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Benefit Assessment of New Ecological and Safe driving Algorithm using Naturalistic Driving Data

Sepehr Ghasemi Dehkordi [a], Grégoire Sébastien Larue [a], Michael E. Cholette [b], Andry Rakotonirainy [a]

a) Queensland University of Technology (QUT), Centre for Accident Research Road Safety-Queensland (CARRS-Q), 130 Victoria Park Road, Queensland 4059, Australia

b) Science and Engineering Faculty, Queensland University of Technology, Brisbane, Queensland Australia

***Abstract*— A new Ecological and Safe (EcoSafe) driving control algorithm has been recently developed by the authors for controlling the longitudinal motion of the vehicle to minimize fuel consumption while respecting safety constraints. The algorithm uses a Model predictive control framework augmented with enhanced safety constraints based on Intervehicular Time (TIV) and the Time to Collision (TTC). This algorithm requires tuning to adapt to traffic condition. In this paper we propose a tuning method for EcoSafe algorithm which is deduced from driver preference and traffic flow information. In addition, to the best of our knowledge, the benefits of similar EcoSafe algorithms have not been tested with naturalistic data. Hence, we assessed the benefits of EcoSafe algorithm in terms of eco-driving and safety by using 1,100 km of naturalistic driving data. We use velocity profile extracted from the Australian Naturalistic Driving Study (ANDS) as the leading vehicle driving behaviour. The results show that our proposed strategy has a 14% reduction in fuel consumption on average while maintaining high safety levels without increasing travel time significantly.**

Keywords—Eco driving; safe driving; naturalistic driving study, Model predictive control.

I. INTRODUCTION

Global warming and its influences on public health and environment are a major concern of this century. The transportation industry, by burning fossil fuels, is one of the major causes of this global warming. While a variety of factors such as infrastructure, vehicle condition and traffic congestion have a direct impact on the fuel efficiency of a road network, the driving style of each individual driver also plays a significant role [1]. Following eco-driving instructions - such as smooth acceleration/deceleration, avoiding hard braking, avoiding over speeding - have been shown to improve fuel efficiency significantly. Eco-driving advisory systems are among several solutions to promote and assist drivers in following eco-driving behaviours [1]. However, current eco-driving advice may compromise safety as they do not consider how drivers react to their surrounding traffic, and the safety margins required. Several studies have outlined various situations where eco-driving practices may compromise safety by increasing the likelihood of high-risk driving behaviours (e.g., inappropriate speeds, reduced headway), which in turn increase the risk of crash with other road users (e.g. vehicles occupants and pedestrians) [1, 2].

Algorithms and computational models have been recently developed for eco-driving advisory systems to incorporate safety constraints [3-5]. The common approach is to use model predictive control (MPC). MPC is used to predict a

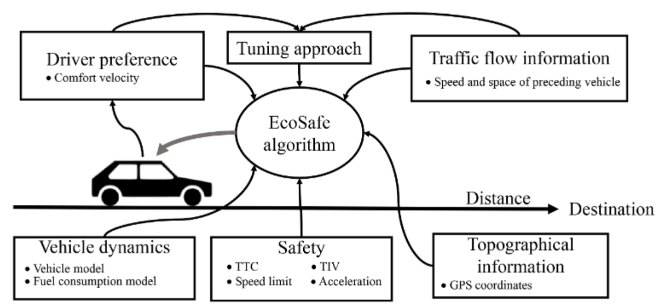

Fig. 1. Configuration of EcoSafe driving system

short horizon speed profile taking into account the traffic conditions [3, 5]. The lack in the design of proper real-time calculation of speed profile with time-dependent safety constraints (i.e. TIV and TTC) is the main concern in existing research on eco-driving algorithm incorporating safety. [6] incorporated TIV as soft constraints in a MPC framework by using *ad-hoc* tuning parameter into the cost function. [5] extended this idea by developing a long term optimization and short term adaptation method to calculate the optimal speed trajectory. However, due to the computational demands of the numerical optimization, the long term optimization cannot be updated in real-time. The long term optimisation is therefore only calculated once at the start of the journey, and is never updated. This means that the long term speed profile cannot adapt to unplanned events related to the traffic, which degrades the performance of the MPC in terms of fuel consumption. In [7], the authors developed a Modified Distance based Dynamic programing (MDDP) algorithm based on the MPC algorithm which considers TTC and headway as safety related factors. Pontryagin's maximum principle (PMP) was used to analytically calculate the long term optimisation. The advantage of an analytical solution from the PMP is that it can be computed time-efficiently and allows updating the reference trajectory in real-time (long term trajectory). Fig.1 shows the conceptual framework of our EcoSafe algorithm. However, the EcoSafe algorithm needs tuning approach by considering traffic flow information and driver preference to adapt the algorithm with the upcoming traffic, with the view to output an adapted real-time velocity profile.

This EcoSafe algorithm (for details see [7]) is based on MDDP and Pontryagin theories. The algorithm calculates an optimal trajectory in terms of fuel consumption while maintaining safety. To our knowledge, no similar EcoSafe algorithm has been tested with real word traffic data. Therefore, this paper aims at evaluating the benefits in terms of fuel efficiency of the proposed algorithm using naturalistic driving data as a way to evaluate the benefits of this approach when considering driving performance recorded naturalistically with a variety of drivers on a variety of road conditions.

The overall objective of this paper is to propose a tuning method for EcoSafe driving algorithm based on traffic conditions, and then we evaluate its effectiveness of it with naturalistic driving data (i.e. real world driving data). Specifically, this paper is organised as follows: in Section II, the EcoSafe algorithm is summarised and the tuning approach for adapting the speed with the traffic condition is introduced. Section III describes the naturistic data set and analysis criteria. Finally, Section IV presents the simulation results, and this is followed by the concluding remarks in Section V.

II. EcoSafe Algorithm

The main idea of the EcoSafe driving algorithm is to define a rigorous framework for ecological and safe driving. In this section, we first introduce the vehicle model employed in this study and then the MPC methodology is summarised, finally a strategy to adjust the speed with the traffic condition is introduced.

1) *Vehicle model*

The vehicle model used in this paper [11] is described in Eq. (1) where P[W] is the engine power, v is speed, $a[\mathrm{m/s^2}]$ the acceleration, I[kg] the overall inertia, and c_k the lumped longitudinal coefficient:

$$P = v \cdot (I.a) + \underbrace{(c_0 + c_r)v + c_1 v^2 + c_2 v^3}_{P_{ss}} \qquad (1)$$

P_{ss} refers to the steady-state power when acceleration is zero. The fuel consumption model is expressed with a low degree polynomial equation [8]:

$$FC(t) = \begin{cases} \alpha_0 + \alpha_1 P(t) + \alpha_2 P^2(t) & P(t) \geq 0 \\ \alpha_0 & P(t) < 0 \end{cases} \qquad (2)$$

Where $FC[\frac{kg}{s}]$ is the fuel consumption rate and $\alpha_{k=0,1,2}$ are the fixed coefficients of the fuel consumption model depending on vehicle characteristics [9].

2) *Safety factors*

Maintaining an appropriate following distance with the preceding vehicle is the main safety criteria used in this paper. As suggested in [10], we considered both the inter-vehicular time (TIV) and the Time to Collision (TTC) as shown in Eq. 3 and Eq. 4, respectively.

$$G_{TIV} = vTIV_{min} + \ell \qquad (3)$$

$$G_{TTC} = (v_f - v_{pre})TTC_{min}|_{v_f > v_{pr}} \qquad (4)$$

Where v_{pr} is the preceding vehicle's velocity, v_f is the following vehicle's velocity and ℓ is the minimum gap when preceding vehicle is stopped. G_{TIV} and G_{TTC} are the required gap between vehicle at the minimum TIV and TTC, respectively. Note that the G_{TTC} is defined when the velocity of the following vehicle is greater than that of the preceding vehicle. In addition to G_{TIV} and G_{TTC}, respecting speed limits and limiting the range of acceleration/deceleration are also constraints included in our approach to ensure safety.

3) *Model Predictive Control Approach*

The EcoSafe algorithm is a distance-based MPC approach where the travelled distance is discretised with step size equals to Δs. The cost function is given by:

$$\zeta = \frac{FC + \psi}{v} \Delta s \qquad (5)$$

where $\frac{FC}{v}$ is the fuel economy (kg/m), ψ is a time penalty and Δs is the distance grid of the trajectory. From Eq. (5), the Optimal Control Problem (OCP) is expressed as follows:

$$\min_{a_{k+1},\ a_{k+2},\dots,\ a_{k+m-1}} \sum_{i=0}^{i=m-1} \zeta_{k+i|k}$$

subject to:

$$\begin{gathered} v_{k+i+1|k} = v_{k+i|k} + a_{k+i|k}(\Delta t) \\ \omega_{min} \leq \omega_{k+i|k} \leq \omega_{max} \\ P_{min} \leq P_{k+i|k} \leq P_{max} \\ v_{min} \leq v_{k+i|k} \leq v_{ff,k+i|k} \\ G_{k+i|k} \geq \max(G_{k+i|k,TIV_{min}}, G_{k+i|k,TTC_{min}}) \end{gathered} \qquad (6)$$

where, $\omega[\mathrm{rad/s}]$ is the engine speed, m is the number of distance steps in the look-ahead horizon, $\Delta t = 2\Delta s/(v_i + v_{i+1})$ is the time-grid spacing, $v_{ff,k+i|k}$ is the optimal free-flow velocity in the absence of safety constraints. Indeed, at each distance step, the maximum allowed velocity is set to the optimum velocity without any traffic. As can be seen in Eq. (6) $v_{ff,k+i|k}$ upper-bounds the feasible optimal velocities and thus helps to reduce the computational burden of the MPC algorithm. v_{ff} is a function of current speed and the comfort speed v_c defined by the driver (speed range that is acceptable to the driver):

$$v_{ff,k+i|k} = f(v_k, v_{c,k+i|k})$$

$$= \begin{cases} P_{ss} + \sqrt{2\dfrac{FC_{ss}(v_k) + \psi(v_{c,k+i|k}) - FC_{ss}(v_{c,k+i|k}) + \varepsilon}{v\alpha_2}} & v_k \geq v_{c,k+i} \\ P_{ss} - \sqrt{2\dfrac{FC_{ss}(v_k) + \psi(v_{c,k+i|k}) - FC_{ss}(v_{c,k+i|k}) + \varepsilon}{v\alpha_2}} & v_k < v_{c,k+i} \end{cases} \qquad (7)$$

where FC_{ss} is the steady state fuel consumption when acceleration is zero, ε is a distance penalty and ψ is the a penalty calculated using comfort velocity as described in [7]. Eq. (7) shows that the choice of comfort velocity is not only related to the driver's preference and the fuel consumption characteristics of the vehicle, but does not account for traffic conditions (i.e. the safety constraints). A method to set v_c is described in Subsection 4.

v_{ff} can be obtained from numerical optimization or analytical solution [11]. PMP is used to calculate v_{adp}, as this approach has the advantage that v_{adp} can be updated in real-time at each distance step for little computational cost. The methodology for calculating the velocity profile with PMP used in this paper was comprehensively detailed in [11] and [7].

The modified distance based dynamic programming (MDDP) algorithm described in [7] is used as the optimisation solution method for Eq. (5). This approach allows considering time-dependent constraints, such as TIV and TTC, in the distance-based MPC framework. Such constraints are also defined as the hard constraints without any *ad-hoc* tuning parameters. This increases the reliability of the outcome of the algorithm in term of safety measures.

4) Tuning method for EcoSafe algorithm

The summary of the proposed tuning method for EcoSafe algorithm is described in Fig. 2. At each iteration, the current state of vehicle (speed, travel distance and intervehicular time) is first identified. If TIV is more than 6 seconds, traffic conditions are considered as free flowing [12]. In this free flow mode, the comfort velocity is set to the driver's preferred velocity, the posted speed limit, by default. Otherwise the vehicle's velocity depends on the traffic ahead.

If v_c is set to the speed limit in this "interacting" mode and the speed of the preceding vehicle is less than the speed limit, accelerations and subsequent decelerations may result as the vehicle's velocity temporarily exceeds that of the preceding vehicle and must be corrected to satisfy safety constraints. The net effect of these accelerations and decelerations is an increased fuel consumption. Thus, instead of using the speed limit, the comfort velocity is set to the average velocity of the preceding vehicle for the past 10 seconds.

v_{ff} is obtained from the PMP formulation using $v_{c,k}$ and v_k. If $v_{c,k} \geq v_k$ the acceleration formulation of PMP is used. In this mode, in order to save fuel, the distance penalty is not considered and the vehicle can accelerate optimally to the comfort velocity. When $v_{c,k} < v_k$ (deceleration mode) a distance penalty is required when decelerating in order to avoid the vehicle coasting, which can result in hard braking later in the deceleration process [1]. In this paper, we impose that vehicles need to decelerate to a new given speed within 700 meters in free flow conditions.

Finally, $v_{c,k}$, vehicle dynamics, safety constraints along with the predicted velocity of the preceding vehicle are used as inputs in the EcoSafe-MPC algorithm. A Kalman filter is used to estimate the velocity of the preceding vehicle for the horizon of the prediction as introduced in [10].

III. Data Set and Analysis

1) Naturalistic Driving Data set

The data used in this paper was gathered by the Australian Naturalistic Driving Study (ANDS) [13]. The ANDS recruited drivers in Australia (New South Wales and Victoria states) and installed a range of sensors in their own vehicles. Then drivers were driving their vehicles as they normally would during a 3 months period. One of the sensors used in ANDS was a GPS sensor, which provides velocity and coordinates of vehicles at a frequency of 5 Hz. We used the GPS data as a simulated realistic preceding vehicle for our algorithm.

We randomly select 700 trips from available data in New South Wales (from Gosford, Sydney Wollongong and Bowral). Then we extract all the trips which include more than 5 km travel distance. The remaining trajectories are filtered to ensure that all those selected consistently report GPS coordinates and velocity. A final sample of 41 trips was selected, for a total travel distance of *1,100 km* at an average speed of 83 km/h to evaluate the EcoSafe algorithm (Fig. 3). The selected trips cover a range of driving situations including rural/urban, low speed, high speed and various driving styles.

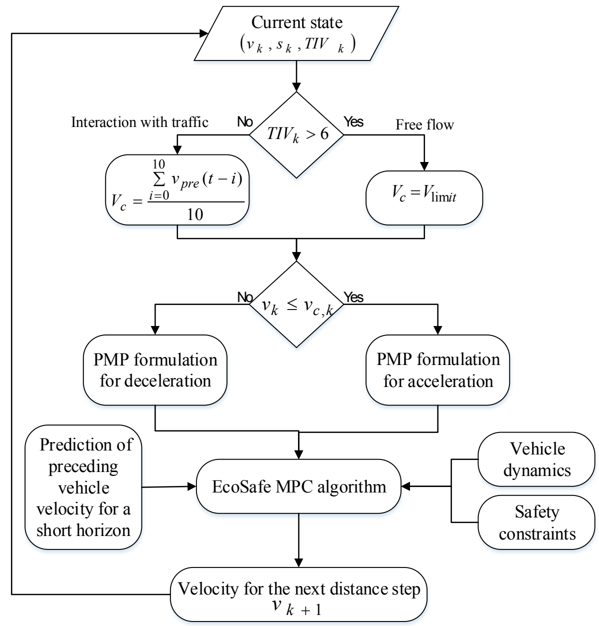

Fig. 2. Tuning method for EcoSafe algorithm

Fig. 3. Trajectory map used in this study with *1,100 km* total travel distance.

We extracted the posted speed limit of the trajectories using the reported speed limit from OpenStreetMap (OSM) [14]. The closest GPS coordinate of OSM with "*highway*" label is matched with the ANDS GPS coordinates and the reported speed limit is used for evaluation. If the speed limit is not reported by OSM, the Australian standard of speed limit based on the road types in New South Wales is used as the speed limit of the trajectory [15]. Finally, the extracted speed limit profile was manually checked to ensure that the trajectory has a realistic speed limit value.

2) Analysis and comparison of EcoSafe Algorithm

The EcoSafe driving performance is compared with a baseline situation. The baseline is defined as a situation where the following vehicle is mimicking the speed and acceleration/deceleration pattern of the leading vehicle. The naturalistic driving data extracted from section III.1 is used for this purpose. The following two subsections describe the eco driving and safety criteria, respectively.

a) Eco-driving criteria

The main criteria for eco-driving is the consumed fuel. We use fuel economy (consumed fuel per travel distance, gr/km) to evaluate the benefits of EcoSafe driving algorithm. The eco driving index is defined in percentage using the following equation:

$$\%F_{eco} = \frac{(FC_{pr} - FC_f)}{FC_{pr}} \times 100 \tag{8}$$

Where FC_{pr} is the total fuel consumption when following vehicle has the behaviour same as preceding vehicle and FC_f is the total fuel consumption when the preceding vehicle follows the EcoSafe algorithm.

The other factor that increases the effectiveness of the eco-driving is the total travel time. Usually, the disadvantage of eco-driving is an increase in the total travel time. In order to overcome this limitation, the strategy described in Fig. 2 changes the value of the comfort velocity to the maximum speed limit which helps to increase the mobility. The difference in travel time is given by:

$$\text{Difference in travel time} = \mathrm{T}_{end,pr} - \mathrm{T}_{end,f} \tag{9}$$

Where $\mathrm{T}_{end,pr}$ and $\mathrm{T}_{end,f}$ are the travel time of leading and preceding vehicle, respectively.

Finally, the acceleration rate is also used as another criterion for eco-driving. The number of time when the vehicle exceeds smooth acceleration (unsmooth acceleration is considered $|a| > 3\ \mathrm{m/s^2}$) is used to evaluate the EcoSafe algorithm.

b) Safety criteria

The main safety criteria is to keep a safe TIV with the preceding vehicle. The number of times in which EcoSafe algorithm has unsafe TIV ($TIV<TIV_{min}$) is a metric to compare different driving styles. In addition to TIV the following criteria are used:

- The percentage of driving time where the vehicle's velocity exceeds the speed limit.
- Number of hard deceleration events

The hard deceleration threshold is set to $a<-3\ (m/s^2)$ based on the existing literature [16]. In the next section, the benefits of EcoSafe driving in terms of eco-driving and safety are addressed.

IV. Results and Discussion

First, the proposed tuning method for EcoSafe algorithm described in section II.4 is tested and compared with the constant comfort velocity when it is set to the speed limit. Then, the impact of EcoSafe algorithm on the fuel consumption and safety is evaluated using several trajectory

Table 1. Vehicle specifications

Symbol	Name	Value
c_0	Lumped coefficients of vehicle dynamics	102.1
c_1		9.503
c_2		0.4402
c_r	Rolling friction	$[1.72, 4.77, 2.83, 2.24, 2.01, 1.91]$
I	inertia	$[1420, 2118, 1673, 1537, 1484, 1462]$
i	Gear ratio	$[45.29, 27.28, 18.55, 13.78, 11.19]$
α_0	coefficients of Fuel consumption model	0.0002525
α_1		$4.358e-08$
α_2		$1.197e-12$
shift schedule (km/h)	-	$[-, 30, 41, 56.6, 76.5]$
ω_{min}	Min. Engine speed	93.6 rad/s

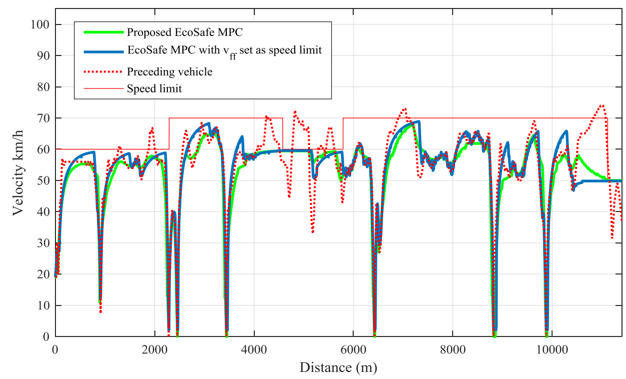

Fig. 4. Comparison between velocity profile of preceding vehicle (dashed line) vehicle, EcoSafe-MPC with proposed strategy (green line), and v_{ff} set as speed limit (blue line)

trips extracted from ANDS dataset. All simulations were performed using MATLAB (version 7.14, R2016a) on a PC with an Intel Core i7 CPU and 6MB RAM to run the simulation. The parameters for the vehicle models are shown in Table 1 and a flat road was assumed.

A pre-set gear shift schedule was used for simulation purposes. To align with the literature, the safety factors are considered $a_{min} = -3[\frac{\mathrm{m}}{\mathrm{s}^2}]$, $a_{max} = 3[\frac{\mathrm{m}}{\mathrm{s}^2}]$, $TIV_{min} = 2[\mathrm{s}]$, $l = 2[\mathrm{m}]$ and $TTC_{min} = 6[\mathrm{s}]$ for the simulation [1, 16]. A distance step equals to $5[\mathrm{m}]$ with $m = 5$ was used for EcoSafe-MPC algorithm. The initial distance with the preceding vehicle is set to the TIV=2[s]. Finally, the fuel reduction is compared with the situation where the following vehicle has a same behaviour as the preceding vehicle (baseline).

A. Proposed EcoSafe tuning method

Fig. 4 shows an example of EcoSafe trajectory for an 11 km trip of ANDS data with the preceding vehicle trajectory (red dashed line) and the speed limit (red line). Two choices of $v_{adp,k+i|k}$ were considered in order to obtain the velocity profile in Fig. 4. For the first experiment v_{adp} was set to the speed limit (blue line). The second experiment used the proposed driving strategy described in Fig. 2 (green line). It is observed that when the speed of the preceding vehicle is not considered when setting v_{ff}, the average velocity is

Table 2. Comparison of eco-driving and safety criteria between EcoSafe driving and leading vehicle

Comparison Criteria		EcoSafe Algorithm				Leading vehicle				Improvement
		Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	
Eco Driving	Fuel economy *(gr/km)*	59	8	43	83	71	11	54	110	EcoSafe driving improves fuel economy by 14.2%
	Travel time *(minutes)*	25	13	8	57.5	24.8	13	8	57.5	The EcoSafe algorithm has approximately same travel time of leading vehicle
	Numbers of unsmooth acceleration $\|a\|>3$ (m/s^2)	1.3	2.5	0	7	2.7	4.1	0	15	EcoSafe driving reduce unsmooth acceleration (2 times less)
Safety	Percentage of time above speed limit	0	N/A	0	0	20.03	0.01	0.11	68.89	EcoSafe driving respects speed limits in all conditions
	Numbers of unsafe headway TIV<2 *(s)*	18.14	18.32	0	90	-	-	-	-	EcoSafe driving keep the TIV more than TIV_{min}
	Unsafe TIV TIV<2	1.95	0.02	1.90	1.99	-	-	-	-	
	Hard Deceleration $(a<-3\ m/s^2)$	0.81	1.2	0	7	2.1	3.4	0	12	EcoSafe driving keep the hard deceleration in the safety range

higher (82.4 compared to 80.1 km/h), but it results in more abrupt and frequent decelerations to respect the safe TTC and TIV constraints. With the proposed strategy, the vehicle can smoothly adapt to the traffic conditions ahead. The result shows that the fuel consumption of proposed strategy is lower than the baseline since it has smoother speed profile by removing unnecessary deceleration. In this way, eco driving index is improved by 15.2%, compared to 10.7%. In this specific scenario, the driving time of the proposed method was approximately the same as the preceding vehicle (around 11 seconds), showing that this fuel improvement was not obtained at the cost of increasing travel time.

B. Benefit assessment of EcoSafe algorithm

Table 2 summarises the Eco and safe driving criteria for each trajectory in form of mean, standard deviation (SD), minimum (Min) and maximum (Max) values. In terms of eco driving, the proposed algorithm improves the average fuel economy by 14.2% compared with leading vehicle. The average travel time of the trajectories for EcoSafe driving and leading vehicle is approximately the same (25 compared with 24.8 minutes). This result shows that the proposed strategy in Fig.2 reduces fuel consumption with a limited impact on travel time by having average difference in travel time less than 10 seconds per trip. It has to be noted that in this condition, the speed limit is chosen as the driver preference. If drivers were willing to spend more time to save fuel by choosing a lower preference velocity, the algorithm would provide even higher fuel economy benefits. Finally, the algorithm reduces the number of unsmooth deceleration by half compared to the conventional option. The result shows that unsmooth deceleration events with EcoSafe driving are close to the threshold used ($|a|=3$ m/s^2), averaging at 3.2 m/s^2 (SD=0.08), unlike the driving behaviour observed from the naturalistic dataset, averaging at 3.8 (SD=0.43).

In terms of safety, the leading vehicle, as recorded by ANDS, drives around 20% of total travel time over the speed limit while the EcoSafe driving always respects to the speed limit. Besides, the number of Unsafe TIV (TIV<2s) averages at 18 times per trajectory.

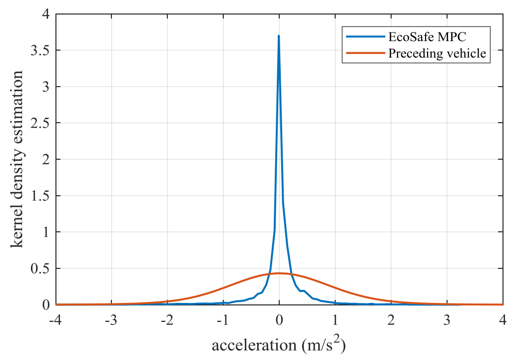

Fig. 5. Distribution of the acceleration for EcoSafe MPC (blue line) and preceding vehicle (red line)

Further investigation shows that the average of unsafe TIV is equal to 2.95s (SD=0.02) which is a consequence of the numerical discretisation of MDDP algorithm. This result shows that the EcoSafe driving algorithm respects safe headways with preceding vehicle up to a discretisation error. Finally, EcoSafe driving reduces the occurrence of hard braking events ($a<-3\ m/s^2$), providing the driver with safer deceleration compared to the leading vehicle.

Fig.5 shows the distribution of the acceleration/ deceleration achieved by the EcoSafe algorithm (red line) compared with the preceding vehicle (blue line). It shows that the EcoSafe algorithm has a lower range for acceleration/deceleration. This is due to the fact that the algorithm (i) provides a smoother change in velocity (small changes in acceleration); (ii) keeps the proper TIV and TTC with the vehicle ahead; and (iii) applies decelerations in the allowable range of decelerations, which cause smoother braking.

Fig. 6(a) shows the benefits of the EcoSafe driving in terms of F_{eco} as a function of the trip's average speed. It also provides F_{eco} histogram. In the studied sample, F_{eco} is varying between 5 and 35%, with average of 14%. Furthermore, this figure shows that the proposed algorithm provides more benefits for average travel speed less than 70 km/h. This is likely to show that the EcoSafe algorithm provides more benefits on urban and congested roads as compared to higher speed roads free flowing. Fig. 6(b) shows the F_{eco} with respect to the number of hard accelerations/decelerations recorded per trip. This figure shows that the more a preceding vehicle travels with hard accelerations or decelerations, the more EcoSafe algorithm provides fuel saving. This is due to the algorithm's ability to reduce unnecessary hard accelerations, which is one of the key factor targeted by eco-driving guidelines. Overall, the performance of the EcoSafe algorithm depends on the roads (speed, traffic), as well as the performance of the driver. These results are aligned with previous research on eco-driving benefits.

V. CONCLUSION

This paper has evaluated the benefits of a new EcoSafe algorithm in terms of fuel economy, safety and travel time using naturalistic data. First, a strategy is proposed to adapt the velocity of the vehicle to the traffic conditions. This resulted in reducing fuel consumption as well as improving safety. Then the proposed method was tested using several naturalistic driving trajectories including 41 trajectories with total 1,100 km driving distance. The simulation results show that EcoSafe algorithm can reduce the fuel consumption with the average of 14% by only increasing average travel time 9.7 seconds. In terms of safety the proposed method has a smoother velocity profile compared to the baseline situation when the vehicle has the same trajectory of the preceding vehicle.

Future research should focus on extending the proposed strategy and algorithm to more complex trajectories, such as trajectories including intersections with traffic lights.

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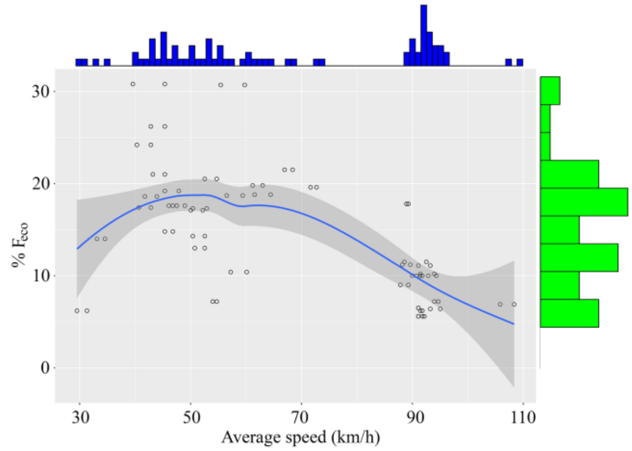
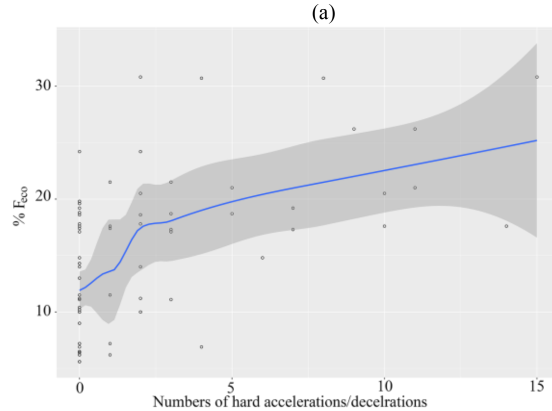


(a)



(b)

Fig. 6. Fuel efficiency benefits of the EcoSafe driving with respect to the average speed (a) and number of hard accelerations/decelerations (b) for different trips of ANDS dataset.

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