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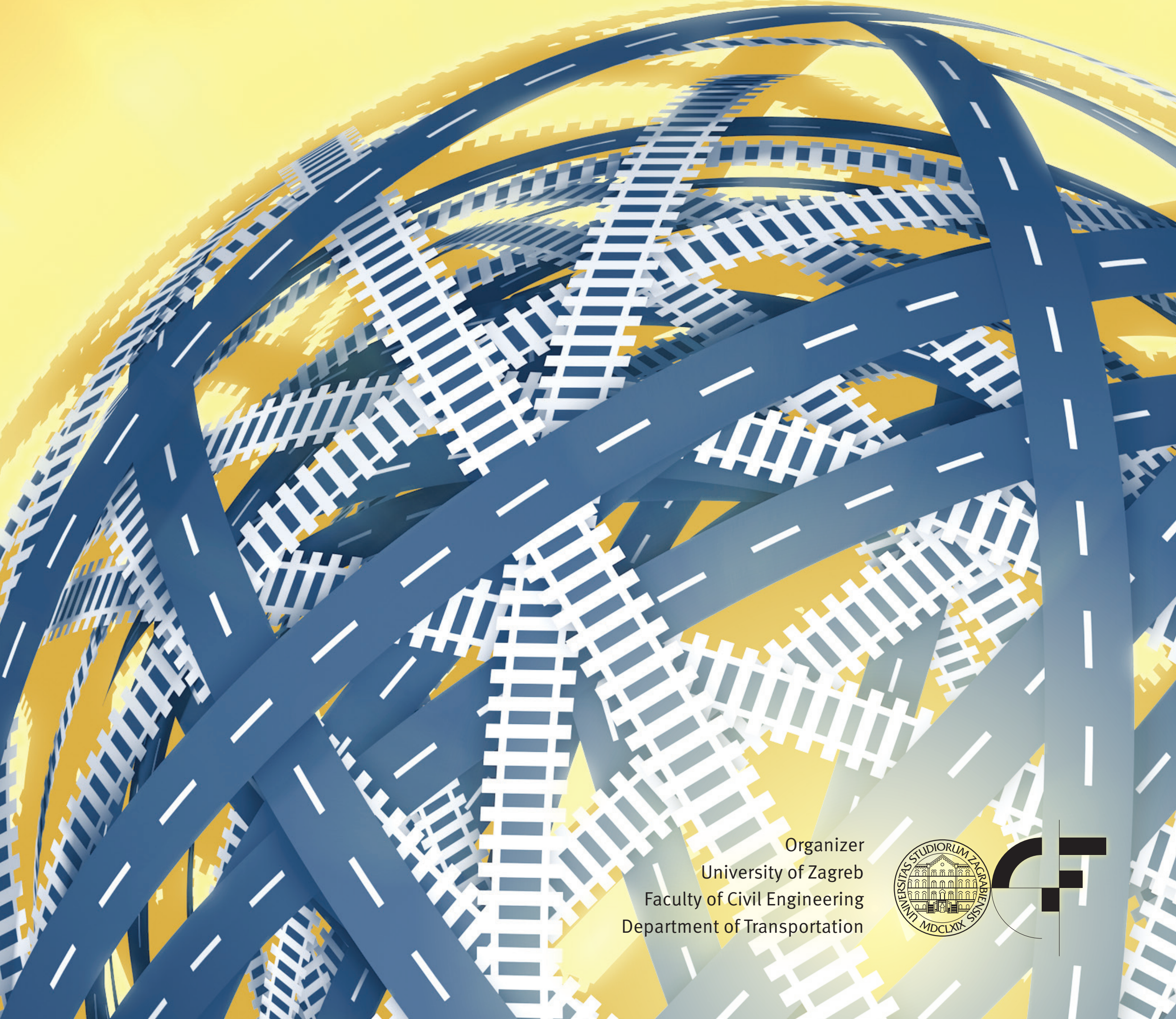
23–25 May 2016, Šibenik, Croatia

Road and Rail Infrastructure IV

Stjepan Lakušić – EDITOR



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ECODRIVING POTENTIALITY ASSESSMENT OF ROAD INFRASTRUCTURES ACCORDING TO THE ADEQUACY BETWEEN INFRASTRUCTURE SLOPES AND SPEEDS LIMITS

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Abstract

The energy associated with the use of road infrastructure exceeds in few years the energy needed for its construction. The link between infrastructure and use energy has not been, however, studied in depth, particularly as the legitimate transport societal expectations are related to efficiency and safety. However, we can consider reducing the energy use by working out minor optimizations of the road infrastructure itself, which is a major challenge in a context of overall decrease of resources and increasing pressures on the environment.
Experimental work is carried out here to develop one of these optimizations by improving the eco-driving potential of roads. It is based on the adequacy between vehicles dynamics, the road longitudinal profile and the speed sectioning of the infrastructure. This sectioning corresponds to the succession of speed limitations (road signs, roundabouts, intersections…). It may allow drivers to eco-drive or not, depending on dynamics, slopes, and secondary parameters as driver reaction time or distance of visibility. Optimal speed sectioning aims to limit the mechanical braking needed by potential energy reduction, due to slopes, which can be encountered simultaneously with the needed kinetic energy reduction.
Evaluation has been made on actual road sections, while recording both vehicle dynamics, driver commands, road signs positions and road longitudinal profile. Results show that energy consumption of vehicles approaching a speed reduction sign can be reduced by moving backward this sign of about 700 meters, without penalizing the primary safety function. The associated gain, for this optimization, has been evaluated to 14 liters of fuel per day for one of the experimental sites, considering traffic data. Application of this method on a network could then lead to considerable energy saving by allowing eco-driving.

Keywords: Eco-design, Eco-driving, energy consumption, use phase, road infrastructure, longitudinal profile, vehicle dynamics, full-scale experiment, public policy

1 Introduction

Roads have mainly been designed by considering criteria of safety, mobility and cost. Up to now, researches focused on these criteria have contributed to the enhancement of roads [1], [2], [3], but it has often been done regardless of the energy aspects of the infrastructures. Nowadays, constraints on resources availability and environment issues have also to be taken into account for infrastructure design or exploitation, in the aim to minimize energy consumptions needed to construct, maintain and operate infrastructures. In Europe, transport systems require a large part, 32%, of the global energy demand [4]. Furthermore, 81% of the transportation used energy is consumed by road transport [5]. Reducing this energy demand is then a key point in fossil resources savings and to mitigate the associated impacts of air pollution [6].

Many countries have promoted Eco-driving as a key element of national strategies to reduce GWP emissions (see for example the european project Ecodriven). However, these research efforts focuse on drivers and cars but not on the infrastructure.
Without altering safety and with small concessions to costs and efficiency, alternatives designs of roads can lead to variations of operation phase consumptions, which represent the energy used by the vehicles traveling on them. Slopes and speed limits are the most evident design or management parameters which can influence significantly operation phase energy consumptions [7], [8].
The originality of this work is that it focuses on the conjonction of vehicle speed limits, vehicle dynamics and infrastructures slopes, whereas most of preceeding works have addressed theses parameters separatedly. Energy consumption linked to of the infrastructure operation phase is considered here, regardless of other contributing phases as construction and maintenance, since our aim is focused on the exploitation of the infrastructure, in a first stage.

2 Experimental phase

2.1 Methodology and setup

Several experimental campaigns have been done with a lightly instrumented vehicle on various secondary roads. 3D Vehicle positions are acquired at a fixed frequency of 1Hz with the help of a GPS Usb module “Garmin” and the “gpspipe” command on a linux-based computer (Fig. 1). High resolution pictures have been captured at chosen instants, corresponding at the perception time and passing time of each road sign. As the computer clock is synchronise with the GPS time, pictures have been afterwards geotagged with the help of a GPS correlation algorithm.

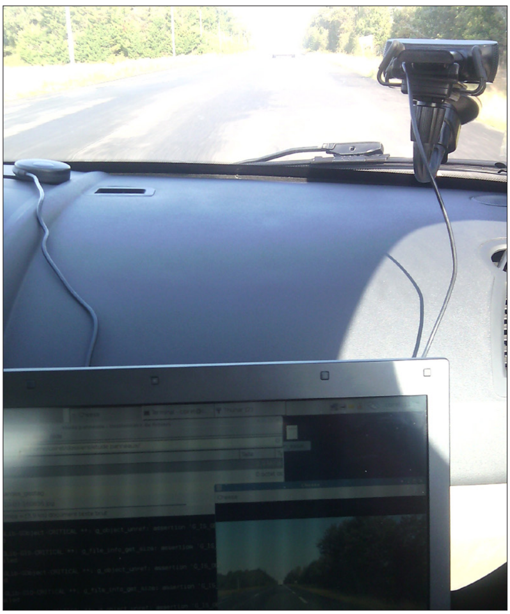

Figure 1 Simple experimental setup; linux-based acquisition computer, Usb GPS module (upper-left), Carl Zeiss Hd1080 camera (upper-right)

Fig. 2 exhibits the acquired data for the particular campaign that is used in this paper. Fig. 3 shows that the GPS precision in space and in frequency is rather satisfying, considering the relatively low speed of the vehicle and the dimensions of the road infrastructure details. Indeed the plotted GPS trace under the Geographical Information System "GpsPrune" is rendering correctly the roundabout visible in the map given in the right part of the figure. Fig. 4 given a large-scale rendering of the 3D GPS trace, as a primary verification of the vertical measurement quality.

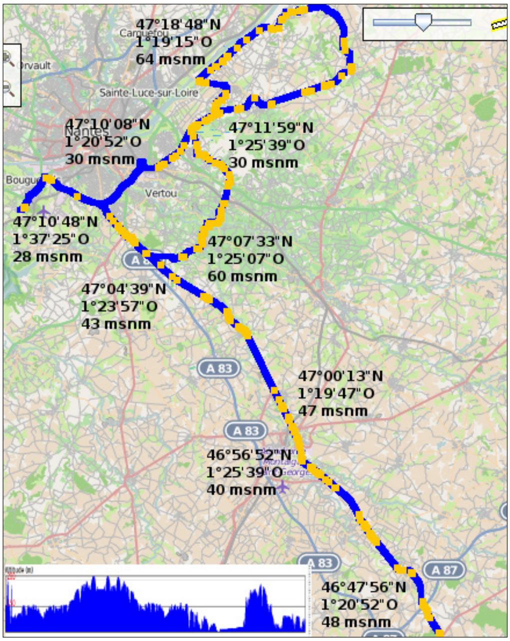

Figure 2 Experimental travelled path around Nantes (GPS trace in blue, taken geotagged photos indicated in yellow)

Figure 3 Left: GPS trace Geographical Information System; right: Map

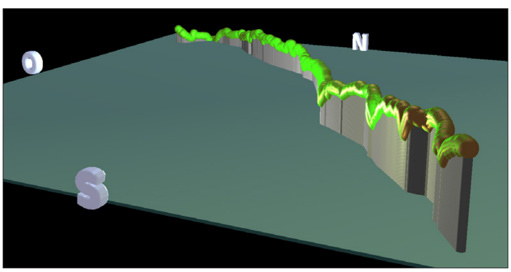

Figure 4 Rendering example of the 3d trace (50x-enhanced Z component)

3 Energy assessment

3.1 Eco-driving potentiality

In this section, we will consider the crossing of the small village “La Brossière”, as despicted in Fig.5. The village is represented in grey on the map and the elevation graph gives first information on the fact that this village is in a “bowl” situation (ie; both of the two village entrances present rather high downhill slope). 16 pictures have been recorded while crossing the village in the two directions, north to south and then south to north. For situating this, these pictures are represented by the southest yellow points in the Fig.2, near the “A87” label.

Figure 5 Experimental car entering in “La Brossière” (and map/elevation)

These geotagged photos can be departed on two sets as presented in Fig. 6 on the GPS trace. Each set, for each travelled direction D_1 and D_2, correspond successively to: the view of the village entrance sign, the crossing of this sign, the view of a sign signalling the entering in a 30 km/h limit zone, the crossing of this sign, view of the ending sign of the 30 km/h zone, its passing position, and finally pictures at first viewing time and passing time positions of the village exit sign. For this considered experimental case of a village in a “bowl” configuration, the necessity to use mechanical brakes for conforming to speed limits is highly probable. For energy consumptions of vehicles, it is clear that it is preferable to decrease speed without braking, by anticipating and avoiding to use energy in excess before reaching the point of speed limit; mechanical braking is a waste of precedently unecessary used energy, in the form of heat. Resort to mechanical braking due to a road sign depends on several parameters:
- road sign sight distance, that is influenced by road curvatures or slopes;
- altitude difference between the sign and the position of its viewing by drivers;
- the reduction in speed imposed by the road sign;
- the level of rolling resistance and aerodynamical resistance of each vehicle;
- the perception-reaction time of the driver; its behavior.

Ecodriving potentiality of a road infrastructure, around a point of change in speed limit, could then be associated in first approximation to differences in speed, difference in altitude, independantly of specific vehicle characteristics as advancement resistance.

Considering a given vehicle with a M mass, traveling at V_1 speed at the position P_1 of altitude h_1 at which a road sign becomes visible. If the road sign impose the speed limit of V_2, at the position P_2 of altitude h_2, the kinetic energy to lessen is;

$$E_c = 1/2M\left(V_1^2 - V_2^2\right) \tag{1}$$

Besides that, its variation of potential energy is;

$$E_p = Mg\left(h_1 - h_2\right) \tag{2}$$

with g the gravity acceleration, taken equal to 9.81 m/s².

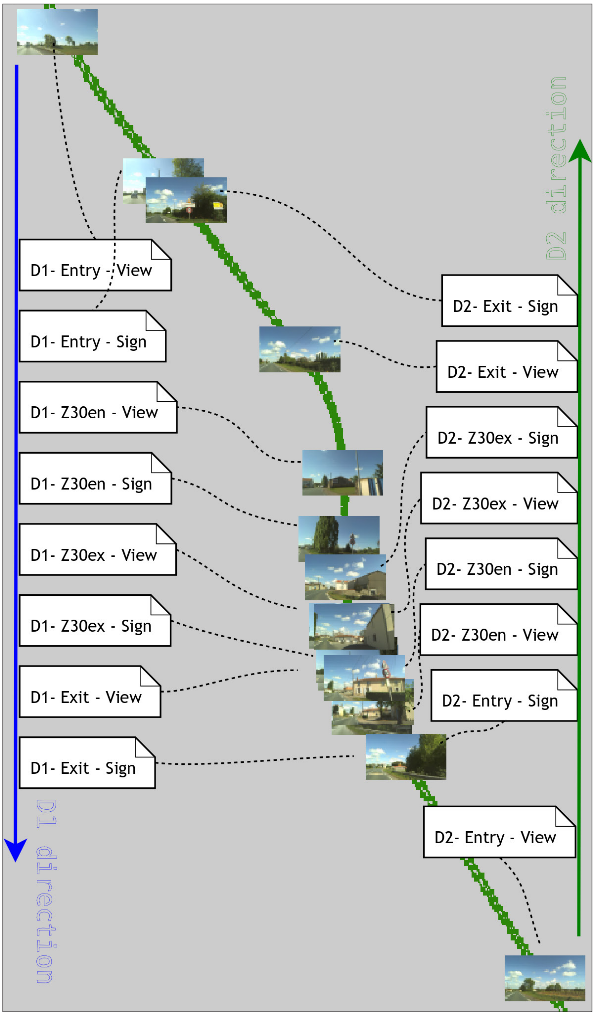

Figure 6 GPS trace and geotagged pictures taken while crossing the "La Brossière" village in the two D_1 and D_2 directions

As an infrastructure-related indicator of eco-driving potentiality, we choose to retain the ratio between the potential energy to the sum of potential and kinetic energy. Indeed, a positive potential energy (downhill) is less favorable than a negative one (ascent) to avoid the resort to mechanical braking. We define this ratio as the following gain criteria G_{opt};

$$G_{opt} = \frac{E_p}{\left(E_p + E_c\right)} = \frac{Mg\left(h_1 - h_2\right)}{Mg\left(h_1 - h_2\right) + 1/2M\left(V_1^2 - V_2^2\right)} = \frac{1}{1 + \dfrac{1/2\left(V_1^2 - V_2^2\right)}{g\left(h_1 - h_2\right)}} \tag{3}$$

This criteria depends only on the speed sectionning and road signs positions and is easy to compute. In our application case, for the positions labelled "D_2 – Entry – View" and "D_2 – Entry – Sign" in the Fig.6, numerical datas are:

- the distance between the two positions is of 300 meters. Nethertheless this distance does not contribute to this first step of road network evaluation with the G_{opt} criteria;
- the respective altitudes are 189.7 m and 178.7 m (difference of 11 meters);
- the speed has to be reduced to 50 km/h from 90 km/h (reduction of 11.11 m/s).

This case (see Fig.7) is then associated to a high potential energy equal to 49.9 % of the kinetic energy. The G_{opt} gain is then equal to 33%, that is to say that the potential energy is equal to the third of the total energy that has to be cut down (potential and kinetic).
Another example can be considered: between the positions labelled "D_1 – $Z30_{en}$ – View" and "D_1 – $Z30_{ex}$ – Sign" (Fig.6), altitudes are of 181.6m and 179.6m, speed has to be reduced to 30km/h from 50 km/h, potential energy equal to 31.8% of the kinetic energy and G_{opt} is equal to 24%.

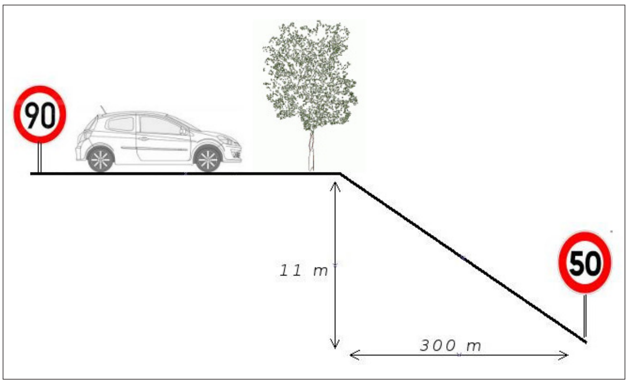

Figure 7 Test case: deceleration imposed in descent

3.2 Energy assessment

In order to assess the energy gains associated with the G_{opt} eco-driving criteria, we have modeled the energy losses by aerodynamic drag and rolling resistance for specific test vehicle, a Renault Clio III. The computation of these energy losses are performed by considering that the driver releases the acceleration pedal (coasting phase) as early as he sees the sign of the limitation speed. In this phase, the fundamental dynamics leads to the following differential equation between the speed and the resistance forces:

$$\dot{v} = \left(\frac{1}{2} C_x S_x v^2 + Mg\left(C_{rr} + \sin(\alpha)\right)\right) / M \tag{4}$$

With C_x the aerodynamical coefficient, equal to 0.32, S_x the vehicle frontal area equal to 2.25 m², C_{rr} a fixed rolling resistance coefficient equal to 0.1, α the mean longitudinal slope.

Eq.4 has been solved numerically, yielding to the computation of speeds and positions, energy losses being the work of the resistance force. For the precedently selected test case at "La Brossière", with a sight length of 300 meters, a 11 m difference in altitude and a 11.11 m/s requirement in speed reduction, the mechanical braking need is of 246.9 kJ. With a road sign placed 700 m upstream, this requirement would be lowered to 139 kJ.
Considering standard daily trafic datas in terms of light and heavy vehicles, theses two braking energy can be converted in fuel equivalent costs of respectively 44.7 and 30.7 liters. Practicaly, in this case, the displacement of a simple road sign could lead to a daily gain of 14 liters of fuel and roughly 34 kg CO_2 emissions. The accuracy of these results could be improved by using several car models and by refining the trafic estimation. However, the actual investigations proves the significant fuel saving achievable by the displacement of a single road sign.

4 Conclusions

This work focused on the use phase of road transportation. It highlights that if potential energy has to be reduced in the same time that kinetic energy, due to the presence of a road sign for example, ecodriving could not be allowed and drivers could be force to resort to mechanical braking. Experimental work based on the adequacy between vehicles dynamics, road longitudinal profile and speed sectioning of the infrastructure has allowed to identify points of road network for which a chosen indicator points out an ecodriving potentiality issue. A further energy assessment at one of these points has shown that energy consumption of vehicles approaching a speed reduction sign can be reduced by moving backward this sign of about 700 meters, without penalizing the primary safety function. The associated gain, for this optimization, has been evaluated to 14 liters of fuel per day for one of the experimental sites, considering traffic data. Application of this method on a network could then lead to considerable energy saving by allowing eco-driving.

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