carriageway width [m],
L_{CR} critical gradient length [km],
L_G average road gradient length [km],
K_{LIM} speed enforcement factor [default=1.10],
K_{VD} desired speed multiplication factor [0.85-1.30],
N_{RF} average number of road rise and fall per kilometre [number/km],
p_{HV} percentage of Heavy Vehicles [%],
P_B braking power [kW],
P_T driving power [kW],
q_p hourly traffic flow in period p [proportion of AADT],
Q_p hourly traffic flow in period p [PCSE/h],
R average radius of road curvature [m],
RF average road rise and fall [m/km],
$V_{B,d}$ constraining speed due to braking capacity and road gradient, for the downhill segment [m/s],
$V_{B,u}$ constraining speed due to braking capacity and road gradient, for the uphill segment [m/s],
V_C constraining speed due to road curvature [m/s],
V_D constraining desired speed [m/s],
V_{D0} desired speed in absence of posted speed limits [m/s],
V_{D2} desired speed on a two lane road [m/s],
V_{DC} desired speed adjusted for carriageway width effects [m/s],
$V_{FL,d,k}$ free speed, for the downhill segment, for vehicle type k [m/s],
$V_{FL,u,k}$ free speed, for the uphill segment, for vehicle type k [m/s],
V_{LIM} posted speed limit [km/h],
V_{kp} average vehicle operating speed, for vehicle type k, for the flow period p [km/h],
V_k annual average vehicle operating speed, for vehicle type k [km/h],
$V_{nom,d}$ speed at the nominal capacity, for the downhill segment, for vehicle type k [m/s],
$V_{nom,u}$ speed at the nominal capacity, for the uphill segment, for vehicle type k [m/s],
$V_{OM,max}$ maximum allowable average rectified velocity of suspension motion of the standard Opala-Maysmeter vehicle in response to roughness [mm/s],
$V_{P,d}$ constraining speed due to driving power and road gradient, for the downhill segment [m/s],
$V_{P,u}$ constraining speed due to driving power and road gradient, for the uphill segment [m/s],
V_R constraining speed due to road roughness [m/s],
$V_{d,kp}$ vehicle operating speed, for the downhill segment, for vehicle type k, for the flow period p [m/s],
$V_{u,kp}$ vehicle operating speed, for the uphill segment, for vehicle type k, for the flow period p [m/s],
X_F speed reduction factor due to roadside friction [0.6-1.0],
X_{NM} speed reduction factor due to non-motorised transport [0.6-1.0].

APPENDIX B

Coefficients for the calibration of HDM-4 desired speed model

2-LANE HIGHWAY

Vehicle type	V_{D2}	a_1	a_2	K_{LIM}
Car	29.25	0.278	0.947	1.20
LGV	24.07	0.067	0.947	1.20
Light truck	22.01	0.067	0.947	1.20
Medium and heavy truck	22.01	0.067	0.947	1.20
Articulated truck	22.01	0.058	0.947	1.20
Bus	22.01	0.058	0.947	1.20
Coach	22.01	0.058	0.947	1.20

4-LANE HIGHWAY

Vehicle type	V_{D2}	a_1	a_2	K_{LIM}
Car	35.82	0.833	0.769	1.30
LGV	28.11	0.201	0.769	1.30
Light truck	24.98	0.201	0.769	1.30
Medium and heavy truck	24.98	0.201	0.769	1.30
Articulated truck	25.00	0.172	0.769	1.30
Bus	25.00	0.172	0.769	1.30
Coach	25.00	0.833	0.769	1.30

4-LANE FREEWAY

Vehicle type	V_{D2}	a_1	a_2	K_{LIM}
Car	39.86	0.833	0.793	1.20
LGV	30.23	0.201	0.793	1.20
Light truck	26.39	0.201	0.793	1.20
Medium and heavy truck	26.39	0.201	0.793	1.20
Articulated truck	26.41	0.172	0.793	1.20
Bus	26.41	0.172	0.793	1.20
Coach	26.41	0.833	0.793	1.20

6-LANE FREEWAY

Vehicle type	V_{D2}	a_1	a_2	K_{LIM}
Car	35.32	1.309	0.0	1.25
LGV	29.32	0.316	0.0	1.25
Light truck	25.33	0.316	0.0	1.25
Medium and heavy truck	25.33	0.316	0.0	1.25
Articulated truck	26.55	0.271	0.0	1.25
Bus	26.55	0.271	0.0	1.25
Coach	26.55	0.271	0.0	1.25

Regression Coefficients for the general equations

ORDINARY 2-LANE HIGHWAY

Coefficients & R^2	Car	Light truck	Medium truck	Heavy truck	Articulated truck	Coach
	Vehicle type					
UPHILL FREE SPEED						
$cost_1$	15.092	15.332	9.837	8.130	10.980	8.996
B_{11}	-0.0139	-0.0176	-0.0437	-0.0058	-0.0444	-0.0296
B_{12}	-0.01120	-0.01050	-0.00478	-0.00531	-0.00595	-0.00420
B_{13}	0.12300	0.11300	0.08569	0.11800	0.05789	0.09202
B_{14}	0	0	0	0	0	0
B_{15}	9.681	8.914	8.535	11.689	5.666	9.243
R^2	*0.845*	*0.827*	*0.760*	*0.804*	*0.689*	*0.646*
DOWNHILL FREE SPEED						
$cost_2$	15.092	15.332	9.796	8.130	10.975	8.992
B_{21}	0.01388	0.01756	0.04479	0.00576	0.04447	0.02970
B_{22}	-0.01120	-0.01050	-0.00478	-0.00531	-0.00595	-0.00420
B_{23}	0.12300	0.11300	0.08560	0.11800	0.05789	0.09202
B_{24}	0	0	0.01744	0	0.002819	0.000393
B_{25}	9.681	8.914	8.527	11.689	5.666	9.243
R^2	*0.845*	*0.827*	*0.755*	*0.804*	*0.689*	*0.645*

VEHICLE OPERATING SPEED (for vehicle type k – Uphill and Downhill)

	Period 1	Period 2	Period 3	Period 4	Period 5	
$cost_3$	18.128	10.762	7.775	4.707	2.745	
B_{31}	0.495	0.735	0.833	0.916	0.958	
B_{32}	0.479	0.265	0.167	0.08384	0.004156	
B_{33}	-0.0010420	-0.0006360	-0.0004571	-0.0002726	-0.0001549	
B_{34}	-13.064	-6.982	-5.244	-3.523	-2.409	
R^2	*0.904*	*0.957*	*0.975*	*0.989*	*0.995*	

HIGH TRAFFIC 2-LANE HIGHWAY

Coefficients & R^2	Car	Light truck	Medium truck	Heavy truck	Articulated truck	Coach
	Vehicle type					
UPHILL FREE SPEED						
$cost_1$	15.092	15.332	9.837	8.130	10.980	8.996
B_{11}	-0.0139	-0.0176	-0.0437	-0.0058	-0.0444	-0.0296
B_{12}	-0.01120	-0.01050	-0.00478	-0.00531	-0.00595	-0.00420
B_{13}	0.12300	0.11300	0.08569	0.11800	0.05789	0.09202
B_{14}	0	0	0	0	0	0
B_{15}	9.681	8.914	8.535	11.689	5.666	9.243
R^2	*0.845*	*0.827*	*0.760*	*0.804*	*0.689*	*0.646*
DOWNHILL FREE SPEED						
$cost_2$	15.092	15.332	9.796	8.130	10.975	8.992
B_{21}	0.01388	0.01756	0.04479	0.00576	0.04447	0.02970
B_{22}	-0.01120	-0.01050	-0.00478	-0.00531	-0.00595	-0.00420
B_{23}	0.12300	0.11300	0.08560	0.11800	0.05789	0.09202
B_{24}	0	0	0.01744	0	0.002819	0.000393
B_{25}	9.681	8.914	8.527	11.689	5.666	9.243
R^2	*0.845*	*0.827*	*0.755*	*0.804*	*0.689*	*0.645*

VEHICLE OPERATING SPEED (for vehicle type k – Uphill and Downhill)

	Period 1	Period 2	Period 3	Period 4	Period 5	
$cost_3$	18.407	10.867	7.862	4.777	2.801	
B_{31}	0.492	0.733	0.832	0.915	0.958	
B_{32}	0.479	0.267	0.168	0.08505	0.004240	
B_{33}	-0.0010510	-0.0006399	-0.0004606	-0.0002756	-0.0001574	
B_{34}	-13.679	-7.245	-5.443	-3.670	-2.512	
R^2	*0.902*	*0.956*	*0.975*	*0.988*	*0.994*	

4-LANE HIGHWAY

Coefficients & R^2	Vehicle type					
	Car	Light truck	Medium truck	Heavy truck	Articulated truck	Coach
UPHILL FREE SPEED						
$cost_1$	19.806	19.889	11.474	10.114	12.365	10.630
B_{11}	-0.0215	-0.0257	-0.0528	-0.0089	-0.0493	-0.0362
B_{12}	-0.01650	-0.01510	-0.07020	-0.00831	-0.00810	-0.00656
B_{13}	0.307	0.270	0.296	0.408	0.191	0.317
B_{14}	0	0	0	0	0	0
B_{15}	6.141	5.388	6.855	9.343	4.333	7.336
R^2	*0.836*	*0.823*	*0.777*	*0.777*	*0.700*	*0.667*
DOWNHILL FREE SPEED						
$cost_2$	19.806	19.889	11.430	10.114	12.361	10.626
B_{21}	0.02147	0.02570	0.05394	0.00886	0.04941	0.03629
B_{22}	-0.01650	-0.01510	-0.07010	-0.00831	-0.00810	-0.00656
B_{23}	0.307	0.270	0.296	0.408	0.191	0.317
B_{24}	0	0	0.01794	0	0.002826	0.000402
B_{25}	6.141	5.388	6.851	9.343	4.333	7.336
R^2	*0.836*	*0.823*	*0.773*	*0.777*	*0.700*	*0.666*

VEHICLE OPERATING SPEED (for vehicle type k – Uphill and Downhill)

	Period 1	Period 2	Period 3	Period 4	Period 5	
$cost_3$	28.522	13.683	7.736	2.314	0.233	
B_{31}	0.457	0.765	0.894	0.979	0.999	
B_{32}	0.314	0.257	0.121	0.02765	0.002044	
B_{33}	-0.0004799	-0.0002546	-0.0001422	-0.0000407	-0.0000038	
B_{34}	-14.586	-10.407	-6.892	-3.176	-0.598	
R^2	*0.826*	*0.931*	*0.966*	*0.993*	*1.000*	

4-LANE FREEWAY

Coefficients & R^2	Vehicle type					
	Car	Light truck	Medium truck	Heavy truck	Articulated truck	Coach
UPHILL FREE SPEED						
$cost_1$	23.283	23.078	13.534	12.698	13.712	12.667
B_{11}	-0.0256	-0.0297	-0.0574	-0.0106	-0.0516	-0.0394
B_{12}	-0.01910	-0.01720	-0.00831	-0.01000	-0.00920	-0.00788
B_{13}	0.200	0.169	0.230	0.321	0.148	0.249
B_{14}	0	0	0	0	0	0
B_{15}	4.458	3.757	5.928	8.143	3.733	6.383
R^2	*0.824*	*0.815*	*0.783*	*0.781*	*0.703*	*0.679*
DOWNHILL FREE SPEED						
$cost_2$	23.283	23.078	13.488	12.698	13.708	12.663
B_{21}	0.02557	0.02974	0.05848	0.01062	0.05165	0.03945
B_{22}	-0.01910	-0.01720	-0.00831	-0.01000	-0.00920	-0.00788
B_{23}	0.200	0.169	0.230	0.321	0.148	0.249
B_{24}	0	0	0.01811	0	0.002827	0.000405
B_{25}	4.458	3.757	5.926	8.143	3.733	6.383
R^2	*0.824*	*0.815*	*0.780*	*0.781*	*0.702*	*0.678*

VEHICLE OPERATING SPEED (for vehicle type k – Uphill and Downhill)

	Period 1	Period 2	Period 3	Period 4	Period 5	
$cost_3$	28.735	13.948	7.948	2.447	0.273	
B_{31}	0.452	0.760	0.891	0.978	0.999	
B_{32}	0.312	0.261	0.124	0.02924	0.002402	
B_{33}	-0.0004808	-0.0002581	-0.0001452	-0.0000427	-0.0000044	
B_{34}	-15.123	-10.968	-7.291	-3.407	-0.688	
R^2	*0.824*	*0.929*	*0.965*	*0.993*	*1.000*	

6-LANE FREEWAY

Coefficients & R^2	Vehicle type					
	Car	Light truck	Medium truck	Heavy truck	Articulated truck	Coach
UPHILL FREE SPEED						
$cost_1$	23.626	23.387	15.076	14.688	14.667	15.361
B_{11}	-0.0260	-0.0301	-0.0587	-0.0112	-0.0523	-0.0423
B_{12}	-0.01930	-0.01740	-0.00873	-0.01060	-0.00956	-0.00923
B_{13}	0.12400	0.10400	0.05082	0.08079	0.03711	0.04718
B_{14}	0	0	0	0	0	0
B_{15}	4.306	3.611	5.637	7.757	3.546	5.488
R^2	*0.823*	*0.814*	*0.785*	*0.785*	*0.704*	*0.690*
DOWNHILL FREE SPEED						
$cost_2$	23.626	23.387	15.029	14.688	14.663	15.357
B_{21}	0.02596	0.03011	0.05986	0.01121	0.05236	0.04243
B_{22}	-0.01930	-0.01740	-0.00872	-0.01060	-0.00956	-0.00923
B_{23}	0.12400	0.10400	0.05080	0.08079	0.03711	0.04718
B_{24}	0	0	0.01815	0	0.002828	0.000406
B_{25}	4.306	3.611	5.635	7.757	3.546	5.488
R^2	*0.823*	*0.814*	*0.782*	*0.785*	*0.703*	*0.689*

VEHICLE OPERATING SPEED (for vehicle type k – Uphill and Downhill)						
	Period 1	Period 2	Period 3	Period 4	Period 5	
$cost_3$	13.340	3.899	0.641	0	0	
B_{31}	0.775	0.958	0.997	1	1	
B_{32}	0.246	0.05116	0.006183	0	0	
B_{33}	-0.0002467	-0.0000696	-0.0000105	0	0	
B_{34}	-10.616	-4.566	-1.371	0	0	
R^2	*0.933*	*0.986*	*0.999*	*1*	*1*	