Rubber powder pollution due to road traffic

Domenichini L.
Full professor – Department of Civil Engineer - University of Florence

Martinelli F.
Researcher – Department of Civil Engineer - University of Florence

SYNOPSIS

Thousand of vehicles pass each day in a road section. Each vehicle leaves, every kilometre travelled on the road surface, a small quantity of rubber powder. Many tons of rubber are therefore introduced each year in the environment. This can produce pollution problem which is often neglected.
Tyre wear is a complex phenomenon. It depends non-linearly on numerous parameters, like tyre compound and design, vehicle type and usage, road conditions, road surface characteristics, environmental conditions (e.g., temperature) and many others. Yet, tyre wear has many economic and ecological implications, e.g. the annual rubber and carbon particle emission by all means of road transport in Europe is about 0.5 Mtonns next to about 240 million junked tyres. The possibility to predict tyre wear is therefore of major importance to tyre manufacturers, fleet owners, road designers and governments.
Analogous observations can be made for road polishing due to tyre passes, which causes high road maintenance costs and traffic safety implications. Tyre wear and road polishing is strongly related; the energy that wears the road is the energy that wears the tyre. There is therefore much to gain from an integrated approach to studying the mechanisms behind both wear phenomena.
Based on these observations, in April 2000 was started the three-year 5th framework EU project TROWS (Tyre and ROad Wear and Slip assessment). The results include tools to analyse tyre wear and road polishing. These are combined in a suitable wear prediction environment.
To evaluate the rubber powder amount introduced in the environment a tyre wear model has been fixed out. This model gives the tyre mass loss of a vehicle travelling on a road, knowing its characteristics.
This model could be used to analyse both existing and projected road sections to evaluate the environment impact of the infrastructure. By the governments point of view this procedure allow to identify the best path for a certain trip from an ecological point of view.

Rubber powder pollution due to road traffic

1. INTRODUCTION

Thousand of vehicles pass each day in a road section. Every kilometre travelled on the road surface, each vehicle leaves, beside other pollutants, a small quantity of rubber powder due to tyre wear. Many tons of rubber are therefore introduced each year in the environment; the annual rubber and carbon particle emission by all means of road transport in Europe is about 0.5 Mtonns next to about 240 million junked tyres [1]. This can produce pollution problems which are often neglected.
Considering that the energy that wears the road is the energy that wears the tyre [2], is possible to study the mechanisms behind both wear phenomena and to develop a model to predict tyre wear and related pollution effects.
The three-year 5th framework EU project TROWS (Tyre and ROad Wear and Slip assessment) was started in April 2000. Its aim was to gain insight into tyre and road wear processes in order to reduce both tyre and road wear. The results of the project are highly interesting to quantify the pollution effects of road traffic related to tyre wear.

2. TYRE WEAR MODEL

Tyre wear is a complex phenomenon based on the interaction between tyre and pavement. The tyre wearing forces are all the actions exchanged between the two surfaces within the contact path: rubber on tyre side and asphalt (or concrete) on pavement side.
Many different variables influence tyre wear, related both to wheel and road surface, namely:

- ✓ Tyre characteristics (inflation pressure, geometry and compound);
- ✓ Vehicle characteristics (mass, number of axles and wheels, geometry);
- ✓ Road characteristics (type of road element, bend's radius, straight length, longitudinal gradients and cross section transversal slope);
- ✓ Pavement characteristics (type of pavement, skid resistance, micro-macro texture, positive or negative texture);
- ✓ Users characteristics (actuated speed and acceleration/deceleration rates);
- ✓ Environmental conditions (temperature, moisture, pavement conditions (wet or dry).

Tyre wear is caused by the work done by the slip forces acting in the tyre-pavement contact area during the travelled paths all along the tyre useful life. Slip forces can be evaluated multiplying the contact forces exchanged between the wheel and the road surface by the relative slip.
One of the aims of the TROWS project was the evaluation of the typical tyre wear potential which could be expected in relation to the different possible driving situations occurring while running along the road network. A tyre wear model, in which the influence of the variable road characteristics is considered, has been therefore developed. The model has been fixed and calibrated for light vehicles and rural conditions.

To develop the tyre model an index able to evaluate the aggressiveness of a generic road section j has been fixed [3]. This index, called "Aggressivity Index" (AI), represents the wearing work done by each slip force acting during the travelled path, normalised by the length of the travelled path and by the weight acting on the tyre. The general expression of the "Aggressivity Index" AI^i_j, for the wheel *i* and the road section *j*, can be obtained by applying the overlaying of the effects of the elementary slip forces:

eq. 1 $$AI^i_j = \left(\frac{1}{P^i_{st}\cdot L_j}\right)\cdot\left[L_j\cdot\left(c_1\cdot\left(P^i_{dj}\cdot\mu_j + P^i_{dj}\cdot sl_j + K\cdot S\cdot V_j^2\right) + c_2\cdot\frac{P^i_{dj}\cdot\beta}{g}\cdot acc_j + c_3\cdot P^i_{dj}\cdot\left(\frac{V_j^2}{g\cdot\left|R_j\right|} - \left|tg\alpha_j\right|\right)\cdot\sin(2\gamma_j)\right)\right]$$

where:

- P^i_{st}, static load on wheel i in road section j;
- L_j, length of road section j;
- P^i_d, dynamic load on wheel i in road section j;
- μ_j, rolling resistance factor in road section j, given by

$\mu_j = 0.01375 + 0.000174 \cdot V_j$ with V_j expressed in m/s;

- sl_j, longitudinal slope on road section j;
- K, air resistance coefficient, given by $K = \rho \cdot c_x$ with c_x the aerodynamic penetration coefficient and ρ the air density;
- S, vehicle surface interested by air flow;
- V_j, vehicle speed on road section j;
- β, coefficient representing the contribution of vehicle rotative masses to the overall inertial force (β=1,10);
- acc_j, vehicle acceleration/deceleration on road section j;
- g, gravity acceleration;
- R_j, planimetric radius of road section j;
- $tg\alpha_j$, cross section slope on road section j;
- γ_j, tyre yaw angle on road section j;
- c_1, c_2, c_3 slip coefficients representing the wearing potential of each force

The slip coefficients to be put in the eq. 1, fixed by the simulations and the tests performed during TROWS project, are:

Table 1: Slip coefficients values

c_1	0.05
c_2	$-0.000009 \cdot P_S + 1.336467 \cdot \frac{1}{V} + 0.01655 \cdot acc + 0.013478$
c_3	0.823

Finally, the tyre mass loss (tyre wear) ML^i_j, occurring while travelling along the road section j can be evaluated with the eq. 2 [4, 5]:

eq. 2 $$ML^i_j = \left(d_1 \cdot {P^i_{wj}}^2 + d_2 \cdot P^i_{wj}\right) \cdot \left(\frac{P^i_{dj}}{N_{ref}}\right)^{d_3} \quad \text{[mg/km]}$$

in which:

- P^i_{wj} is the wearing power exchanged by wheel i during the manoeuvres performed in section j, it is given by:

  $$P^i_{wj} = AI^i_j \cdot P^i_{st} \cdot V_j \cdot L_j$$
- d_1, d_2, d_3 are empirical coefficients depending on the tyre compound;
- N_{ref} is a normalising reference dynamic wheel load.

The values of d_1, d_2, d_3 and N_{ref} were determined during the TROWS project with reference to a specific vehicle (Peugeot 406) and a specific tyre and are given in Table 2:

Table 2: Wear law parameters

N_{ref}	6940
d_1	2e-4
d_2	1e-2
d_3	1

The tyre wear model, which allows the evaluation of the rubber mass loss occurring during a travel on a road section, is therefore given by eq. 1 and eq. 2.
The model doesn't take in account the pavement conditions that could be less wearing, as for instance when it is in wet conditions, nor the higher or less wearing potentials of the pavement texture. This is due to the fact that in the TROWS experimental data it has not been possible to isolate these additional variables. The model could be therefore further developed to include also these variables.

3. SENSITIVITY ANALYSIS OF THE "AGGRESSIVITY INDEX" (AI)

A sensitivity analysis of the general expression of eq. 1 has been performed to understand how the "Aggressivity Index" AI^i_j is influenced by road characteristics (curvature radius, slope, speed, acceleration,

cross section gradient). The analysis has been performed applying a 30% increment-decrement to each variable.
Two cases has been performed. The first one was characterised by low aggressive conditions that are:

- Radius = -1400 m
- Slope = 2%
- Speed = 80 km/h
- Acceleration = 0.8 m/s2
- Cross section gradient = 0.04

The second case was characterised by more aggressive conditions, represented by lower curvature radius and higher acceleration values:

- Radius = -300 m
- Slope = 2%
- Speed = 80 km/h
- Acceleration = 1.5 m/s^2
- Cross section gradient = 0.04

In the first case, the relative influence of a variation of ± 30% of the variables considered is shown in Figure 1.

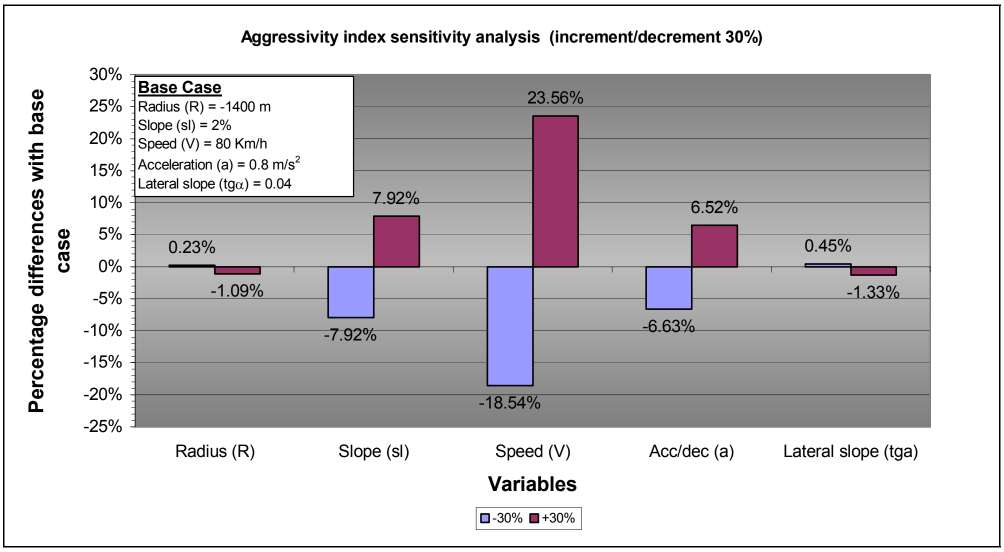

Figure 1: "Aggressivity Index" sensitivity analysis, case 1

The same analysis was repeated for the second case and gave the results shown in Figure 2:

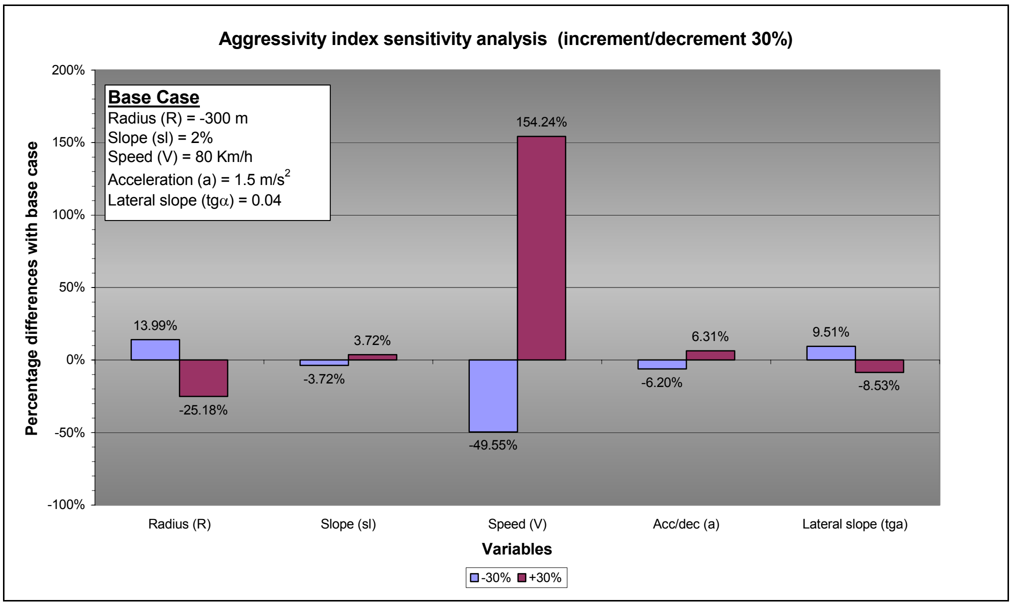

Figure 2: "Aggressivity Index" sensitivity analysis, case 2

The comparison of Figure 1 and Figure 2 shows the deviation of each parameter's influence caused by an increase of the aggressiveness. From Figure 1, it can be clearly seen that the influence of the variables considered by the model can be defined as:

- HIGH: for the variable speed (V);
- MEDIUM: for the variables slope (sl) and acceleration/deceleration (acc);
- LOW: for the variables curvature radius (R) and cross section gradients (tgα).

The speed values have the highest influence on the "Aggressivity Index" also in case 2 of Figure 2. In a more aggressive environment (case 2) an increment of the bend's radius of curvature has a higher influence on the "Aggressivity Index", and the slope and the acceleration decrease their influence. Particularly, the weight of each parameter depends on the amount of longitudinal or transversal friction (f_t) used. If the transversal friction required is low (case 1), the acceleration/deceleration and the slope terms have a big influence on the "Aggressivity Index" if compared to the other parameters. If the transversal friction required is high (case 2), the radius term becomes the one with the higher weight.
The dependence among the "Aggressivity Index" and the other parameters can be highlighted by means of some graphs. Figure 3 shows the "Aggessivity Index" sensitivity to speed variations in a straight segment. The "Aggressivity Index" doubles its value when speed increases from 80 to 140 km/h. This fact justifies the big influence of this parameter on the final results.

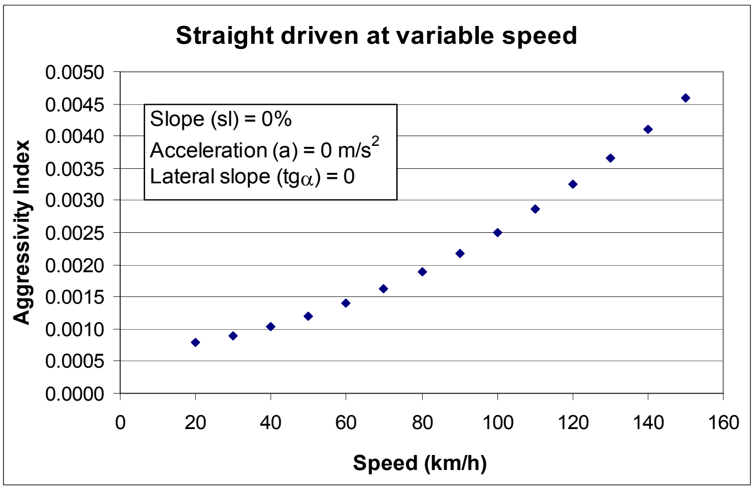

Figure 3: "Aggressivity Index" variation as function of variable speed along straight segments

The relationship between curvature radius, speed values and the "Aggressivity Index" is explained by the diagram of Figure 4: the "Aggressivity Index" is highly influenced by small values of the curvature radius, especially at lower speed values. For each speed value a radius beyond which AI increases with an asymptotic trend can be identified. As an example: for V=50 km/h the "Aggressivity Index" assumes values lower than 0.01 since R is higher than 100 m, if the radius becomes lower than 100m the AI increases terribly its values.

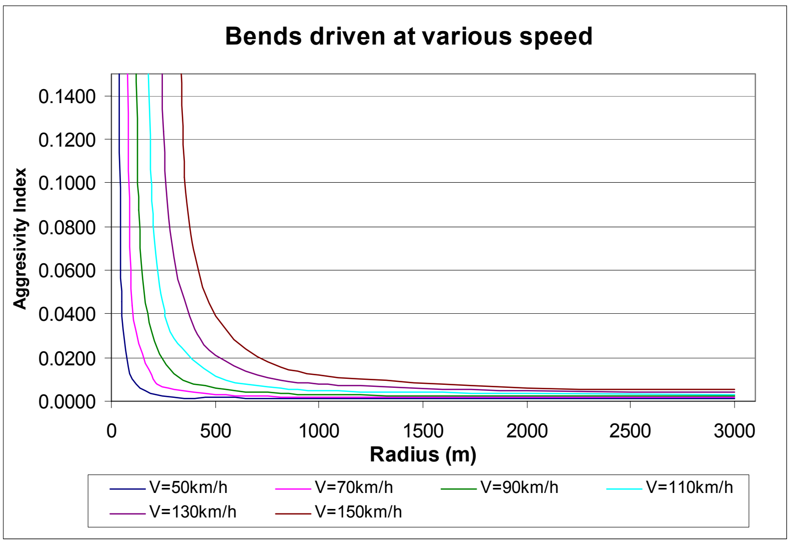

Figure 4: "Aggressivity Index"-speed-radius nomogram

Figure 5 contains the reversed analysis of the dependence between curvature radius, speed values and “Aggressivity Index”. The nomogram shows the high influence of speed on AI especially for low curvature values: for a radius of 100 m, AI increases its value more than four times passing form 60 to 80 km/h.

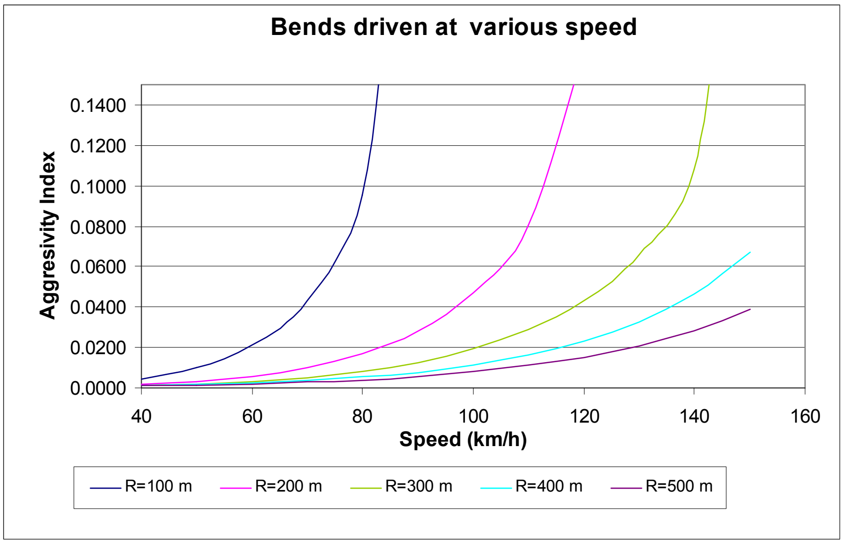

Figure 5: “Aggressivity Index”-radius-speed nomogram

Figure 6 shows the linear relationship existing between the “Aggressivity Index” and acceleration/deceleration rates. With reference to the two acceleration extreme values (±3 m/s^2) it can be seen that AI assumes two different values: 0.0054 for a deceleration maneuver and 0.0046 for an acceleration maneuver. The difference depends on the different values assumed by the term “dynamic weight” of eq. 1, depending on the wheel (front or rear) considered in the calculations. The diagram of Figure 6 is related to the front axle wheels on which a deceleration maneuver increases the dynamic weight, and consequently an increase of the “Aggressivity Index”; the opposite occurs for the acceleration maneuver.

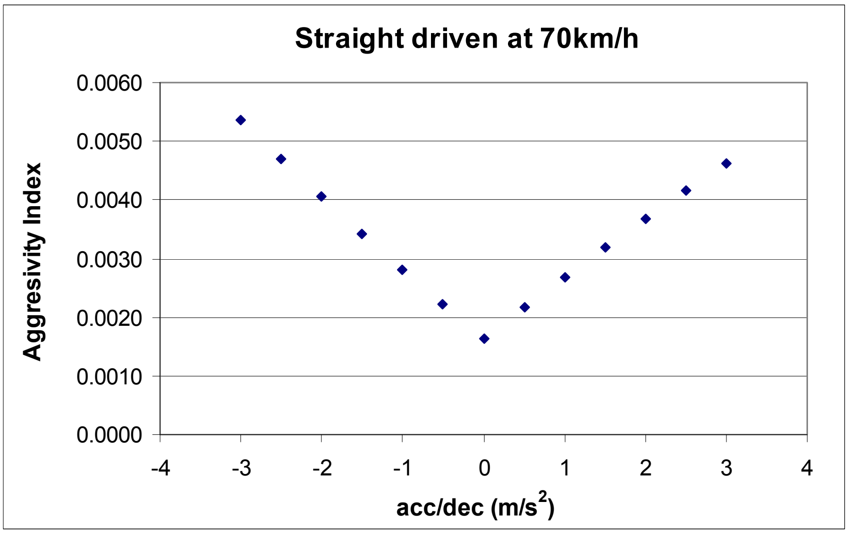

Figure 6: “Aggressivity Index” variation as function of variable acc/dec values along a straight segment

Figure 7 contains a diagram that shows the relationships between the “Aggressivity Index” and curvature radius for a given speed value (80 km/h) and several acceleration/deceleration values, denoting that the influence of acceleration/deceleration is much less than that of the speed. The curves sheaf in Figure 7 is referred to a front axle wheel, so the deceleration manoeuvre are more aggressive than the acceleration ones.

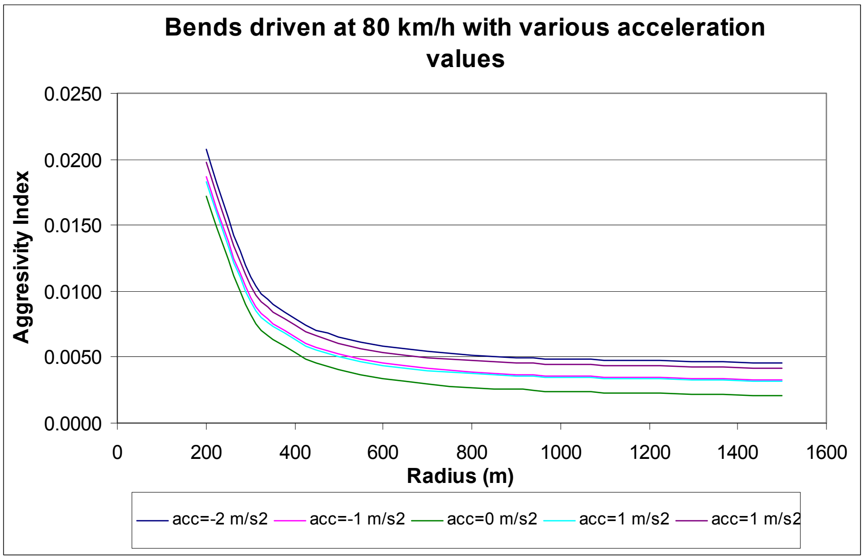

Figure 7: "Aggressivity Index"-radius-acc/dec nomogram

4. THE "CISA CIRCUIT"

To obtain some reference values of the tyre mass loss occurring during a vehicle travel path, the tyre wear model has been applied to the road profile used in the full scale testing experiment performed on the "CISA Circuit" during the TROWS project to calibrate the model itself [3, 6].

The "CISA Circuit" is a road circuit in province of Parma, Emilia Romagna, Italy (Figure 8) having a total length of approximately 130 kilometres and consisted of 68 km of Motorway (A15), 58 km of secondary road (SP308 and SP523) and 4 km of local road (on/off ramps of the Motorway). One third of the circuit length is placed in plain zones and the other two thirds in mountain and hilly areas. The "CISA Circuit" was subdivided in 8 sections according to the type of roads and type of environment (Table 3).

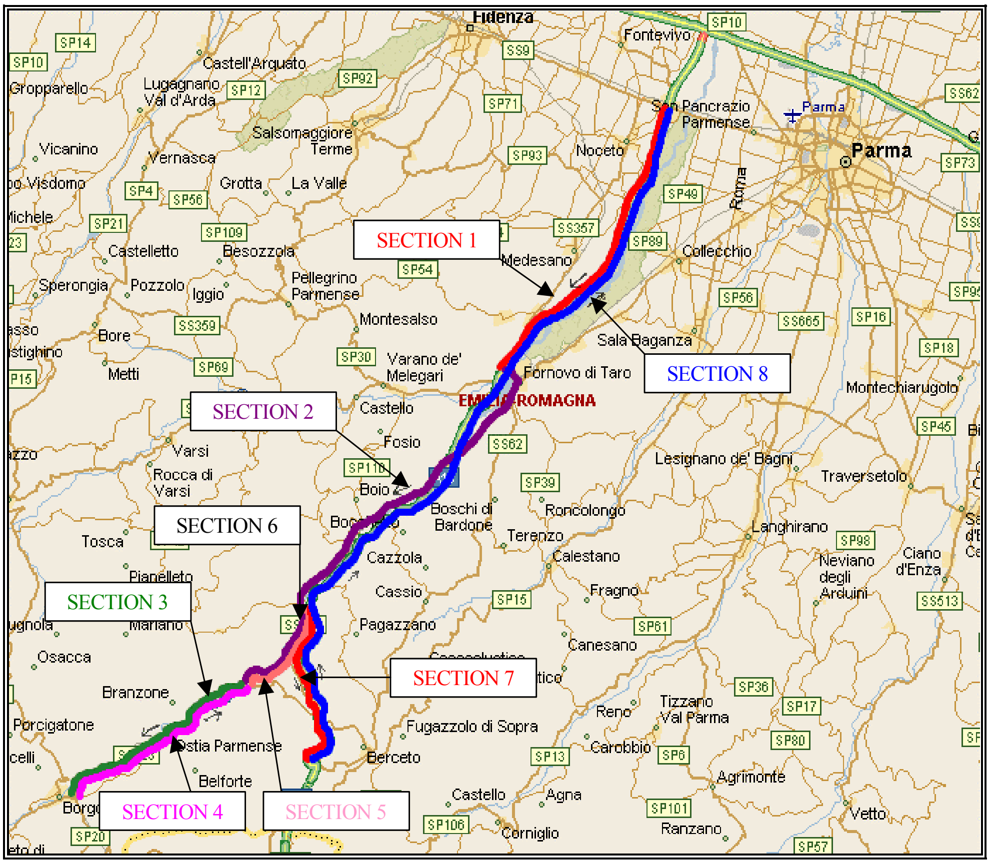

Figure 8: "CISA Circuit"

Table 3: "CISA Circuit" composition

Section	Road class	Lenght (m)	Environment
1	Motorway	18.084	Plain
2	Secondary road	27.900	Hilly
3	Secondary road	11.195	Hilly
4	Secondary road	11.195	Hilly
5	Secondary road	4.801	Hilly
6	Local road	913	Mountain
7	Motorway	9.785	Mountain
8	Motorway	45.585	Mountain (9.785 m) - Hilly (17.716 m) – Plain (18.084 m)

In order to characterise the geometry, the pavements and the cinematic and dynamic characteristics of the "CISA Circuit", experimental campaigns were carried out by the different partners during the TROWS project. All measures were geo-referenced to allow cross comparisons and an internal reference based on a kilometric progressive were constructed. All data were collected in a database and a Matlab application, able to manage this great amount of data, has been fixed up.
The geometric description of the circuit (slope, cross section gradients, radius of curvature of bend elements, length of straight and of bends elements) has been measured with the ARAN equipment. The results where graphically represented in the form of itinerary diagrams as shown in Figure 9, part a, c and d.

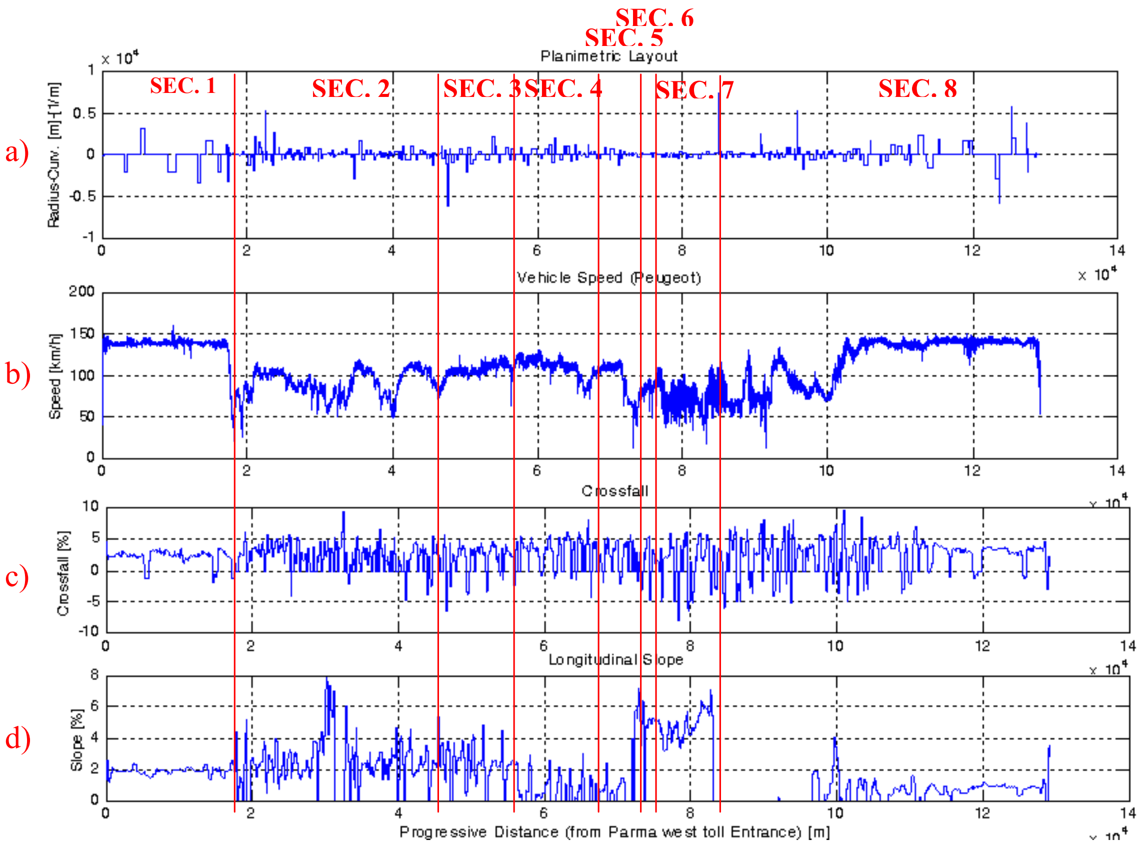

Figure 9:"CISA Circuit" characteristics

The cinematic and dynamic characteristics were identified by means of instrumented vehicles (two Peugeot 406 vehicles, one Xantia vehicle, one MAN truck) running along the circuit with the purpose of measuring tyre wear under controlled testing conditions (endurance tests). The Peugeot vehicle, driven by different users, run for 16'000 km, performing more than 100 loops of the "CISA Circuit", and the tyre wear occurred during the test was measured. Its speed and acceleration data were collected respectively with a microwave radar and a three axle accelerometer located near the centre of gravity of the vehicle. Data were buffered in

one second long time period and average values were calculated. Other means of filtering were not applied. The data have been filtered to eliminate fault data and the average speed and acceleration/deceleration values has been determined every 100 m long subsections. An example of the results of the analysis, referred to the Peugeot 406 speed, is shown in Figure 9 part b. Each speed value is referred to a 100 m long subsection and represents the average of all the measurements taken at each loop in the same subsection. As it can be seen, the motorway section 1 (which has a flat altimetric profile) and the final portion of section 8 (which is parallel to section 1) were run at the maximum speed of 140 – 150 km/h, while the other sections at lower speeds, ranging from 50 to 120 km/h.
The tyre mass loss (ML) of each road section composing the "CISA Circuit" was afterward evaluated as the average value of the ML of each 100 m long subsection belonging to the considered section. Finally, the global ML value of the "CISA Circuit" was calculated as the weighted average of the ML of the eight sections composing the circuit, keeping the length of each section as weight. The ML values were calculated for each of the four wheels of the test vehicle and the average value was assumed.
The MLs of the eight sections (with Section 8 subdivided in three subsections, belonging respectively to its mountain, hilly and plain portions) and that of the entire "CISA Circuit" are listed in Table 4. The comparison of the total predicted and the total measured mass loss is also shown in the last two rows of the table; as it can be seen, the model accuracy is high (approx. 95%).
The relative aggressiveness of all the sections, keeping section 1 as reference, is shown in Figure 10.

Table 4: "CISA Circuit" Mass Loss and Tyre wear values

Section	Predicted Mass Loss [mg/km]	Predicted Tyre Wear [mm]	Normalized values
1	118.0	0.006	1.00
2	45.5	0.004	0.39
3	48.3	0.002	0.41
4	45.9	0.001	0.39
5	36.8	0.001	0.31
6	23.9	0.000	0.20
7	44.2	0.001	0.37
8.1	27.2	0.001	0.23
8.2	59.1	0.003	0.50
8.3	99.0	0.005	0.84
TOT predicted	**63.3**	**0.023**	**0.54**
TOT measured	**66,4 (*)**		
(*) Average value for the four wheels			

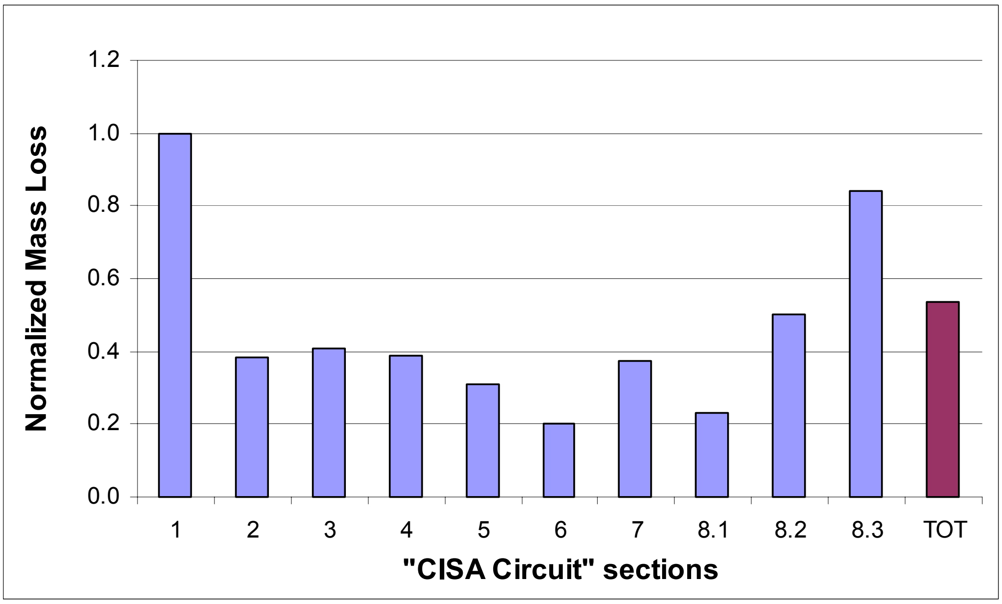

Figure 10: "Mass Loss" normalized values on CISA Circuit sections

The big difference between the mass loss occurring running along Section 1 and subsection 8.3 and the other 8 sections is due to the high speed values performed in the first two cited road segments. The eq. 2 shows that Mass Loss depends on the term "wearing power" that is evaluated multiplying the "Aggressivity Index" for load, length and speed. This means that the influence of the speed values on Mass Loss is even higher than that on "Aggressivity Index". The difference between section 8.3 and 1, as well as section 7 and 8.1 (which belong to the same motorway segments run in opposite directions) are due to the fact that section 8.3 and 8.1 are characterised by downward profile while section 1 and 7 upward. Different result shows section 5 compared to sections 2-3-4 (all belongings to secondary road segments): even if it includes a portion with a high upward longitudinal slope (which causes a higher aggressiveness if the other variables remain equal) its contribution to tyre wear is less than the one of the other sections because the speed reduction caused by the upward slope is higher than on motorway.

5. ENVIRONMENTAL EVALUATIONS

The "CISA Circuit" offered the possibility to define the possible reference values of the mass loss occurring in different types of road classes.
The "CISA Circuit", in fact, included four different road types: a motorway in a mountain or plain environment, a secondary road in a hilly environment and a local road in a mountain environment. For each type of road, the geometric and cinematic data measured during the TROWS project, averaged every 100 m long subsections, were used to evaluate the local tyre mass loss produced by the road characteristics for the four wheels of the test vehicle. The total mass loss was after words calculated summing up each 100 m contribution. The Mass Loss values obtained are reported in Table 5. These are referred to one wheel that covers one kilometre of road. The representative goodness of the values reported in Table 5 can be considered as high for motorway and secondary roads, as they are based on data acquired on more than 50 km of road length. For local roads the model is based only on data referred to the 913 m of section 6 and therefore the result is less sound.

Table 5: Mass Loss values for each road condition

Road Class	Environment	Km	ML [mg/km]
Motorway	Mountain	19.570	34.9
	Hilly	17.716	59.1
	Plain	36.168	104.3
Secondary	Hilly	50.290	44.8
Local	Mountain	0.913	23.9

The mass loss values contained in Table 5 confirms the influence of the speed variable: the higher ML value occurs in the motorway in a plain environment, driven with the higher speed values. For the mountain motorway condition the model fix a lower mass loss value than for plain motorway and even for secondary roads. The latter fact depends from the speed and the slope values. In fact the secondary roads considered are located in a hilly environment, with little slope factors and bends with high curvature radius and, consequently, high speed values. On the contrary, the mountain motorway (section 7 and Section 8.1, from Berceto to Borgotaro) has a severe geometry with narrow bends and high slope factors, causing a lowering of the operative speed.

To evaluate the amount of rubber powder left on a road segment during a fixed time period, the mass loss values for one wheel of Table 5 have been multiplied by 4 (the four wheels of the vehicle) and by the average light vehicle traffic over the fixed time period. Figure 11 shows the mass loss values left in ten year by light vehicles in function of their traffic, reported in terms of Average Daily Traffic (ADT).

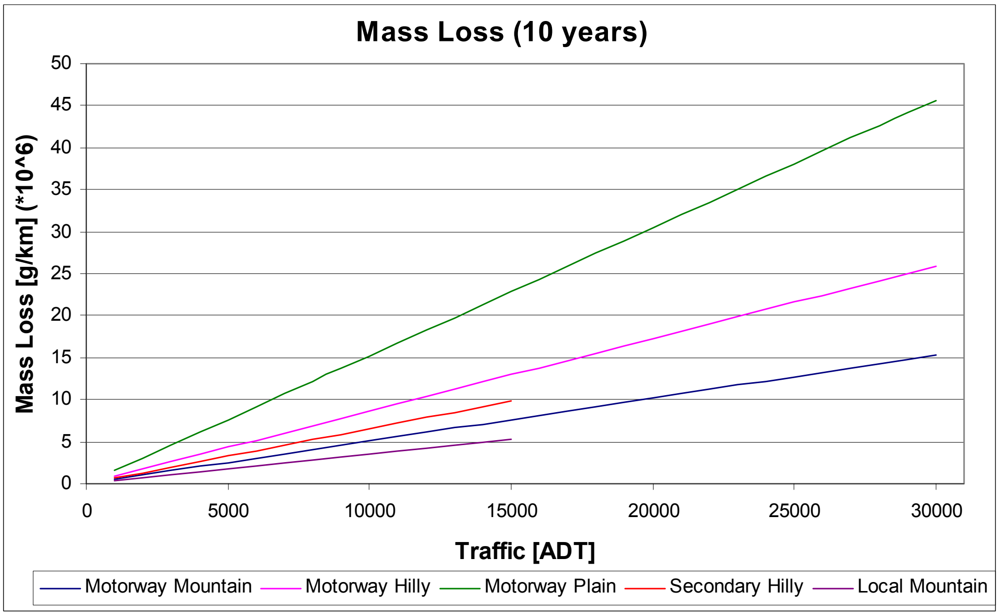

Figure 11: Mass Loss amount in 10 years

Figure 11 allows to compare the effects of different traffic conditions in terms of environmental pollution. The diagram takes in account the free flow conditions only, in fact, in all the other traffic conditions, the speed values could be sensible lower than the ones used to apply the model and to evaluate the Mass Loss.
This analysis shows that in a plain motorway with an ADT higher than 20'000 the amount of rubber left in ten years on each road kilometre is about 30 tons, this means a really huge amount of pollutant in the air and on the pavement surface.

The application of the general values shown in Table 5 to road characteristics different from those of the "CISA Circuit" can be misleading. On the other hands, the developed model allows to evaluate the amount of rubber powder introduced in the environment each year by the traffic, once the geometric features of a road section (bend's radius, longitudinal gradients, cross-section transversal slope) and the traffic characteristics (number of vehicles, user's operative speed and acceleration/deceleration rates) are known.

This can be very usefully applied in an Environmental Impact Analysis procedure performed during the development of a road design, allowing the comparison of the different proposed design options in terms of pollution due to rubber powder.

6. CONCLUSIONS

The influence of the road characteristics and driving conditions on the tyre wear were investigated during the EU funded TROWS project. A tyre wear model was developed based on the evaluation of the work done by the slip forces acting in tyre-pavement contact area. It allows to account for the different geometric characteristics of the roads, the vehicle and tyre characteristics and driving conditions, the latter represented by the driving speed and by the acceleration-deceleration rates.

The model does not account for the pavement texture characteristics because of, during the experimental activities performed to validate the models, it has not been possible to isolate this variable. The model could be therefore further developed to include also the influence of the pavement texture.

The model is able to differentiate the wearing potentials of the different road and driving environments and allows to estimate the amount of rubber powder annually introduced in the environment along a given roadway section, once its geometric characteristics, the amount and composition of the traffic travelling on it and the prevailing driving conditions are known. Therefore it can be fruitfully used within the environmental impact analysis procedures of road infrastructure's design.

The model application to the "CISA Circuit" shows that different road types have different inherent pollutant potentials and that the most influencing variable is the travelling speed. The relative influence of the longitudinal slope, the bend's curvature radius and the acceleration/deceleration rates depend on the more or less aggressiveness of the road layout. Very little influence seems to have the road cross section transversal slope.

ENDNOTES

TROWS (Tyre and ROad Wear and Slip assessment): Contract G3RD-CT-2000-00247; partners are: TNO Automotive, Centre d'Etudes Techniques de l'Equipement de Lyon (CETE'), Pirelli Pneumatici S.P.A., Nokian Tyres Plc, Helsinki University of Technology (HUT), Politecnico Di Milano - Dipartimento di Meccanica (POLIMI), Università degli Studi di Firenze (UNIFI), Peugeot Citroen Automobiles, Viagroup

REFERENCES

[1] LUPKER, H.A. "Tyre and road wear prediction", TNO, Reifen-Fahrwerk-Fahrbahn, Hannover-Germany, 2003

[2] GOTHIE', M. "*Methods and results of TROWS for roads polishing*", CETE', PIARC congress, Durban-South Africa, October 2003

[3] DOMENICHINI, L. MARTINELLI, F. "Influence of the road characteristics on tyre wear", University of Florence, SURF 2004, Toronto-Canada, June 2004

[4] BRAGHIN, F. CHELI, F. MELZI, S. RESTA, F. "*Tyre wear estimation through a physical 3D model*", POLIMI, Aimeta International Tribology Conference, Italy, 2002

[5] LUPKER, H.A. CHELI, F. BRAGHIN, F. GELOSA, E. "*Numerical prediciton of car tyre wear phenomena and comparison of the obtained results with full-scale experimental tests*", Tire Society, Akron-USA, September 2003

[6] HALEN, I. SAINIO, P. LEHTONEN, T.J. "*Assessment and monitoring of tyre wear testing*", HUT, FISITA World Automotive Congress, Helsinki-Finland, 2002

ACKNOWLEDGEMENTS

The TROWS research is the result of a common effort that involved the whole structure of the "Roads area" of the Department of Civil Engineer of the University of Florence and required the co-operation of many TROWS Partners whose contribution has been essential to achieve the programmed goals.

The work done by many young engineers and technicians provided a valuable and very useful help in performing the experimental activity. The technicians of the Road Laboratory of the University of Florence (Paolo Bencini, Raffaele Gualdani). The student performing his PhD Thesis (Lorenzo Ballerini). The student performing his final thesis for Degree (Simone Faelli). The research contractor Simone Lusini. Finally, the administrative staff Roberta Boniotto and all the personnel of the Department of Civil Engineer Administration.

UNIFI team wishes to acknowledge the strongly profitable co-operation with all the Partners involved in the TROWS project and particularly Francesco Braghin, Federico Cheli, Stefano Melzi (POLIMI). A special acknowledgement is to be devoted to the TROWS Project Manager Eng. Henk Lupker.