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Management of road speed sectioning to lower vehicle energy consumption

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Abstract

Efforts to limit climate change should concern the transportation sector which is responsible for roughly a quarter of greenhouse gas emissions. Aside from vehicle's technical progress and driver eco-driving awareness, road infrastructure has a role to play in this environmental aim. At the project stage, the design of roads can avoid energy losses linked to marked ramps, but afterwards, during the use phase, road management can be a lever too.

In this use phase framework, our paper is focused on energy saving that can be achieved by managing speed sectioning. The key point is to ensure consistency between vehicle dynamics, road longitudinal profile and speed policy. Indeed, eco-driving could be impeded if a limiting speed sign is encountered on a steep slope or in a sharp turn. In such a situation the speed sign will be qualified as misplaced. Mechanical braking has then to be used instead of simple natural deceleration. In 2018 the French government lowered authorized speed on secondary roads, from 90 to 80 km/h, with road safety as the primary motivation. In order to assess energy impact of speed-sectioning for these two speed limits, experiments have been carried out in four experimental sites. Furthermore criterion and dissipated energy computation have been developed. The developed energy computation yields to determine the expected fuel economy for the entire traffic over a day on a selected route or network.

As a result, over consumption for a misplaced speed sign can reach up to 40 liters of fuel per day with an approaching speed of 80 km/h and 50 liters of fuel per day with an approaching speed of 90 km/h according to traffic data. Significant energy savings could therefore be achieved by sign placement optimization.

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Keywords: road ; vehicle consumption ; speed management ; eco conception ; climate change

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1. Introduction

To maintain global warming below 1.5°C one of the needed actions is to achieve a 15% energy reduction of the transportation sector by 2050 compared to 2015 (Rogelj et al., 2018).

Road vehicle emissions can be lowered by several means to comply with this environmental emergency. The most simple but less acceptable mean is to limit the global use of cars generating CO_2. This is particularly sensitive in low density cities and suburban areas where car dependency is high (Gao et al., 2018).

Beyond that, car manufacturers are continuously enhancing motors and vehicles' efficiency, thus it should contribute to lower transport energy use. But society expectations are limiting this benefit, with a strong demand for Sport Utility Vehicles, generalization of air conditioning, accumulation of safety equipment linked to heavier vehicles. As an example, in the Canadian vehicle fleet there has been a 287% growth of SUV part between 1989 and 2002, followed by minivans (160%) and pickup trucks (34%), and a 2% fall of the passenger cars part (Fredette et al., 2008).

Moreover, with a given vehicle, energy use can be reduced by drivers while applying learned or instinctive eco-driving behaviors. For that, most involved actions in eco-driving are acceleration and deceleration maneuvers, driving speed and route choices (Huang et al., 2018).

At last, infrastructure can be designed and managed in order to lower its energy demand, and even to favor eco-driving. Road infrastructures have been far less studied in this aim than vehicle efficiency or drivers behaviors since roads are usually seen as unchangeable energetic constraint. Nevertheless some studies have shown that infrastructure has a significant role to play to reduce vehicle fuel consumption. For example, a recent report of the Federal Highway Administration has shown that fuel consumption savings from 2 to 21 % could be attributed to driving conditions facing varied terrain conditions such as slopes (Jiaqi et al. (2017) and Park and Rakha (2006)). Design of roads can be energy-efficient oriented too, while considering both building and use phases of infrastructures (Vandanjon et al., 2019).

Road exploitation can be optimized too in order to save vehicles use energy. Indeed, there are some locations on a route where drivers apprehend a speed-sectioning change without having the necessary distance to decelerate. Then they have to brake heavily and they are deprived of eco-driving possibility. In fact, better adequacy between road slope and speed sectioning could avoid resorting to brake and lower beforehand speed and energy consumption.

Then eco-driving can be favored by improving consistency between vehicle dynamics, longitudinal road profile and the succession of speed limits. Road exploitation can be oriented to optimize this succession of speed limitations by road signs, roundabout and crossings, that can be called speed sectioning. In this case, benefit of changing a road sign position has been demonstrated in situations where vehicles are forced to decelerate on slopes (Coiret et al., 2016).

Approaching speeds are of importance too. Particularly, in France where government has decided to lower speed limits of secondary roads from 90km/h to 80km/h, for safety reasons, the lowering of vehicle approaching speed should lower the energy waste of an inadequate speed sectioning.

In this work the impact of a given speed sectioning is analyzed at four experimental sites, by developing a detection criterion and energy evaluation, for both approaching current and former allowed speeds of 80 and 90km/h. After that, this energetic evaluation will be extrapolated to a realistic traffic and daily energy impact of a given speed sectioning will be determined for each speed and situation case.

2. Road speed-sectioning eco-driving Criterion

In the following a criterion is established to evaluate if a decreasing speed sectioning is susceptible to impede eco-driving. For that a road speed sign is considered to be misplaced, in the eco-driving meaning. This speed sign is placed at the MSP position which stands for Misplaced Speed-sectioning Point. The SPD position is also defined as the position where the driver apprehends the speed sign and applies an effective command to decelerate, i.e releasing the gas pedal, SPD standing for Starting Point of Deceleration. The approaching speed of vehicles is V_{SPD} and the restricted speed imposed by the speed sign is V_{MSP} (with the hypothesis of a speed sign imposing a deceleration, $V_{MSP} < V_{SPD}$.)

To evaluate if eco-driving is allowed, driver is considered to release the gas pedal as soon as he sees the speed limiting sign, thus initiating its decelerating maneuver at the SPD point and for the d_{man} distance before reaching the MSP speed sign location. Speed sectioning maximizing eco-driving potential should result in reaching the sign location at exactly the V_{MSP} speed, just by natural deceleration, without braking.

The evaluation criterion is based on the dissipation energy by rolling without braking nor accelerating between the MSP and SPD points, with associated speeds of V_{MSP} and V_{SPD}.

The energy to be removed for a given vehicle of mass m between the SPD and MSP points is:

$$\Delta Em = \Delta Ek + \Delta Ep \tag{1}$$

with $\Delta Ek = \frac{1}{2}m(V_{SPD}^2 - V_{MSP}^2)$ and $\Delta Ep = mg(h_{SPD} - h_{MSP})$ with h_{SPD} and h_{MSP} the respective altitudes at SPD and MSP points.

The desired first level criterion aims to be vehicle-independent for a convenient use by road managers. However dissipation forces are car-specific. Particularly rolling and air resistance are linked to the mg weight, directly for the rolling resistance and indirectly for the aerodynamic drag. This energy being an integration of power along the maneuver distance, a dimensionless criterion is proposed χ_{EASM} (EASM standing for Energy Alert Speed Management):

$$\chi_{EASM} = \frac{\Delta Em}{mg \log_{10}(d_{man})} \tag{2}$$

where d_{man} is the driver maneuvering distance, which separates SPD and MSP points. It is assumed that $\log_{10}(d_{man}) > 0$.

This distance is active through a logarithm function because an important part of the dissipation is the aerodynamic drag which decreases as the vehicle decelerates along the maneuver distance.

By developing this equation, the criterion is independent of vehicle parameters (first term linked to kinetic energy and second term linked to potential energy):

$$\chi_{EASM} = \frac{1}{2}\frac{V_{SPD}^2 - V_{MSP}^2}{g \log_{10}(d_{man})} + \frac{h_{SPD} - h_{MSP}}{\log_{10}(d_{man})} \tag{3}$$

Road managers have therefore a convenient criterion to evaluate their network speed transitions, since a low value of this criterion indicates a better eco-driving potentiality of a speed sectioning point.

3. Energy evaluation of a Misplaced Speed-sectioning Point

The criterion χ_{EASM} defined in the preceding section is improved towards an energy assessment, E_{MSP}, which takes into account more explicitly vehicle dissipating forces.

The vehicle is modeled by a point in a natural deceleration situation from V_{SPD} to V_{MSP}. Applied forces are:

- the aerodynamic drag: $\frac{1}{2}\rho S C_d w_a{}^2$, with ρ the air density, S the frontal surface, C_d the drag coefficient, w_a the apparent wind (temporary assumed to be equal to the speed v)
- rolling resistance: mgC_{rr}, with m the vehicle mass, g the acceleration of gravity, C_{rr} the coefficient of rolling resistance,
- internal forces of the vehicle : F_i which sums frictions and motor resistance, according to the engaged gear and auxiliaries components,
- the gravity forces: $mg\sin(\alpha_r)$, with α_r the angle of the slope in radian.

The following equation is obtained

$$\dot{v} = -\Big[\frac{1}{2}C_d S v^2 + (mg[C_{rr} + \sin(\alpha)] + F_i)\Big]/m \tag{4}$$

And so:

$$\dot{v} = a v^2 + c \tag{5}$$

with $a = -(\frac{1}{2} C_d S)/\mathrm{m}$ and $c = -\mathrm{g}[C_{rr} + \sin(\alpha)] - F_i/\mathrm{m}$

In the case of the simple, but usual, configuration without variation in slope, the analytical solution of this ordinary differential equation is:

$$\mathrm{v}(t) = -B \tan(A(t + K)) \tag{6}$$

with $B = \sqrt{c/a}$, $A = \sqrt{ac}$, $K = -\arctan(\mathrm{V_{SPD}}/B)/A$.

The integration of the last equation yields to the travelled position x as a function of time:

$$\mathrm{x}(t) = E \times \left(\log\left[\cos\left(A \times (t + K)\right)\right] - \log\left(\cos\left(A \times K\right)\right) \right) \tag{7}$$

with $E = 1/|a|$.

By setting the boundary condition $\mathrm{x}(t) = \mathrm{d_{man}}$ and by inverting Equation 7, it yields that the time t_f taken by the vehicle to travel the distance $\mathrm{d_{man}}$ is given by the following equation.

$$t_f = \arccos\left(\mathrm{e}^{\mathrm{d_{man}}/E} \times \cos\left(AK\right)\right)/A - K \tag{8}$$

The energy to be dissipated by the brake system due to the misplaced speed sign, E_{MSP}, is:

$$\mathrm{E}_{MSP} = \frac{1}{2}\mathrm{m}\left(\mathrm{v}^2(t_f) - \mathrm{V_{MSP}^2}\right) \tag{9}$$

E_{MSP} could be seen as the ”energy saving” achievable if sign has been ideally placed. In this ideal eco-driving friendly situation, the vehicle reaches $\mathrm{V_{MSP}}$ through only natural deceleration.

4. Speed-sectioning experimental evaluation

Experiments have been worked out in order to verify on real road routes the adequacy between vehicle dynamics, road longitudinal profile and speed-sectioning, in term of eco-driving capabilities. Then the developed criterion and energy evaluation will allow the quantification of this adequacy, according to Equations 3 and 9.

As detailed in Coiret et al. (2016), experiments have been done while crossing the French small village “La Brossiere”. The village is represented in gray on the map (Fig. 1), with the yellow dot on the blue route representing the village entrance panel. This panel is located in a long and strong descent forcing drivers to brake to conform to the regulatory speed.

Fig. 1. Experimental car reaching the limiting speed sign at “La Brossiere”

In the present work, experiments have been renewed at this location and have been strengthened by new experiments with the ”VERT” vehicle dedicated to precise localisation achieved through hybridization of RTK or PPK GNSS positioning and inertial navigation technology. (VERT vehicle), in three other locations of interest (The “La Brossiere” situation case will be referred to be the “location 1” experimental case):

- location 2: similar straight line downhill slope, but with a shorter sight distance due to the presence of trees masking the road sign,

- location 3: slope in a short radius curve leading to a very short sight distance,
- location 4: combined slope and curve, leading to a short sight distance.

Respective latitudes and longitudes for the four locations are: (46.828805,-1.154361), (47.126944,-1.422222), (47.132222,-1.422916) and (47.143833,-1.403694).

For each situation, the limiting sign is considered to be misplaced in an eco-driving potentiality meaning, at the MSP position, and the position where the test driver begins to slow down is considered as the SPD point.

Experiments have consisted of the following rules.

- To drive through the selected locations with a test vehicle, while recording vehicle route with a differential GPS.
- The driver had to to comply exactly with the speed limits and to simply decelerate as soon as he realizes that the speed sign informs him that he has to do so,
- He was instructed to maintain speed if he reached the speed limit before reaching the speed sign and to brake mechanically if he reached the speed sign with an excessive speed.
- Both instants of deceleration starting (SPD) and sign reaching (MSP) are recorded by the mean of taking a picture of the scene with an inboard camera, time-synchronized with the differential GPS.

The VERT vehicle is able to provide accurate positions, angles and speed, by combining inertia unit and GNSS measurements; for the present experiments only differential GNSS measurements have been used, from the vehicle unit and from a roadside fixed unit. Height precision is limited to 2 or 3 dcm, but it is sufficient to evaluate the potential energy, considering the one second precision limitation of the driver actions (perception of the sign, crossing the sign).

The table 1 summarizes the experimental parameters of decelerating phases for 3 repetitions for each of the 4 situations points. These parameters are computed from the GPS positions of the MSP and SPD locations corresponding to the recorded picture instants.

Table 1. Experimental data for 4 road sites

Location	Repetition	Maneuver Duration (s)	Height (m)	Distance (m)	G_{ratio}
Location 1	test 1	14	8.3	297.1	0.028
	test 2	15	9.3	316.7	0.029
	test 3	14	8.4	302.7	0.028
Location 2	test 1	8	4.5	159.6	0.028
	test 2	7	4.3	150.4	0.028
	test 3	8	4.8	169.6	0.028
Location 3	test 1	7	5.5	108.0	0.051
	test 2	6	5.0	98.9	0.051
	test 3	6	5.0	98.8	0.051
Location 4	test 1	6	5.7	113.6	0.050
	test 2	5	4.7	95.0	0.050
	test 3	6	5.6	112.7	0.050

Distances are computed from in-plane projections of GPS positions, while assuming straight vehicle movement and earth spherical form by:

$$Dist = \arccos\left(\sin(\mathrm{lat_{SPD}}) \times \sin(\mathrm{lat_{MSP}}) + \cos(\mathrm{lat_{SPD}}) \times \cos(\mathrm{lat_{MSP}}) \times \cos(\mathrm{lon_{MSP}} - \mathrm{lon_{SPD}})\right) \times 6.371 \cdot 10^6 (m) \quad (10)$$

With $\mathrm{lat_{SPD}}$, $\mathrm{lat_{MSP}}$, $\mathrm{lon_{SPD}}$, $\mathrm{lon_{MSP}}$ latitudes and longitudes in radian at SPD and MSP points.

The geometrical ratio G_{ratio} of height over distance between the SPD and MSP points give first indications about the constraint in speed imposed by the speed sectioning:

- location 1: large sight distance but high altitude lowering, leading to a high geometrical ratio G_{ratio} of 0.028,
- location 2: smaller sight distance but similar slope intensity leading to a the same geometrical ratio G_{ratio},
- location 3: sharp turn leading to a very short sight distance, associated with a 5 meters lowering in altitude and so a very high geometrical ratio G_{ratio} of 0.051,
- location 4: similar turning case than for the location 3 case.

5. Results

The developed criterion and energy evaluation will be used to assess the environmental impact of speed sectioning of the four experimental locations. In order to model a full traffic, both a passenger car and a heavy vehicle are considered to travel these locations before being constrained to slow down at the speed of 50km/h required by the road sign, while being alone in a free flow situation.

Moreover, both french former and new speed regulations of respectively 90 and 80km/h are taken into account in order to verify if the new speed regulation less impedes eco-driving than the former regulation.

The passenger car and the heavy vehicle have respectively the following characteristics: mass of 1,539 and 29,333kg (= $\frac{2}{3}\times$ 44,000, mean weight of Heavy Goods Vehicle is assumed to be the two thirds of maximum weight), C_d drag coefficient of 0.32 and 0.65, S aerodynamic frontal surface of 2.25 and 8 m^2, C_{rr} rolling resistance coefficient of 0.01 and 0.0057.

5.1. Energy evaluation considering the former speed regulation case

The table 2 displays the results for the χ_{EASM} criterion, the E_{MSP} energy dissipated in the braking system, linked to the presence of speed sectioning at the four selected sites, for a passenger car and a heavy vehicle which approaching speeds of 90km/h. This dissipated energy is translated in fuel over-consumption.

Straight line cases such as location 1 and 2 are leading to criterion of around 12, and fuel over-consumption of around 8.8ml for passenger cars (pc) and around 215ml for heavy vehicles (hv).

Locations situated in sharp turns, as location 3 and 4 are showing higher criteria of 13 and 14, with mean over-consumption of 10.3ml for passenger cars and 219ml for heavy vehicles.

Table 2. Criterion and Energy results for the four sites: 90km/h case

Location	Repetition	χ_{EASM}	E_{MSP} (kJ)		fuel over-consumption (ml)	
			pc	hv	pc	hv
Location 1	test 1	12	289	7,477	8.5	219.4
	test 2	13	293	7,675	8.6	225.3
	test 3	12	288	7,481	8.4	219.6
Location 2	test 1	12	309	6,970	9.1	204.6
	test 2	12	311	6,951	9.1	204.0
	test 3	12	308	7,015	9.0	205.9
Location 3	test 1	14	352	7,467	10.3	219.1
	test 2	14	350	7,362	10.3	216.1
	test 3	14	350	7,363	10.3	216.1
Location 4	test 1	13	352	7,500	10.3	220.1
	test 2	14	348	7,293	10.2	214.0
	test 3	13	351	7,476	10.3	219.4

5.2. Energetic evaluation considering the new speed regulation case

The table 3 displays the criterion, dissipated energy and over-consumption for approaching speeds of 80km/h, consistent with the new French speed regulation case.

Straight line cases such as location 1 and 2 are leading to criterion of around 9 and 10, and mean fuel over-consumption of 6.1ml for the passenger car and 159.4ml for the heavy vehicle. These values are smaller than for the former speed regulation case.

Locations situated in sharp turns, as location 3 and 4 are showing criteria of 10, with mean over-consumption of 7.5 and 162.2ml for the car and heavy vehicle, which are again much smaller than the 90km/h speed case over-consumption.

Table 3. Criterion and Energy results for the four sites: 80km/h case

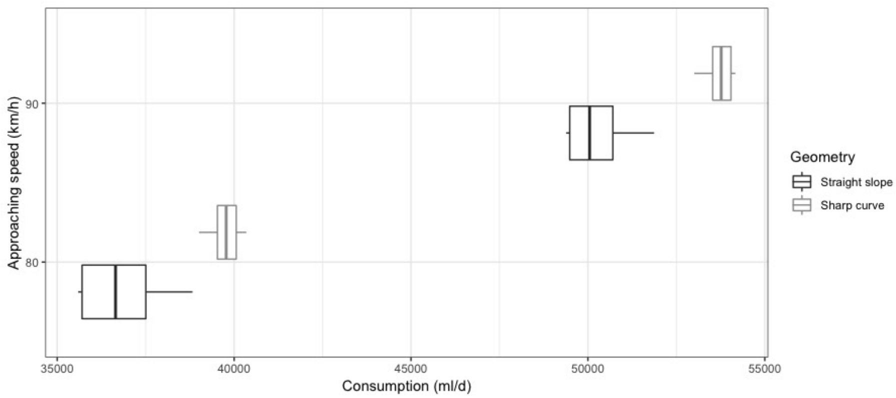
Location	Repetition	χ_{EASM}	E_{MSP} (kJ) pc	E_{MSP} (kJ) hv	fuel over-consumption (ml) pc	fuel over-consumption (ml) hv
Location 1	test 1	10	202	5,670	5.9	166.4
	test 2	10	207	5,877	6.1	172.5
	test 3	10	201	5,577	5.9	166.6
Location 2	test 1	9	216	5,110	6.3	150.0
	test 2	9	218	5,088	6.4	149.3
	test 3	9	215	5,159	6.3	151.4
Location 3	test 1	10	257	5,586	7.5	163.9
	test 2	10	254	5,479	7.5	160.8
	test 3	10	254	5,478	7.5	160.8
Location 4	test 1	10	257	5,623	7.5	165.9
	test 2	10	252	5,407	7.4	158.7
	test 3	10	256	5,596	7.5	164.2

6. Discussion

This work demonstrates that energy can be saved by allowing eco-driving while informing drivers they have to decelerate at a beforehand location, for which mechanical braking could be entirely avoided. Comparison between real speed-sectioning and this optimal situation leads to define dissipated energy related to misplaced speed signs (MSP). Considering the French new regulation speed, this over-consumption is of only 6 ml of fuel for a passenger car which can be seen as being very little. It is much more for an heavy vehicle with around 160 ml.

Nevertheless, these single vehicle low over-consumption appears to become much more sensible if a daily traffic is considered at a given misplaced panel. On the considered roads the mean traffic is around 2,000 vehicles by day, with a 8% proportion of heavy vehicles and 92% of light vehicles, and so, the Fig. 2 summarizes the over-consumption for such a traffic composition at the considered speed sectioning points.

Fig. 2. Daily trafic over-consumptions



For the two approaching speed cases and for the two main geometrical situations of slopes in straight line (locations 1 and 2) and sharp turns (locations 3 and 4). It can be seen that the new speed regulation case of 80km/h is implying fuel over-consumption, of 36.38 and 39.37 liters a day for respectively the straight slope and sharp turn cases (with standard deviations of 1.44 and 0.46). The former speed regulation case of 90km/h where implying even more fuel over-consumption, of 50.26 and 53.69 liters for the same cases (with standard deviations of 1.15 and 0.46).

These results show that speed sign situations at the four chosen experimental cases are very improper in terms of energy use.

The high amount of modeled over-consumption should therefore encourage road designers and managers to take into account eco-driving potentialities of infrastructure in their policies. Solutions would be to displace beforehand a given speed sign in order to increase the visibility distance (sharp turn case) or to displace the deceleration maneuver in a plane section (slope case). With such solutions, by requiring less high deceleration, by increasing visibility distances, road safety would be improved too.

7. Conclusion

This methodology is dedicated to road managers since it is focused on optimization of route speed-sectioning, which consists of the succession limiting speeds along the route. The work is centered on the energetic impact of some misplaced speed changing points which do not allow drivers to eco-drive.

Firstly a EASM criterion has been developed, rapidly usable by road managers to detect these points, named Misplaced Speed-sectioning Position (MSP), in relation to the Starting Deceleration Point (SDP) of approaching vehicles and road characteristics as slopes and turns.

In a second step, Energy dissipated in the braking system has been computed to further inform road managers of the impact of a MSP-type speed change on vehicles over-consumption. The first step provides a vehicle independent criterion. The second allows the computation of an energy assessment of a misplaced sign for any given vehicle. Experiments have been conducted to demonstrate the applicability and possibilities of these theoretical analysis.

This efficient methodology, validated on real data, inexpensive to implement, is proposed to managers in order to make their infrastructures more eco-driving friendly. At last the dissipated energy computation is able to determine the fuel economy that can be expected for a whole traffic over a day on a selected route or network. Traffic size consumption for the misplacement of a single speed sign have been found to reach about 40 liters of fuel with an approaching speed of 80 km/h and 50 litres with an approaching speed of 90 km/h.

These two approaching speed cases were selected to show that the new french speed regulation has an advantage in terms of energy savings in addition to initial safety advantages which was the main goal.

Significant energy savings, assessed in this paper, is justifying optimization methods to move speed signs or to alter speeds regulation, with road safety improvement by lowering high deceleration requirements.

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