CONSEQUENCES OF PAVEMENT MAINTENANCE WORKS ON FUEL CONSUMPTIONS AND GREENHOUSE EFFECT GAS EMISSION

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ABSTRACT

Pavement maintenance works aim at the restoration of the road operational qualities, which determine safety, comfort, silence, but also decrease fuel consumption and greenhouse effect gas emissions (mainly carbon dioxide). On the other hand, the vehicles consume and emit more during works, because of slowdowns, bottlenecks and diversions. In the course of the FORMAT (Fully Optimised Road Maintenance, 2002-2005) European contract, a calculation of time lost during works was proposed, for which a complement about fuel consumption and emissions was needed. This was assigned to LCPC as one of the tasks of a national research project called PROPICE (Preservation and Rehabilitation Optimised for the existing Patrimony of Infrastructures under strong Constraints of traffic, Environment and residents). For this purpose, a light vehicle was equipped for the measurement of fuel consumption and other operating parameters, in order to carry out tests at different speeds on a special track, then at normal speed on a road circuit, and finally in congested traffic conditions. This allowed to know the variations of consumption and emissions in different worksite configurations, according to traffic levels. Further studies will aim at extending these results to a diversified traffic flow, in order to make assessments for the complete lifecycle of a pavement.

1. CONTEXT AND EXECUTION OF THE EXPERIMENT

1.1. The research framework: the PROPICE contract

Road maintenance involves costs, for the road owner of course, but also for the user, who undergoes disturbances during works [1,2]: increased travel time, discomfort, additional fuel consumption and other vehicle operating and capital costs. To this, one must add the consequences for residents and the environment, including extra noise and pollutions. Among vehicle air emissions, CO_2 (carbon dioxide) is the main greenhouse effect gas, cause of global warming.
Signed with the French National Research Agency (ANR) for a three years duration (2006-2009), the PROPICE contract (Preservation and Rehabilitation Optimised for the existing Patrimony of Infrastructures under strong Constraints of traffic, Environment and residents) is aimed at developing strategies for asset management and technological and methodological tools in order to design and realise “stealth works” (i.e. discreet and rapid works), leading to the least possible trouble for users, the environment and local residents.
Several participants take part in the contract: with the EGIS group as coordinator, it brings together a motorway operating company (ASF), road builders (Colas and Bouygues-TP), research agencies (LCPC and CSTB) and a university department (the LGC –Civil engineering laboratory- of the Blaise Pascal University in Clermont-Ferrand).
The work described in what follows concern only a part of the contract (task 1.2), entrusted to LCPC and concerning the modelling of the inconveniences resulting from works. As a result of task 1.1, LCPC already produced a report analyzing the various types of

inconveniences resulting from road works [3]. A first modelling work was carried out by LCPC within the framework of the FORMAT (Fully Optimised Road Maintenance) European project [4], concerning the calculation of travel time during works; the present aim was to complete it through a model calculating fuel consumption and CO_2 emissions.

1.2. The equipped vehicle

The objective consisted in measuring the actual fuel amounts consumed by a light vehicle in diverse conditions, concerning both the road itself (geometry and condition) and the vehicle operating parameters (speed and acceleration). The dedicated vehicle was a petrol-driven Peugeot 406 1.8L sedan, provided with a specific instrumentation: distance, speed et acceleration sensors, inertial measurement unit yielding the vehicle position through the movements of its barycentre. It was also possible to mount a dynamometric wheel, in order to measure the forces undergone by the vehicle in the three directions (longitudinal, vertical and transverse). As for the consumption measurements, two flow meters were inserted on the fuel pipes: the first device measures the quantity sent by the fuel pump towards the engine, the second one measures the excess of fuel returning to the tank. The vehicle consumption results from the difference between both measurements.

1.3. The road data

The measurements [5] characterizing the road pertain to three types: geometry, roughness and surface texture depth. Geometric data include the radius of curvature, the longitudinal gradient and the transverse slope, measured by the VANI (*Véhicule d'ANalyse d'Itinéraires*) equipment, based on a gyroscopic unit. This device was designed and is managed by the *Laboratoire Régional des Ponts et Chaussées* of Lyon.
The road roughness and mean texture depth (MTD according to ISO standard [6]) measurements were carried out thanks to a new equipment: the MLPL (*MuLtiProfilomètre Longitudinal*), equipped with several lasers performing a contactless measurement, a gyroscope and an accelerometer, all this allowing to reconstitute the longitudinal profile of the road surface in the considered waveband. The recorded profile allows the calculation of a roughness index; subsequently, two calculation methods were considered: the IRI [7] (International Roughness Index), and the NBO [8,9] (*Notation par Bande d'Ondes* = waveband gradation), used in France, and which consists in calculating the energy in three wavelength ranges (SW, MW and LW, -short, medium and long waves- i.e. 0.7-2.8. 2.8-11.3 and 11.3-45.25 m ranges), in reference to a gradation scale from 0 to 10 (10 indicating a perfect evenness).

2. MEASUREMENTS CARRIED OUT ON A TEST TRACK

2.1. The LCPC test track

LCPC owns within its Nantes site a dedicated test track (figure 1). It includes a concave profiled bend for vehicle acceleration, and a straight line where are located the test zones, as well as a bend to study dynamical phenomena. It provides the appropriate safety and reliability conditions to conduct a multitude of tests, at speeds in the 0 to 130 km/h range. Designed to test, calibrate and certify continuous measurement instruments used to quantify pavement surface characteristics, its range of application has been extended to the analysis and modelling of various types of vehicle performance, such as noise generation or braking distances.

The main objective was here to carry out tests under mastered speed, without undergoing constraints because of the other vehicles, in safe conditions, on a straight line or in a bend. The presence of various kinds of surface allows to study the influence of surface texture.

Figure 1 – General view of the test zones and the bend on the track

2.2. Measurement series

Measurements were first made with the stationary vehicle, then at the various speeds, stabilized thanks to the cruise control, by 10 km/h steps from 20 to 130 km/h, for various gears, at first according to an "economic" driving (changing gear at 20, 40, 60 and 80 km/h), and then cases of low or high engine speed. The first series were carried out on the "E2" road surface ("old" 0/10 mm SCAC -semi-coarse asphalt concrete-). The following series concerned several test zones, which have each their own texture characteristics on a 250 m length (sometimes slightly less) and a 3 m width, and are representative of various techniques used in pavement surfacing, except for some whose objective is precisely to get a low skid resistance (zones G, L1 and L2). Table 1 displays the roughness and texture characteristics of these zones (the long wave NBO does not appear in the table because the length are too short to get a significant value).

Table 1 – Texture and roughness data of the test zones

Zone	Technique	Texture (mm)	Roughness IRI (m/km)	MW grade		SW grade	
				L	R	L	R
E1	New SCAC 0/10	0.81	1.37	9	9.5	8	8
E2	Old SCAC 0/10	0.93	1.51	9	9	7	7
M2	VTAC* 0/6	1.30	1.84	9.5	9	7	6
L1	Resin	0.20	1.34	10	9	9.5	8
L2	Sand asphalt	0.50	1.66	8	8.5	7	8
F	Patented process	0.77	1.52	9	8.5	6.5	7
G	Low skid resist. AC 0/10	0.62	1.33	8	9	9	8.5

* VTAC = Very Thin Asphalt Concrete

In order to study the impact of curvature, the track includes a 110 m radius bend (figure 1), where measurements were performed at speeds from 40 to 90 km/h.

2.3. Model calibration

The vehicle movement opposes several types of forces, each one having its own equation. All participate in the energy spending, and thus in the fuel consumption; furthermore, these strengths are not mutually independent, and the interactions are rarely linear. Fortunately, the phenomena can be described according to well identified laws of nature, hence the relevance of a numerical model, which furthermore allows extrapolations to vehicles of the same kind but with different characteristics. The proposed relationships are the same as in the HDM model, which was created in the 1970s under the World Bank's aegis; in 1996 PIARC resumed the responsibility of the management of this project, which has now been externalized [10].

The procedure (proposed in the HDM volume "guide for calibration and adaptation") follows several steps:

1 Measure the fuel consumption with the engine idling.

2 Measure the fuel consumption at different constant speeds on the same flat and straight road (in the present case, the LCPC track).

3 Calculate for each speed the power required for the vehicle movement, according to equations in the model.

4 Calculate the engine and accessory power, using the default parameters.

5 Calculate the total power in use.

6 Divide the instant measured fuel consumption (in ml/s) by the total power; this gives the power-to-fuel factor for that power.

The equations of the model (third step) allow to calculate, according to the speed and the characteristics of the vehicle and the road, the various strengths which oppose the movement (gravity, inertia, cornering, resistances). At constant speed and in a straight line, only are concerned the rolling and air resistances and the gravity, positive or negative according to the gradient direction (rise or fall).

Figure 2 shows the power required for movement as a function of speed, on the "E2" zone of the test track, in straight line and without acceleration, and the total power spent when driving "economically". Figure 3 shows the resulting calibration.

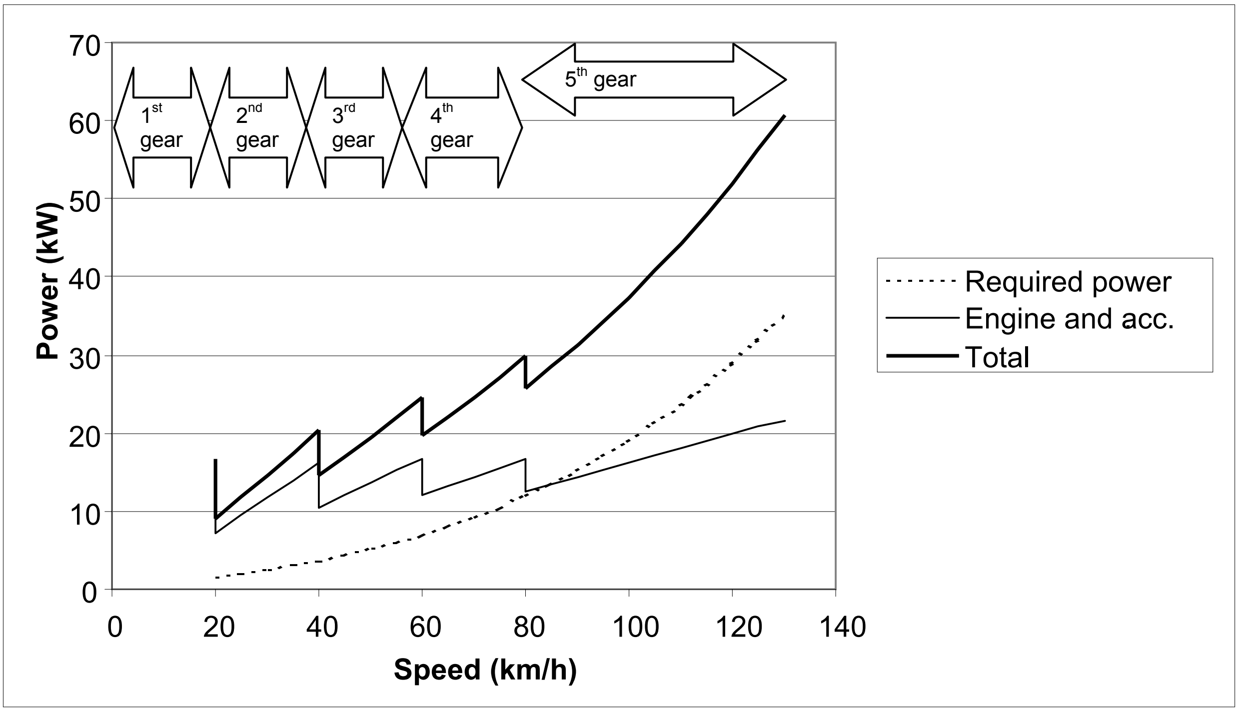

Figure 2 – Principle for total power demand calculation

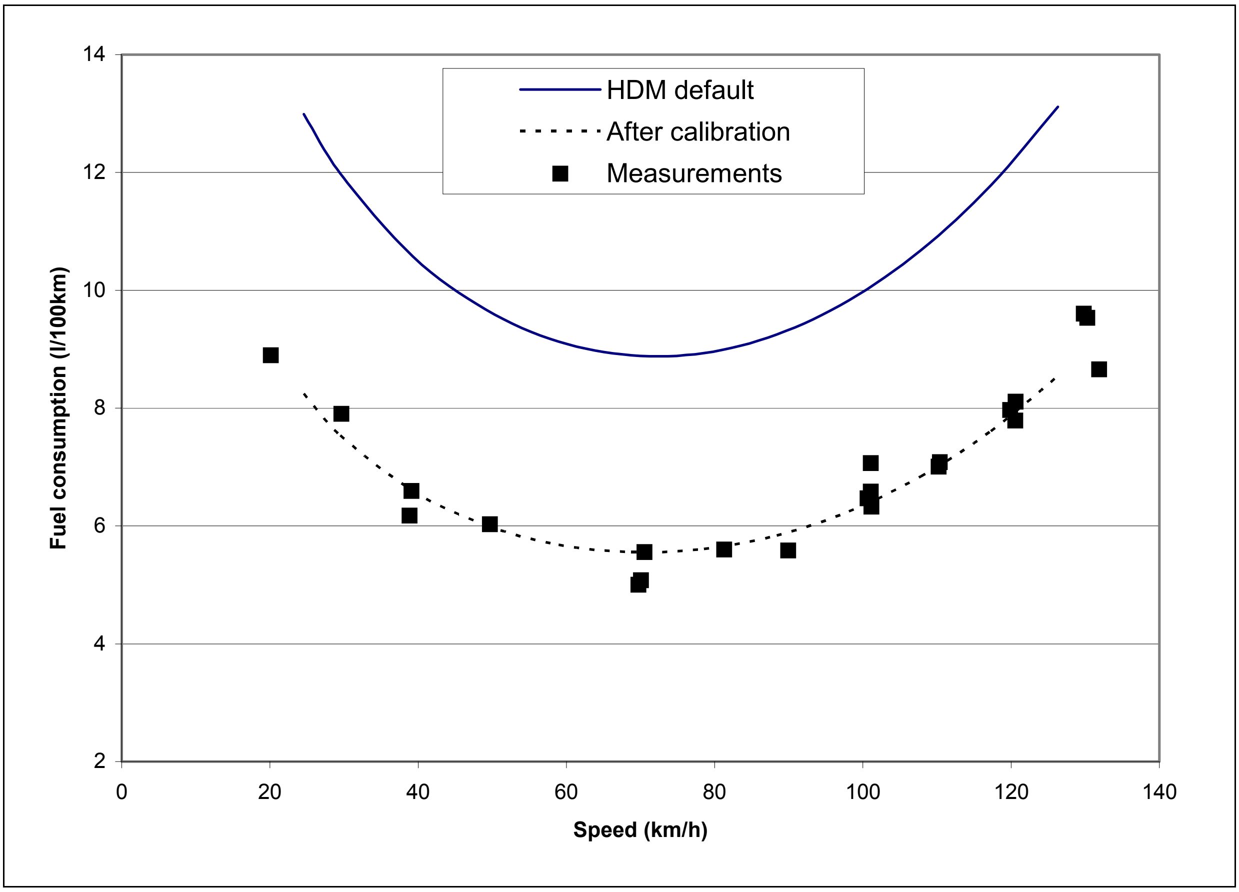

Figure 3 – Results of model calibration at constant speed in straight line ("economical" driving)

Tests carried out in the bend and on the other zones of the track allowed the calibration of coefficients related to curvature, and to rolling resistance, function of road surface characteristics (texture and roughness). The HDM formula accounts for IRI as roughness index, but an alternative was created here to account for NBO roughness scales.

3. MEASUREMENTS ON THE ROAD IN REAL CONDITIONS

3.1. The road circuit

A circuit made of departmental country roads, about 70 km long, was used for this series of measurements, which had several objectives:

- Validate the results obtained on the LCPC track, especially the model calibration coefficients, with the vehicle operating in real and normal conditions, on routes several kilometres long;
- Study influence factors, such as the roughness and longitudinal gradient, whose variations were very small on the track;
- Account for speed variations, and hence accelerations and decelerations, in a context of normal driving.

Data describing the road were collected by means of the VANI vehicle and the MLPL (*cf.* 1.3). During fuel consumption tests, the driver had to drive economically, conforming to speeds normally practised on road, including the variations caused by route events (bends, villages, intersections, posted limits) but also by random events (interactions with the other vehicles).

3.2. Model calibration on the road circuit

The results of the measurements carried out on the on road were collected into spreadsheet type file, in which every column corresponds to a variable and every line to a unit section of road, of constant length (for some analyses, continuous homogeneous sections based on geometry were created by grouping). Variables characterize as well the road (curvature, longitudinal and transverse slopes, texture depth, roughness in IRI and NBO) as the vehicle operation (velocity, engine speed). The calibration was resumed on the same bases as for the measures on track, but by taking into account all the available variables, including the longitudinal acceleration, calculated by difference between recorded speeds. With a minor adaptation of coefficients, the consumptions agreed very well, statistically, with the values predicted by the model (figure 4). An analysis of "residuals" (differences between observed and predicted values) showed that most of the variables are not correlated to them, what is a favourable indication as for the good calibration of the model. It remains that longitudinal slope and acceleration influences seem to be underestimated by the model.

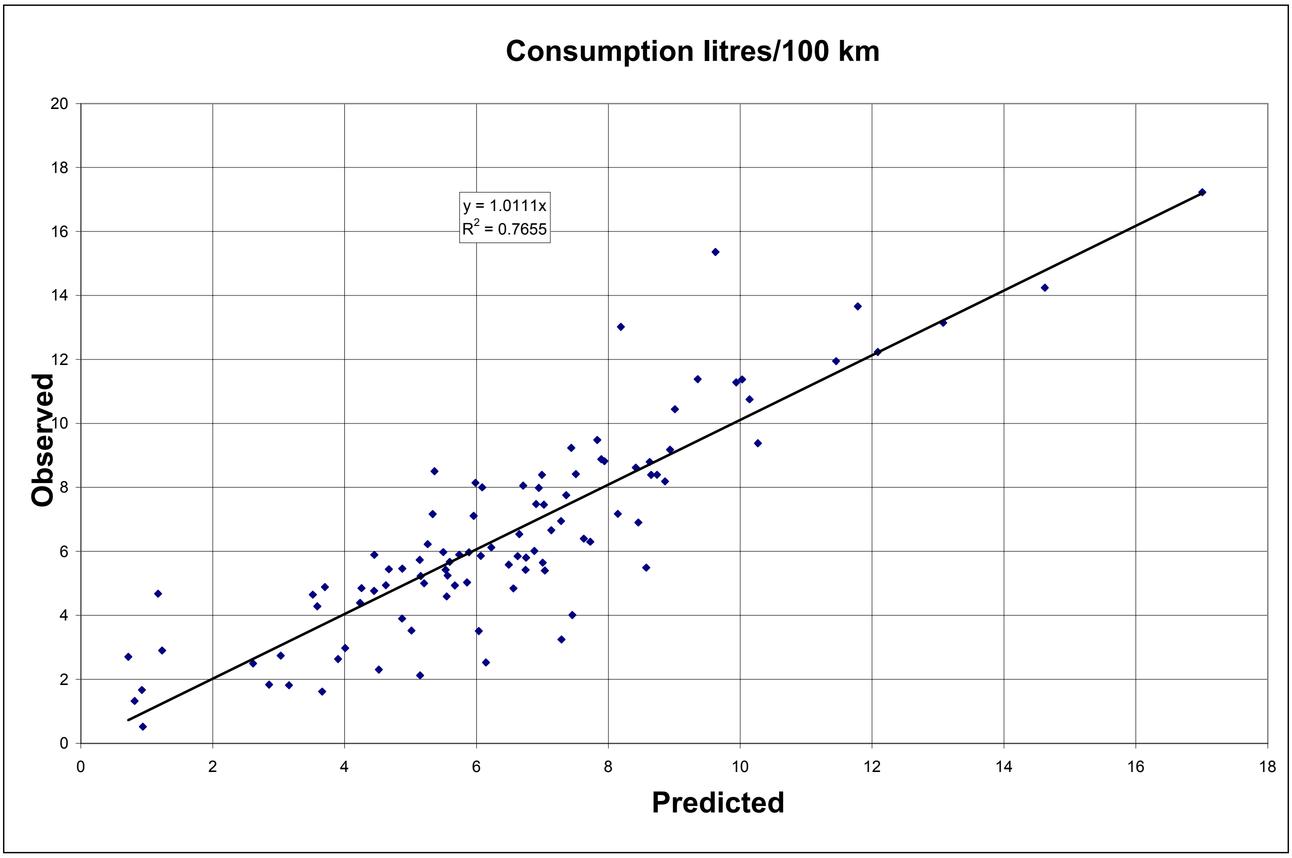

Figure 4 – Correlation between observed and predicted consumptions (after grouping unit sections into geometrically homogeneous continuous sections)

3.3. Conclusions about measurements on the road circuit

According to the assigned objective, the measurements carried out on the road circuit allowed to take into account the parameters like roughness, longitudinal and transverse slope, as this was not possible on the test track, with the following results:

- Confirmation of coefficients resulting from track tests, as the engine power-to-fuel ratio, the rolling and curvature resistance;
- Slight raise of the slope in the power-to-fuel relation;
- Adjustment of the roughness and texture coefficients, using two models, based respectively on the IRI and NBO scales (the latter seeming more pertinent).

It seems however that, with regard to the measured consumptions, the model tends to underestimate the effect of the accelerations and to a lesser degree the longitudinal slopes. This could have a metrological (smoothing of acceleration variations) or physical origin (existence of ignored dynamic phenomena).

If we examine the effects of the road variables, it is the longitudinal slope which influences the most the consumptions, followed by the curvature; the influence of the characteristics of surface of the road comes later, without being unimportant at all (variations about 2 to 3 % for both ranges found on the circuit).

4. MEASUREMENTS IN TRAFFIC CONGESTION

4.1. The measurement program

The tests on the Nantes ring road (RN 844, an urban 2x2 lane expressway), 40 km long, were carried out in order to measure speeds, accelerations and fuel consumption during periods of dense traffic, including bottleneck conditions, with the objective of reproducing the situation prevailing during road works. Two successive runs were completed, one during the rush hour (8-9 AM), the other during an off-peak period (2-3 PM).

4.2. Analysis of speeds and accelerations

Figure 5 shows the speed variations which were recorded during both tests (off-peak and rush hour); one may identify three situations:

- Fluid flow, when the speed oscillates around the ordered speed, normally equal to the speed limit (90 km/h), with some temporary slowdowns, during which the speed can fall down to about 60 km/h;
- Stop and go, characterised by cycles of accelerations more or less rapid and regular and quick decelerations;
- Bottleneck, alternating stops and slow motion periods.

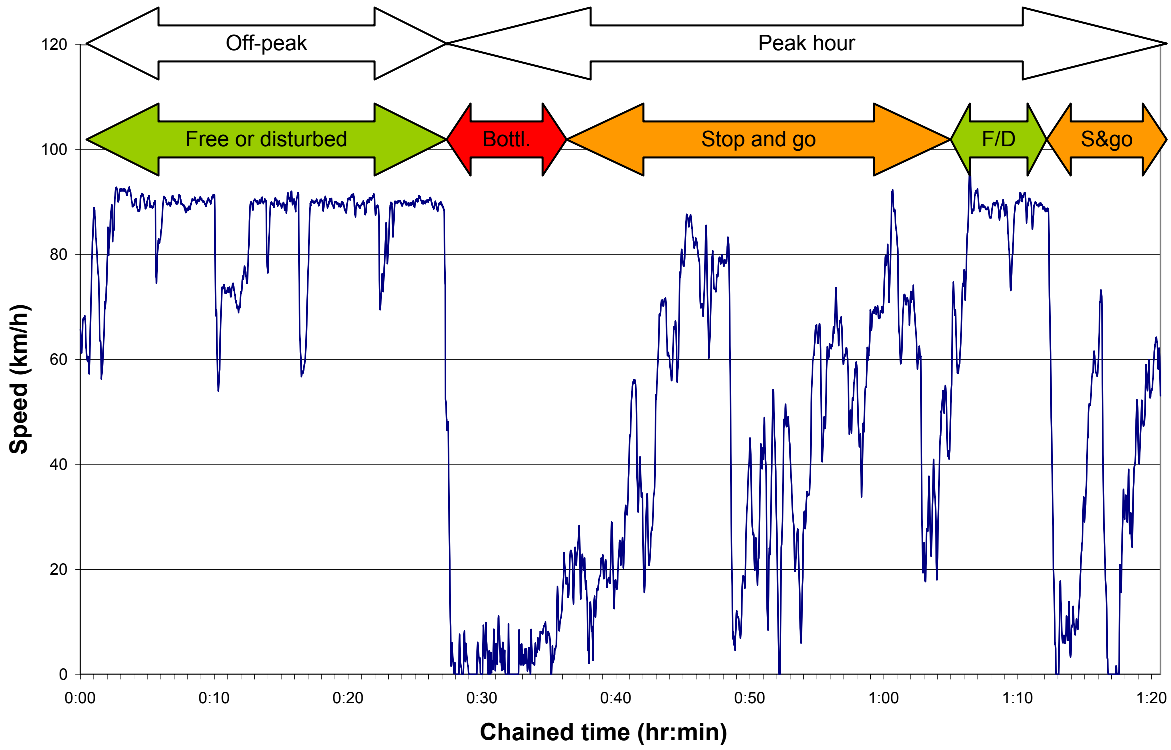

Figure 5 – Speed diagram

In fact, it was advisable to separate, in the case of the "fluid flow", the cases with and without disturbance, so as to be able to cover all the range, from the free flow without any disturbance to the case of bottleneck. In what follows, the case "fluid" will thus be split into two: "free" and "disturbed". Table 2 displays the statistics of the so defined cases.

Table 2 – Average and standard deviation of speed, accelerations and fuel consumption

	Traffic			
Data	**Stop & go**	**Bottleneck**	**Free**	**Disturbed**
Average speed km/h	46.01	3.74	89.88	74.37
Speed standard deviation km/h	23.09	3.78	1.13	8.92
Acceleration standard deviation m/s²	0.42	0.32	0.11	0.38
Average fuel consumption L/hr	3.38	1.39	5.09	5.11
Fuel consumption standard deviation L/hr	2.72	0.87	1.85	2.85
Average fuel consumption L/100 km	7.35	37.11	5.66	6.87

4.3. Fuel consumption model calibration

The applied simulation principles are the same as on the road circuit, with the following differences:

- Road data were set to constant values,
- Accelerations were measured and not calculated,
- Engine speed was calculated according to the calibrated HDM formula.

On the other hand, the consumptions are expressed in litres per hour and not in litres per 100 km, considering the periods when the vehicle was stopped in bottlenecks. The calibration resulting from track tests, and adjusted on the road circuit data, led to good results, except at very low speed, what led to increase the “idle” parameter, and to return to the initial "track” calibration for the power-to-fuel relation.

5. APPLICATION TO ROAD WORKS

5.1. Speed model

The relations between traffic flow and speed are the object of numerous models, more or less complex, which may describe many situations [11]; the macroscopic models (which assimilate traffic to a fluid) consider that, at a given time t on a point which abscissa is x, the instant traffic flow is $Q(x,t)$ and the instant speed $V(x,t)$; The number of vehicles can be expressed in "all vehicles" data (flow expressed in vehicles per hour, veh/hr), or in Passenger Car Space Equivalent (PCSE), taking into account the space occupied by the various categories of vehicles. The occupation rate is defined as $R(x,t) = V(x,t) * Q(x,t) / Dmax$ where $R(x,t)$ is expressed as the ratio between the observed density (in veh/km or PCSE/km) and a theoretical maximum of density D_{max}. Between both extremes (free traffic and bottleneck), the maximal flow is reached for a "critical rate", associated with a critical speed V_c and a critical flow Q_c. If $Q > Q_c$, a bottleneck situation occurs, with formation of a queue. To simplify, the proposed model considers here that the flow / speed curve is a parabola, which cuts the Y axis at zero and at the maximal allowed speed V_{max}; this implies a critical speed V_c equal to $V_{max} / 2$. The speed is then calculated as follows:

$$V = V_c * (1 + \sqrt{1 - \frac{Q}{Q_c}})$$

This formula can naturally apply only if $Q \leq Q_c$; beyond that, only a flow equal to Q_c continues to run, the extra vehicles forming then a queue, which moves at the speed observed in a bottleneck situation. In these conditions, a given vehicle can reach the point of abscissa x only after a given time, which can be calculated (the FORMAT model does so). However, the transition between the "critical" situation and the bottleneck is difficult to model, because of its chaotic character (in the reality, a simple brake by a single driver can be enough to create the bottleneck). In the FORMAT model, this kind of effect is eased by the probabilistic character of the variable Q (which takes simultaneously several values to which are attributed various probabilities). In order to keep the calculation simple while remaining realistic, the speed through the work site was considered in what follows as equal to the critical speed. The critical flow Q_c applicable to the Nantes ring road was estimated, on the basis of SIREDO counts [12] (devices distributed on the whole national network, and which perform continuous counts of vehicles), at 4 700 veh/hr for one direction (maximum observed in 2002).

5.2. Acceleration model

Most of the models (including HDM) assume the additivity of the squares of accelerations, the causes of which are diverse, due on one hand to the vehicle and driver (γ_0 observed in the total absence of disturbance, here 0.1 m/s ², see Table 2), and on the other hand in the disturbance caused by the rest of the traffic, γ_1. The resultant is then $\gamma^2 = \gamma_0^2 + \gamma_1^2$. In the "stop and go" situation, the resultant equals (still as a root mean square) 0.42 m/s², and this, if one considers that γ_1 is proportional to the flow, yields a maximum γ_{1max} of 0.41 m/s². The formula giving the acceleration is therefore:

$$\gamma = \sqrt{\gamma_0^2 + (\frac{Q}{Q_c}\gamma_{1\max})^2}$$

5.3. Flow model

In the framework of the FORMAT project, a probabilistic model was developed to predict traffic flows. This model considers, for a given type of day (for example an off-summer week day), an evolution summing up a base value and three bell-shaped curves, according to the formula:

$$Q_p(t) = a_0 + \sum_{i=1}^{i=3} a_i * \exp(-\lambda_i * (t - m_i)^2) + \sigma * N(p)$$

where:

- $Q_p(t)$ is the hourly vehicle flow in one direction, function of time t and probability p,
- Function $N(p)$ is the standard normal distribution,
- Parameters a_i, λ_i, m_i determine the three bell-shaped curves,
- σ is the standard error (root mean square of residuals, i.e. differences between observations et prediction).

These ten parameters may be calculated by means of a non linear regression. The studied case will be based on data collected on the Nantes ring road (SIREDO 2002 data), for days defined as "week days" (in fact, Fridays, Wednesdays and Thursdays, excluding holidays) and "off-summer" (which excludes July and August months). The results of the formula, for various probabilities, are displayed on Figure 6.

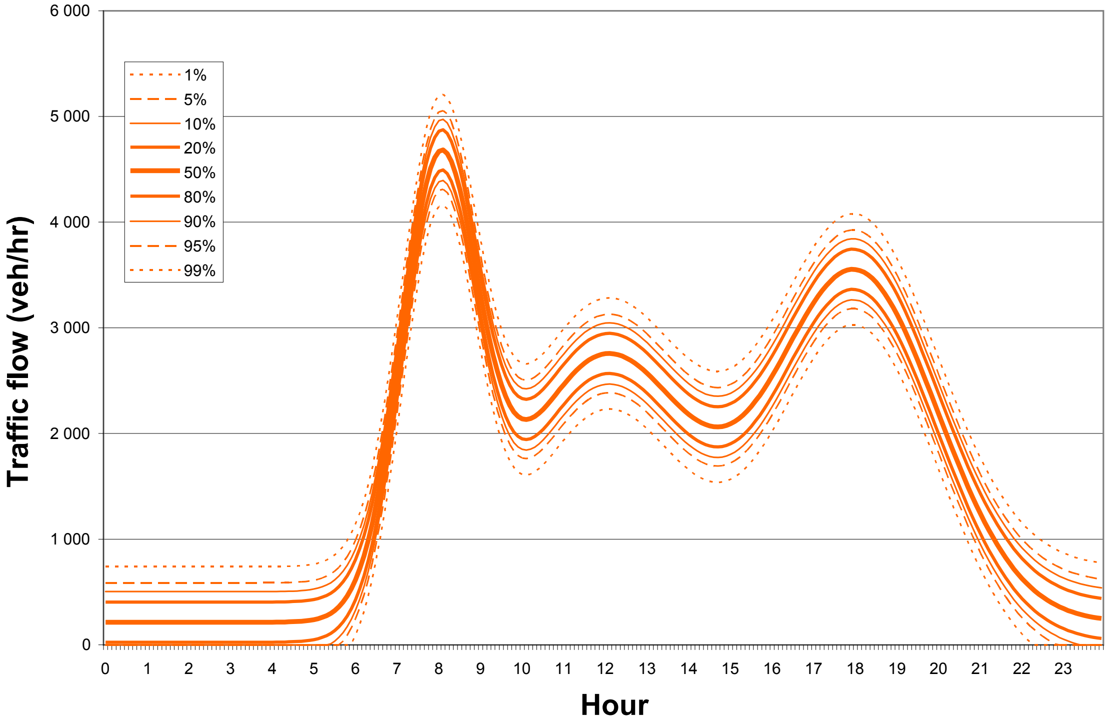

Figure 6 – Probabilistic calculation of traffic flows

5.4. Road works simulation

On the basis of previously defined elements, a simple work case was considered, with prediction of the consequences for the user (in this particular case, the one who would use the test vehicle), in travel time, fuel consumption and CO_2 emissions. The considered works implies the closing of one of two traffic lanes of the carriageway at a given hour t, on a 5 km length. The considered vehicle arrives on the zone one hour after the closure, i.e. at time $t + 1$. The following hypotheses were made about the traffic demand and the road residual capacity:

- Traffic demand remains unchanged, for the same time, whatever the congestion (no driver try to change his/her route, and no one cancels his/her trip);
- The road residual capacity equals half its normal capacity;
- The posted speed limits remain unchanged during works (Logically it should be 70 km/h but considering the flow this speed would be exceeded only during off-peak periods).

The following calculations were performed:

- Traffic flow, as a function of time t and probability p, according to the FORMAT model formula ;
- Waiting time from FORMAT;
- Speed and acceleration from previously defined formulae;
- Engine speed according to the HDM formula calibrated for an “economical” driving;
- Consumption from calibrated HDM formulae;
- CO_2 emissions proportional to consumptions (2 390 g per litre of fuel);
- Mathematical expectancy for travel time, consumption and CO_2 emissions.

Figures 7, 8 and 9 display respectively the travel times, fuel consumption and CO_2 emissions, as a function of the time t of the lane closure. The three components are:

- The value which would be expected in “normal” times;
- The “slowdown”, difference between situations with and without works, limited to the work zone;
- The “waiting” time before entering the work zone.

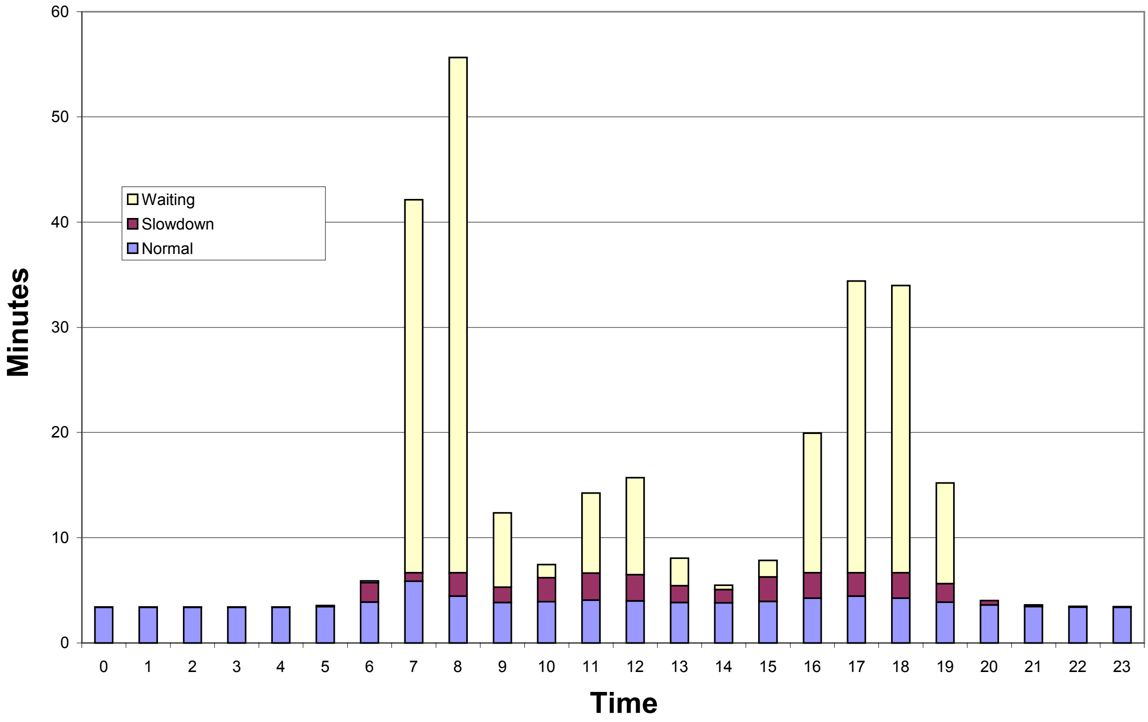

Figure 7 – Travel time on the considered work site

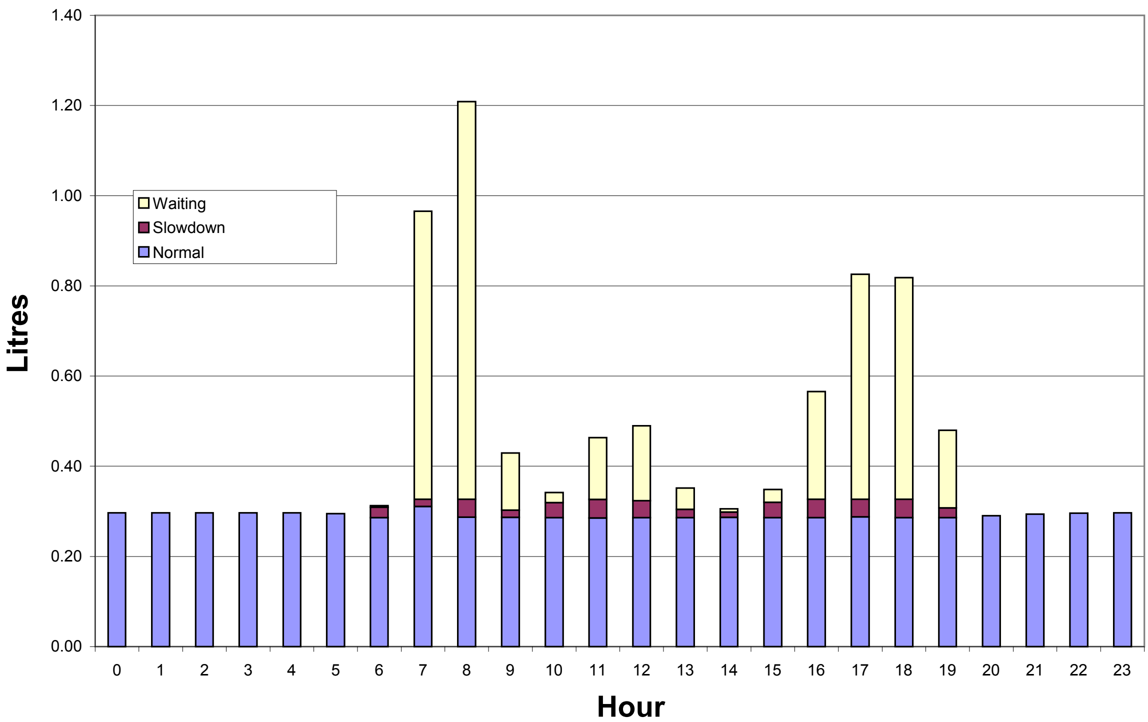

Figure 8 – Fuel consumption on the considered work site

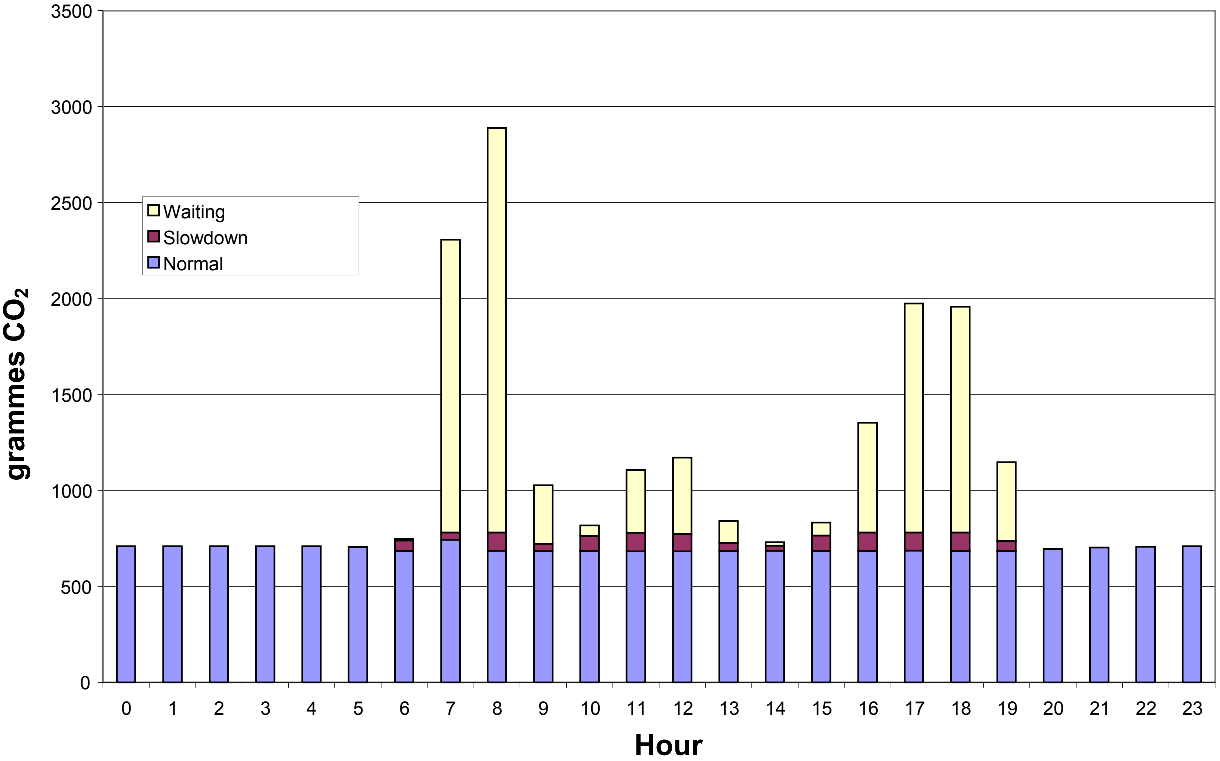

Figure 9 – CO_2 emissions on the considered work site

6. CONCLUSIONS AND PERSPECTIVES

6.1. The model

A model can be proposed for the calculation of fuel consumption by a light vehicle of a given type (petrol-driven sedan), according to the characteristics of the road (geometry and condition) and traffic flows (speeds and accelerations practised by a typical driver). The studied cases allow to take into account about any type of road, since the narrow local road up to the motorway, from free flow down to traffic bottleneck.

6.2. Extension to a diversified traffic flow

The main limitation of the model such as it is proposed is that it was validated on one vehicle, and the hypothesis according to which all the vehicles in circulation would be similar to it is not acceptable. However, the model is essentially based on laws of nature, what allows to extend it without any trouble to similar vehicles, but with different characteristics (such as mass, power, dimensions of tyres). It would thus be advisable to segment the current vehicle fleet by classes of size and by age brackets, for which the power-to-fuel ratio calibrations would be different. A specific calibration should also be applied to the Diesel motor vehicles. As for trucks, the task is more difficult, because they do not make a homogeneous set, and a similar experiment of consumption measurement would require very big means. The application of the model remains however possible, on the condition of exploiting the available data, notably from transport professional associations or fleet operators.
Finally, a further task will consist in converting the "static fleet" (distribution of registered vehicles at national level) into the "rolling fleet" (vehicles running on a given road section) according to the previously defined typology.

6.3. Interface with the FORMAT model

The FORMAT model (existing at present as a spreadsheet prototype) allows to estimate users travel time, as a function of traffic demand including its variations, the characteristics of the road and those of a possible work site (for which one defines the schedule, the calendar, the type of lane closure, the proposed diversions, etc.). In this way, it calculates the consequences of works, concerning time lost by users. It thus remains to complete this model, by using the intermediate data which it generates, such as the traffic flows by lane, to describe the conditions of traffic flow and predict the fuel consumptions. It will consist in inserting into the spreadsheet the calculation formulae applied in the present study. A later step will consist in "hard coding" all the formulae and relations of the completed model, so that they may be part of professional road management software, such as SAGIR [1] in the future.

6.4. Emissions from vehicles

Pollutants emitted by vehicles into the atmosphere have two main consequences: at the local level the toxicity for the human health, and at the global level the greenhouse effect, which is the cause of the global warming. Other effects concern more specifically the biosphere, as it is the case of the acid rains. The main atmospheric pollutants emitted by vehicles are:

- Carbon dioxide CO_2 (main greenhouse effect gas),
- Carbon monoxide CO (toxic),
- Sulphur dioxide SO_2 (toxic and acidifier),
- Nitrogen oxides NO_x (toxic and acidifier),
- Unburnt hydrocarbons (methane CH_4 is a greenhouse effect gas, and aromatic compounds are carcinogen),
- Solid particles (carcinogen and dirty).

Among these emissions, two of them may be evaluated easily from consumed fuel amounts:

- CO_2 has already been mentioned here above; It is indeed the form under which is emitted almost all of the carbon (the other carbon emissions, such as hydrocarbons, CO and soot particles, are much weaker in quantities, but more annoying); and the carbon contents of fuels are constant and well known;
- SO_2, form under which is emitted all of the sulphur contained in the fuel, may also be easily calculated (the sulphur content of fuels is subject to regulations).

As for other pollutants, things are more complex, because amounts depend on the engine operating parameters, and on the presence of antipollution devices (such as catalytic converters and particulate filters); European standards set limits, expressed in g/km, for new vehicles, but amounts emitted by existing vehicles are more difficult to assess.

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