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Impact of the penetration rate of ecodriving on fuel consumption and traffic congestion

Keywords: Ecodriving, Fuel consumption, Traffic congestion

Abstract

Since many years, as a consequence of fossil fuels rarefaction and climate changes, ecology has become a major challenge of our society. In this field, many improvements could be realized on the transportation side and more precisely on passenger cars which are an important source of pollution. A quick and efficient solution to reduce fuel consumption and so, greenhouse gases emissions, is to adopt an ecological way of driving, called ecodriving.
However, is ecodriving really efficient in terms of mobility and environment at a global point of view? The benefits of ecodriving have often been studied for an isolated vehicle and rarely for a whole network. The aim of this work is to estimate the effects of ecodriving on traffic congestion and fuel consumption according to the percentage of ecodrivers in the population. This has been achieved using a class of ecodriven vehicles with a car-following model (Intelligent Driver Model) and with a transport simulation software (Aimsun). Results show that the effect of ecodriving on the traffic congestion and pollution is not linearly linked to the proportion of ecodrivers and this effect varies according to the driving conditions. In some cases, ecodriving is cons-productive and fuel consumption increases. Future works will concentrate on experimental validation, on modeling the effect of ecodriving on road safety and on improving the different models.

1. INTRODUCTION

1.1 Context

The fact that fossils fuels are running out faster than they are generated by nature is in all minds. While waiting for new and viable solutions to produce energy, the world population has to learn how to make the remaining reserves last as long as possible by reducing the consumption. More particularly, strong efforts should be concentrated on the transportation side as it represents 30% of our energy consumption (U. S. Energy Information Administration). Research is underway to improve the vehicle and road technologies to lower fuel consumption but a direct method, known as eco-driving, consisting in modifying the driving style, could be deployed rapidly. Although researchers are agree on the fact that ecodriving should reduce the fuel consumption for an isolated vehicle, the information about a whole population of drivers practicing ecodriving is still lacking. This information could be important for policy makers to assist them in the decision to promote or not ecodriving but also for car manufacturers to design driver assistance systems and for road managers to optimize their networks. At first, a precise definition of ecodriving is needed.

1.1.1. Ecodriving. In the literature, ecodriving is often referred as a way of driving allowing to reduce fuel consumption and so greenhouse gases emissions (Beusen *et al.*, 2009; Barth and Boriboonsomsin, 2009). This is rather subjective and a precise definition could be difficult to propose. In most publications (Saboohi and Farzaneh, 2009; Wåhlberg, 2007; Zarkadoula *et al.*, 2007), ecodriving is defined for thermal engine vehicles as following several driving advice such as:

- do not drive too fast,
- do not accelerate too quickly,
- shift gears sooner to keep engine speed lower,
- maintain steady speeds,
- anticipate traffic flow when accelerating and slowing down,
- keep the vehicle in good maintenance.

These advice are also subjective but the choice has been made to model this definition because it is the most common. This definition has the advantage to be rather simple to model. In this study, the attempt to model ecodriving will be focused on tuning driver parameters such as desired acceleration and speed, time headway,...
However, a complete definition should be more complex knowing that the driver practicing ecodriving has to consider other constraints than reduce fuel consumption.

1.1.2. Ecodriving definition proposal. Here, I propose a basis for the definition of ecodriving founded on a weighted balance of criteria. In figure 1, weights for 4 criteria are presented: safety, fuel economy, travel time and comfort. In fact, in real driving conditions, the way humans balance these criteria varies according to their driving styles (hypermiler, ecodriver, typical driver, sport driver). The curves on figure 1 define the evolution of weights with the driving styles and the pie charts below describe the weights repartition for four different driving styles:

- hypermiler: this category of drivers concentrates all its efforts on minimizing fuel consumption, trading off safety, comfort and travel time (Barkenbus, 2010). An example of a dangerous technique allowing to minimize fuel consumption consists in shutting down the engine in downhill.
- ecodriver: this category of drivers optimizes its commands to reduce fuel consumption without trading off safety. Examples of strategies to practice an ecodriving have been previously exposed.
- typical driver: represent the mean driver present on roads. This driver often preferred safety and comfort to fuel economy.
- sport driver: this category of drivers only considers its travel time without taking into account safety, comfort and fuel economy.

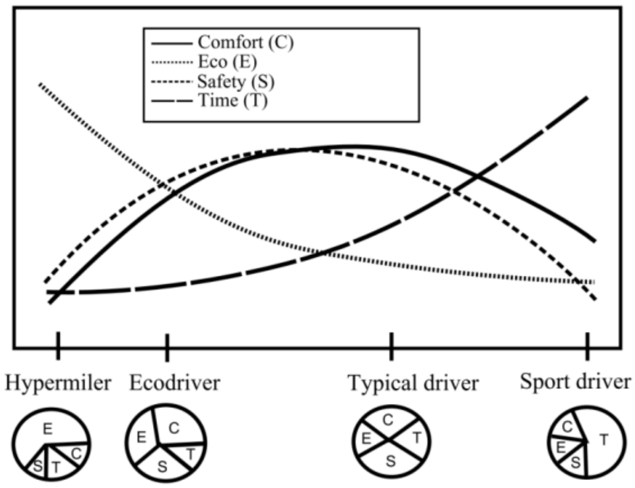

Figure 1: Driving criteria weights

The way humans balance these constraints also varies according to their actions (navigation, control, stability) but this has not been represented in this study. In the next future, this definition will be employed to describe driving styles by building speed profiles. The idea is to compute four speed profiles, each of them dedicated to a criteria. Then, a global speed profile can be calculated using a weighted mean, depending on the driving style, of the four speed profiles previously computed.

1.2 Objective of this study

To provide the information about a whole population of drivers practicing ecodriving, the aim of this work is to study the impact of the penetration rate of ecodrivers, from 0% to 100%, on fuel consumption and traffic congestion. The impact on fuel consumption has been assessed through the quantity of fuel consumed and the impact on traffic congestion has been evaluated with the temporal mean speed of the vehicles.

The paper is structured as follows: section 2 presents the methodology of the study, while section 3 develops the modeling and section 4 exposes the results. Section 5 contains the discussions and sections 6, 7 and 8 are respectively the conclusion, the acknowledgments and the references.

2. METHODOLOGY

To analyze the impact of the proportion of ecodrivers on fuel consumption, different car-following and fuel consumption models have been used. The idea is to compute a speed profile for each vehicle that feeds into a simple fuel consumption model. For each numerical try, different combinations of the following parameters have been simulated: the number of vehicles constituting the population, the proportion of ecodrivers in this population, and the road type. The number of vehicles has been selected to represent free, intermediate and congested traffic state. These three situations have been tested on two types of road: inter urban and urban. For each study case, the proportion of ecodrivers has varied from zero to one hundred percent (by a step of 10) and each simulation has been replicated ten times. A total of 660 simulations were therefore performed. An advantage of testing a wide range of ecodriver proportions is that the effect of increasing the number of ecodrivers will be assessed. However, a drawback is that the current proportion of ecodrivers is unknown. To represent ecodrivers, a class of ecodriven vehicles has been defined with several parameters such as acceptable acceleration, time headway, maximum desired speed,... These parameters have been chosen on the basis of real world experiments (Saint-Pierre, 2010).

To compute the speed profile of a whole network, a car-following model has been employed on inter urban roads. The chosen model is the Intelligent Driver Model (IDM) (Treiber *et al.*, 2000) as it takes into account the velocity differences between vehicles. This model has been slightly modified to represent the speed variation in curves where drivers are considered to travel at the V_{85} operating speed (Louah *et al.*, 2009). Other speed profiles could have been used (Glaser and Aguilera, 2003; Orfila *et al.*, 2010) but the simplest has been selected in a first attempt. For urban situations, Aimsun simulation software has been used. This software, based on the Gipps car-following model (Gipps, 1981), can represent complex situations such as traffic lights, lane change, give way or roundabouts. In this study, the case of a district with four traffic lights has been modeled. The computed speed and position of each vehicle through time have been recorded.

Using the precedent speed profiles, a fuel consumption model, founded on the mechanical energy consumed with a performance ratio function of the vehicle speed, computes the instantaneous and cumulated fuel consumption for inter urban roads. The performance ratio has been assessed using experiments on a specific car at various speeds and gear ratio (Wang *et al.*, 2008). More complex models (Giakoumis and Lioutas, 2010) could not have been used but they will be tested in future works to take into account the engine speed. For urban roads, the Aimsun integrated fuel consumption model (Akçelik, 1983), has been used. For each study case, the level of traffic congestion has been assessed through the temporal mean speed of all vehicles.

3. MODELING

3.1 Modified car following model

In this study the IDM (Intelligent Driver Model) has been used for interurban situations. This model has the advantage to represent the selected drivers parameters and it also can be adapted to take into account the road curvature.

$$\begin{cases} \dot{x_\alpha} = v_\alpha \\ \dot{v_\alpha} = a\left(1-\left(\frac{v_\alpha}{v_0}\right)^\delta-\left(\frac{s_0+v_\alpha T+\frac{v_\alpha \Delta v_\alpha}{2\sqrt{ab}}}{s_\alpha}\right)^2\right) \end{cases},$$

where, $x_\alpha\ (m)$ is the α vehicle position, $v_\alpha\ (m.s^{-1})$ is the α vehicle speed, $a\ (m.s^{-2})$ is the desired acceleration, $v_0\ (m.s^{-1})$ is the desired velocity, $s_0\ (m)$ is the minimum distance between vehicles, $T\ (s)$ is the desired time headway, $\Delta v_\alpha = v_\alpha - v_{\alpha-1}\ (m.s^{-1})$ is the approaching rate, b is the comfortable braking deceleration and $s_\alpha = x_{\alpha-1} - x_\alpha - l_{\alpha-1}\ (m)$ is the net distance between vehicles with $l_{\alpha-1}$ the length of the leader vehicle.

This model has been modified to represent the driver behavior in curves by adding a term to $\dot{v_\alpha}$. The speed desired by drivers in curves can be assessed using the operating speed V_{85}, defined as the 85th percentile of the speed distribution of free-moving cars (Vertet, 2006).

$$\dot{v_\alpha} = a\left(1 - \left(\frac{v_\alpha}{v_0}\right)^\delta - \left(\frac{s_0 + v_\alpha T + \frac{v_\alpha \Delta v_\alpha}{2\sqrt{ab}}}{s_\alpha}\right)^2 - \left(\frac{v_\alpha - V_{85}(x_\alpha + v_\alpha T_r)}{2T_r\sqrt{ab}}\right)^2\right),$$

where $V_{85}(x_\alpha + v_\alpha T_r)$ is the operating speed at the distance $x_\alpha + v_\alpha T_r$ and T_r is the headway time to the road events (curve,...). An example of speed profiles obtained for 50 vehicles is given in figure 2.

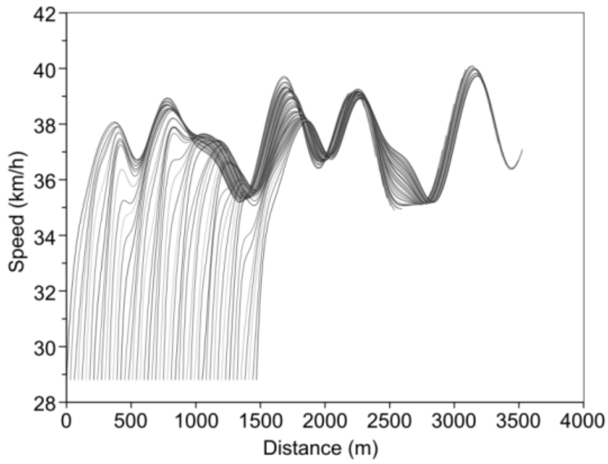

Figure 2: Vehicle speed versus distance

3.2 Fuel consumption model

The theoretical consumed energy, E_{theo}, in a time step dt can be evaluated by the following formulae:

$$E_{theo} = \left(\frac{1}{2}\rho_{air} S C_x v_\alpha^2 + C_{rr} mg + mp + ma_\alpha\right) v_\alpha dt,$$

where $\rho_{air} \approx 1.2\, kg.m^{-3}$ is the density of the air, $S\,(m^2)$ is the end face, C_x is the longitudinal drag coefficient, $C_{rr} = 0.015$ is the coefficient of rolling resistance, $m\,(kg)$ is the vehicle mass, $g = 9.81\, m.s^{-2}$ is the standard gravity, $p\,(\%)$ is the road grade, $a_\alpha\,(m.s^{-2})$ is the α vehicle acceleration and $dt\,(s)$ the time step.

Then, an efficiency ratio has been applied to take into account the energy lost in the combustion and transmission processes. This ratio comes from real experiments from Wang et al. (Wang *et al.*, 2008) where the fuel consumption has been measured at different speeds.

$$\eta = \frac{E_{theo}}{E_{meas}} = 10^5 \times \frac{\frac{1}{2}\rho_{air} S C_x v_\alpha^2 + C_{rr} mg + mp}{f(v_\alpha).\, e_{carb}.\, \rho_{carb}},$$

where E_{theo} is the theoretical energy consumed if the vehicle was the one tested by Wang *et al.*, E_{meas} the measured energy consumed by the test vehicle, $f(v_\alpha) = 0.05 v_\alpha^2 - 1.8 v_\alpha + 21$ is a function fitted on the works of Wang *et al.* giving the fuel consumption in liters per hundred kilometers versus the vehicle speed, $e_{carb} = 42.5 \times 10^6\, J.kg^{-1}$ is the energy density of fuel and $\rho_{carb} = 0.84\, kg.L^{-1}$ is the fuel density. The computed efficiency ratio can be seen on figure 3.

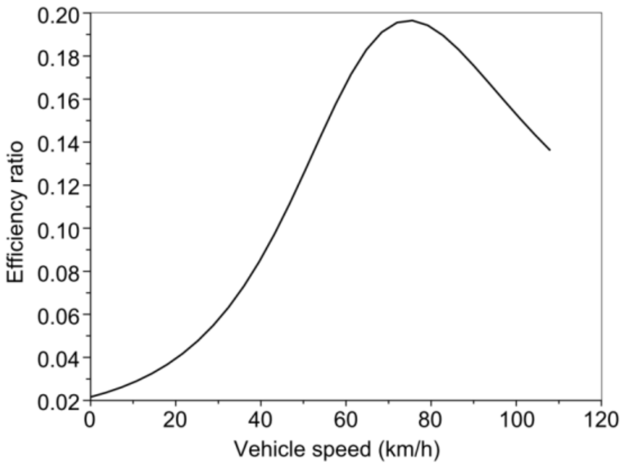

Figure 3: Efficiency ratio

4. RESULTS

Table 1: Drivers parameters

Parameter	Normal driver				Ecodriver			
	Mean	Sd	Min	Max	Mean	Sd	Min	Max
Desired speed v_0	30	5	20	40	25	3	21	29
Headway time T	1.5	0.4	0.8	2.3	2	0.2	1.6	3
Road headway time T_r	3	0.9	1.2	3.8	4	0.5	3	5
Desired acceleration a	1	0.3	0.5	1.5	0.8	0.2	0.4	1.2
Braking deceleration b	3	0.9	1.5	4.5	1.5	0.4	1	2
Minimum distance s_0	2	0.6	1.3	2.7	4	0.4	3.3	4.7

Simulations have been run with different driver parameters for normal drivers and ecodrivers. For each virtual driver, parameters have been randomly generated using values from table 1 with a Gaussian distribution. To each parameter is associated a mean value, a standard deviation (Sd), a minimum and a maximum value.

4.1 Interurban cases

To analyze the impact of ecodriving in interurban situations, a theoretical road has been designed. It consists in a straight line and a curve every 1500 meters introduced and concluded with a clothoid. On this road, three traffic conditions have been applied from a free traffic to a congested one. These three situations have been arbitrarily determined on the assumption that, in a free traffic, vehicles reach their maximum speed and in a congested traffic, vehicles travel very slowly. For interurban cases, the situation where vehicles are stopped has been avoided because the fuel consumption model does not take this case into account. The third situation is an intermediate state between the free one and the congested one. The fuel consumption, given in liters per 100 km, is the mean consumption of all vehicles for the ten numerical tries. To analyze the impact on traffic, the mean speed has been selected.

4.1.1. Free traffic state. This situation has been reached with 10 vehicles traveling on the virtual road. In figure 4, fuel consumption is steadily decreasing from 9.05 to 8.35 L/100 km, that is 7.7%. The solid line represents the mean and the dotted lines represent the standard deviation on the ten replications. Mean speed is also decreasing but in a quadratic way from 60.5 to 55 km/h, that is 9.1%. This is equivalent to 2 minutes lost on a 20 minutes travel. For this situation, it could be said that increasing the proportion of ecodrivers, as defined previously, is a good way to reduce fuel consumption without loosing too much time.

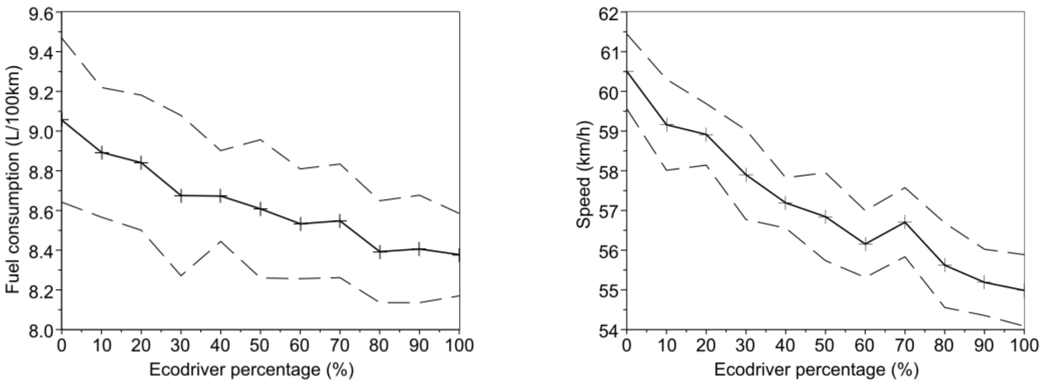

Figure 4: left, fuel consumption for 10 vehicles ; right, speed

4.1.2. Intermediate traffic state. This situation has been reached with 50 vehicles travelling on the virtual road. In figure 5, it can be seen that fuel consumption drops from 8.2 to 7.5 L/100 km, that is 8.5%, between 0 and 20% of ecodrivers. Then, it increases to reach 8.4 L/100 km for 100% of ecodrivers, that is 2.4% more than without any ecodriver. This can be explained by the mean speed, which is sharply decreasing from 47 km/h to 29 km/h, a difference of 38%. Indeed, when speed drops sharply, the efficiency ratio of the engine also drops sharply from 0.13 to 0.06, doubling the lost energy. This effect should not appear for electric vehicles. This sudden drop in speed could be explained by the traffic instability occurring when the traffic goes from a free state to a congested one. In this particular situation, increasing the percentage of ecodrivers above 20% is not recommended and trying to reach this optimum of 20% of ecodrivers warrant a decrease in speed of only 7.5%.

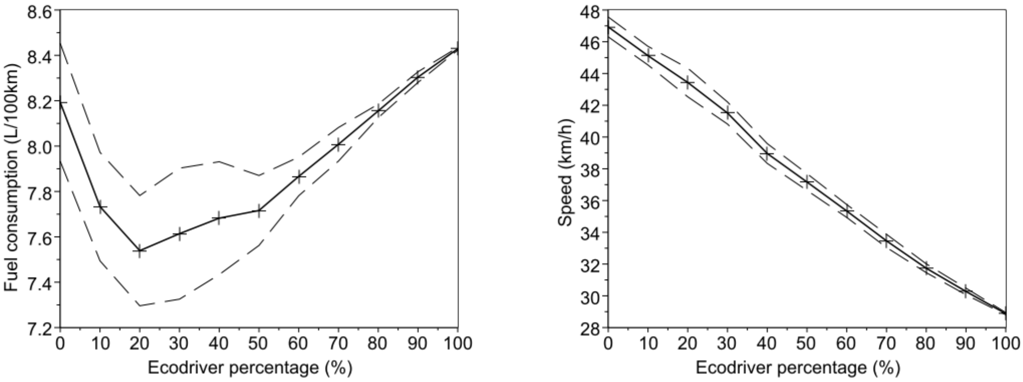

Figure 5: left, fuel consumption for 50 vehicles; right, speed

4.1.3. Congested traffic state. This situation has been reached with 100 vehicles travelling on the virtual road. In figure 6, the fuel consumption decreases rapidly from 13.4 to 10.9 L/100 km, that is 18.6%, between 0 and 30% of ecodrivers. Then, it decreases steadily to reach 8.6 L/100 km. This traffic state is the one where eco-driving has the strongest effect as the total gain is about 35.8% between 0 and 100%. However, in the same time, the speed has decreased of 55.1%, doubling the travel time. A good compromise could be the proportion of 30% of ecodrivers where fuel consumption has been reduced of 18,6% while the speed has decreased of 23.7%.

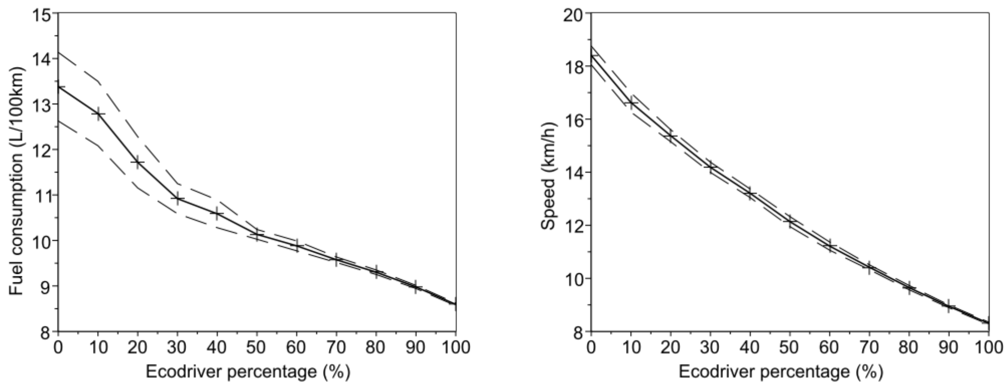

Figure 6: left, fuel consumption for 100 vehicles ; right, speed

4.2 Urban cases

Urban cases have been treated with Aimsun simulation software (from TSS company) to represent a complex situation such as a district with four traffic lights. In figure 7, the three tested conditions are represented. Light gray vehicles are ecodriven and dark ones are normally driven. The fuel consumption is given in liters and is defined as the quantity consumed by all vehicles that have finished their trip during the simulation process. The speed is the mean speed for all vehicles that have left the network.

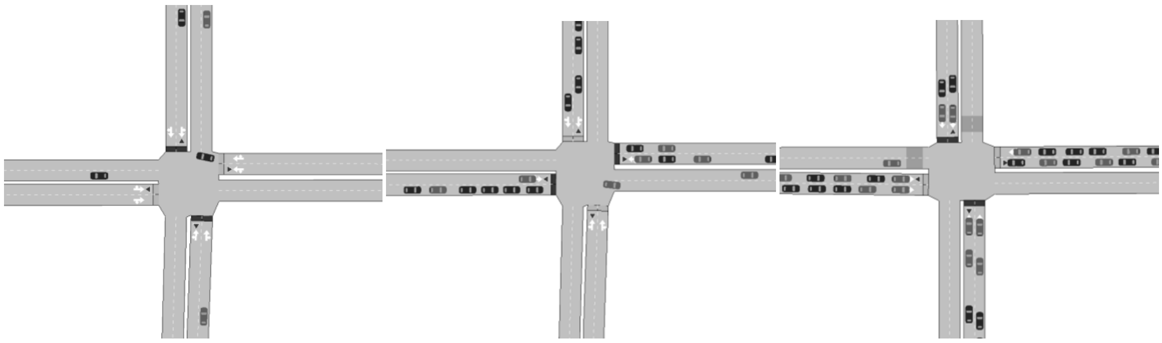

Figure 7: traffic states: left, free; center, intermediate; right, congested

4.2.1. Free traffic state. This situation has been reached with a traffic flow of 100 vehicles per hour for each of the 8 entrances of the network. In figure 8, the fuel consumption decreases slowly from 3.55 to 3.2 liters, that is 9.8% and the speed decreases from 26.9 to 21.6 km/h, that is 19.7%.

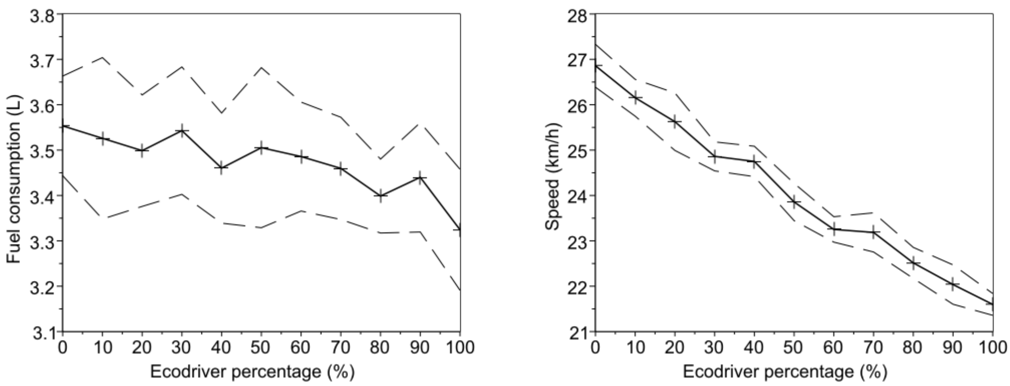

Figure 8: left, fuel consumption for a free traffic state; right, speed

4.2.2. Intermediate traffic state. This situation has been reached with a traffic flow of 400 vehicles per hour for each of the 8 entrances of the network. In figure 9, the fuel consumption seems to increase from 37 to 38.5 liters then decreases to 34.2 liters for 100% of ecodrivers.

The fuel economy between 0 and 100% of ecodrivers is about 7.6%. The mean speed decreases from 6.5 to 4.4 km/h, that is 32.3%. Finally, in this situation, the proportion of 40% should be avoided for a fuel economy purpose and the proportion of 80% and above should be avoided for a travel time purpose.

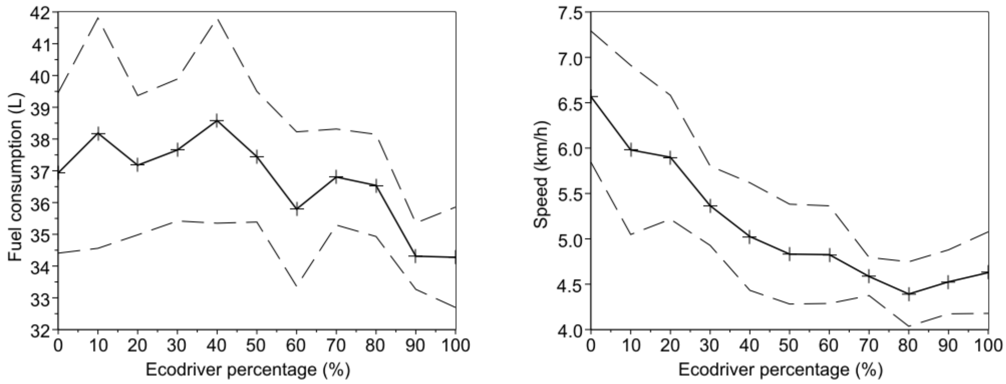

Figure 9: left, fuel consumption for an intermediate traffic state ; right, speed

4.2.3. Congested traffic state. This situation has been reached with a traffic flow of 800 vehicles per hour for each of the 8 entrances of the network. In figure 10, fuel consumption decreases slowly from 0 to 20% of ecodrivers then drops to 37 liters for 100% of ecodrivers what represents 19.6% of economy. The mean speed is very lightly increasing around 4 km/h. In this situation ecodriving could be generalized to all drivers and this situation is the one where ecodriving is the more efficient.

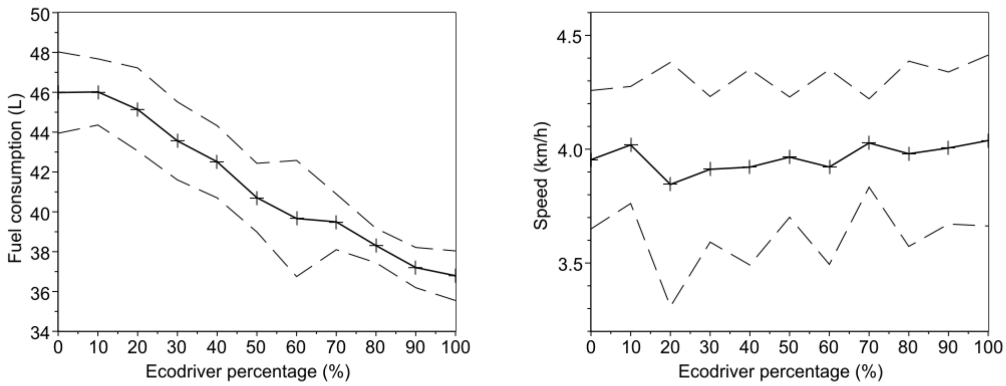

Figure 10: left, fuel consumption for a congested traffic state ; right, speed

5. DISCUSSIONS

In this study, two road infrastructures with three traffic states have been tested. Results for inter urban roads show that:

- increasing the proportion of ecodrivers is efficient on a free traffic state as the fuel consumption decreases significantly while the mean speed varies in the same order.
- for the intermediate traffic state, an optimum proportion of 20% of ecodrivers has been found. Increasing the percentage of ecodrivers above this threshold degrades the situation because the speed suddenly drops.
- for the congested traffic state, a compromise has been highlighted for 30% of ecodrivers. At this level, the fuel consumption has been reduced and speed has been maintained at a suitable value.

Results for urban roads show that:

- for a free traffic state, speed and fuel consumption are linearly decreasing with the proportion of ecodrivers. In these conditions, the optimal proportion of ecodrivers depends on the politicians and their choice to encourage ecology or traffic fluidity.
- For the intermediate traffic state, the fuel consumption increases from 0 to 40% of ecodrivers and the optimum should be about 60% because the speed is very low above. Proportions below 50% and above 80% should be avoided for a traffic fluidity purpose.
- For the congested traffic state, ecodriving is very efficient as the fuel consumption strongly decreases while the speed is almost steady.

In this work three main results have to be highlighted:

- Firstly, ecodriving is, in most of simulated cases, an efficient way to reduce fuel consumption from 7.6 to 35.8%.
- Secondly, in some situations such as the intermediate traffic state on an inter urban road, the fuel consumption has increased with the proportion of ecodrivers. This unexpected result, mainly explained by the engine efficiency ratio and by the traffic instability, proved that in particular cases, generalizing ecodriving could be cons-productive.
- Thirdly, the optimal proportion of ecodrivers is different from a situation to another. In some situations, drivers cannot know if they have to practice ecodriving or not because they do not have the information of the optimal proportion of ecodrivers nor the current proportion of ecodrivers.

On the basis of these results, three solutions can be proposed:

- a short term one consisting in promoting ecodriving only in clearly identified situations such as totally free and congested traffic. Ecodriving learning processes should include this consideration.
- a middle term one consisting in informing drivers on the driving style they have to perform, for example by the way of variable-message signs.
- a long term one consisting in optimizing driver assistance systems such as ACC (Adaptive Cruise Control) according to the driving conditions. Information concerning

the traffic state and the road infrastructure could be exchanged by vehicles and infrastructure in order to compute the optimal parameters for all vehicles in the network. Works in this direction, for an isolated vehicle in realistic traffic conditions (Kamal *et al.* 2010) and for a whole network (Barth and Boriboonsomsin, 2009), have already started.

It should be kept in mind that, in this study, some hypothesis have been made and must be considered in the analysis of results:

- efficiency of ecodriving highly depends on the relative importance that drivers set on fuel economy and time spent. Previous analysis of results are valuable on the hypothesis of an equivalent importance of these two criteria.
- Although it is one of the main criteria of drivers, the effect of the proportion of ecodrivers on safety has not been assessed in this work.
- The impact of ecodriving on traffic congestion has been studied through the mean temporal speed of ten numerical tries. This could be completed by analyzing the mean speed of the 10% of vehicles that are the most delayed in comparison with a free traffic state.
- In the results, fuel economy is measured in comparison with a situation without ecodrivers. However, an unknown proportion of ecodrivers is already in the population and it is unreasonable to estimate that 100% driver will ecodrive tomorrow.
- Although it is an important parameter of ecodriving, the engine speed has not been taken into account in the fuel consumption models. This choice, that has been made to simplify the model, could have an effect, especially for congested traffic states which imply numerous gear changes. Furthermore, experiments used to specify the driver parameters were not dedicated to the car-following models used in this work.
- The only tested vehicles are thermal engines vehicles. It could be interesting to test other vehicles such as electric vehicles with an efficiency ratio less dependent on the speed and a possibility to regenerate energy while braking. Also, trucks and buses, which can represent an important part of fuel consumption, have not been modeled.

6. CONCLUSIONS

This paper has studied the impact of the penetration rate on fuel consumption and traffic congestion by running simulations on different situations. According to these simulations, the optimal proportion of ecodrivers is radically different from a situation to another. For a congested traffic, ecodriving, as defined in this study, is almost beneficial while it could be cons-productive with an intermediate traffic state on inter urban roads. As this cons-productive effect is rather limited (only 2.5% of increase in fuel consumption) for a traffic state, *a priori*, less frequent than others, it should still be advised to encourage ecodriving.

Theoretically, this study will have an impact on the way ecodriving is considered in our research. In practice, these results can be implemented in three ways:

- promoting ecodriving only in situations such as totally free and congested traffic. Ecodriving learning processes should also include this consideration.
- informing drivers on the driving style they have to perform, for example by the way of variable-message signs.
- designing driver assistance systems that could communicate with the infrastructure to evaluate the traffic state and so, automatically adapt the vehicle behavior. This can be performed with Adaptive Cruise Control (ACC) systems automatically parameterized by the network according to the driving conditions (road, traffic state,...).

Future works will be concentrated on validating these simulations experimentally and on improving the fuel consumption and car-following models to take into account drivers safety. The optimization process allowing to find the best driver parameters according to the driving conditions will also be studied.

7. ACKNOWLEDGMENTS

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