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Research Article

Modelling Eco-Driving Support System for Microscopic Traffic Simulation

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Microscopic traffic simulation is an ideal tool for investigating the network level impacts of eco-driving in different networks and traffic conditions, under varying penetration rates and driver compliance rates. The reliability of the traffic simulation results however rely on the accurate representation of the simulation of the driver support system and the response of the driver to the eco-driving advice, as well as on a realistic modelling and calibration of the driver's behaviour. The state-of-the-art microscopic traffic simulation models however exclude detailed modelling of the driver response to eco-driver support systems. This paper fills in this research gap by presenting a framework for extending state-of-the-art traffic simulation models with sub models for drivers' compliance to advice from an advisory eco-driving support systems. The developed simulation framework includes among others a model of driver's compliance with the advice given by the system, a gear shifting model and a simplified model for estimating vehicles maximum possible acceleration. Data from field operational tests with a full advisory eco-driving system developed within the ecoDriver project was used to calibrate the developed compliance models. A set of verification simulations used to illustrate the effect of the combination of the ecoDriver system and drivers' compliance to the advices are also presented.

1. Introduction

Eco-driving, which constitutes of a set of behaviours that drivers can adopt to save fuel, and reduce emissions, holds significant promise in substantially contributing to transport sustainability [1]. It may furthermore enhance traffic safety as a positive side effect as a result of lower speeds dictated by the system. While, eco-driving behaviours in the wider scope include strategic decisions (e.g. vehicle selection and maintenance), tactical decisions (e.g. route selection and vehicle loading) and operational decisions like gradual acceleration and decelerations [2], recent research have focused more on real-time operational measures that a driver can adopt to reduce fuel consumption and emissions given the instantaneous traffic conditions. These can include guidance on optimum gear configuration and acceleration, the anticipation of downstream network and traffic conditions and guidance on avoiding unnecessary acceleration and deceleration [3, 4]. All these aspects are heavily reliant on properly designed driver support systems. This has prompted research in optimum design and extensive testing of appropriate eco-driving driver-support systems using driving simulator [e.g. 5, 6] and field data [e.g. 7]. However, eco-driving also has a significant impact on the speed and acceleration of the surrounding vehicles. For example, since an eco-driver may accept to drive at a lower speed or start deceleration for upcoming lower speed limits earlier than usual, the surrounding drivers may be forced to adopt similar speeds and accelerations. At the network level, this may lead to increase (due to slower vehicles) or decrease in congestion (due to smoother flows). Thus, eco-driving can have a significant network wide effect which needs detailed investigation.

Effects of driver support systems are commonly assessed using driving simulator experiments or field trials. Such investigations give important information on how eco-driving and other support system affect individual driver's behaviour and energy usage. However, in order to estimate the network-wide effects, a translation of the effects of individual driver behaviour to a larger scale and future years with higher penetration rates than can be achieved in field tests is needed. Microscopic traffic simulation tools, where individual driver behaviours can be replicated to deduce network level traffic conditions, is an ideal tool for evaluating such traffic system level impacts of eco-driving support systems. By using microscopic traffic simulation, the potential of the eco-driving support systems can be investigated for different networks and traffic conditions and under varying penetration rates and driver compliance rates. The reliability of the traffic simulation results, however, rely on how accurately the driver support system and the response of the driver to the eco-driving advice are represented in the simulation, as well as on how realistically the basic driver behaviour is modelled and calibrated.

Driving simulator studies and field trials provide important information on how eco-driving support systems affect individual driver's behaviour. The fidelity of the traffic simulation tools for estimating the real potential of eco-driver support systems, therefore, depends on proper implementation of the findings of the field trials in the simulation framework. However, the existing traffic simulation studies investigating the benefits of eco-driving are primarily based on ad-hoc variations of the driving behaviour models estimated using normal traffic data [e.g. 8], simulated data [e.g. 9] and test track data [e.g. 10, 11]. Data from the field tests of the FIAT [12] eco-driving feature have been used by Morello et al. [13] and Garcia-Castro and Monzon [14] to calibrate a car-following model for eco-drivers without explicit modelling of the system properties or the drivers compliance. The state-of-the-art microscopic traffic simulation modelling thus excludes detailed modelling of the driver behaviour in response to eco-driver support systems.

The aim of this article is to fill in this research gap by presenting a framework for extending traffic simulation models with sub model's for drivers' compliance to advice from a full eco-driving support systems (FeDS). The developed simulation framework includes among others a model of driver's compliance with the advice given by the system, a gear shifting model and a simplified model for estimating vehicles maximum possible acceleration.

This article is organised as follows: an overview of approaches for traffic simulation modelling of driver support systems is presented in Section 2. Section 3 presents the details of the FeDS – the eco-driver support system considered in this work. The framework developed for the simulation is described in Section 4. Section 5 presents the models developed for handling the drivers' interaction with advice from the eco-driving systems, including calibration of model parameters using field trial data. Section 6 describes the vehicle model utilised to extend the traffic simulation models with engine speed and max acceleration calculations. Results from a verification simulation is presented in Section 7. Section 8 ends the paper with conclusions and need for further research.

2. Traffic Simulation of Driver Support Systems

Microscopic traffic simulation models are a common tool for estimating impacts from driver support systems on the traffic system. Analysis of adaptive cruise control (ACC) is the most widely studied driver support system [e.g. 15, 16–27], but other systems such as route guidance [e.g. 28]; intelligent speed adaptation (ISA) [e.g. 29, 30]; collision avoidance [e.g. 31], fuel-minimizing cruise controllers [e.g. 32] and overtaking assistants [33] have also been examined.

However, as reported by Tapani [34, 35], many of these studies considered only the driver support system's functionality and did not concentrate on the changes in driver behaviour that the systems may induce. Some studies [see e.g. 21, 31, 36] include modelling of drivers interaction with the support system, but this is not a common practice and certainly not part of the standard commercial microscopic simulation tools. For example, microscopic simulations of ACC commonly use the approach of replacing the car-following model with an ACC controller [e.g. 15, 16–20, 22, 23, 25–27] and directly or indirectly assume that an ACC equipped vehicle always use the ACC. However, there are several situations in which drivers have been observed to deactivate the ACC-function [21]. To be able to capture the full effect of ACC both [21] and later [24] extended microscopic traffic simulation models with modelling of drivers de- and reactivation of the ACC-function. Drivers were for example found to deactivate the ACC in congested traffic or when overtaking. A similar approach was also used in [32, 37] to model truck driver's de- and reactivation of a fuel minimising cruise controller for trucks. Real truck drivers were for example found to sometimes deactivate the fuel minimising cruise controllers during overtakings when the cruise controller decreased the speed to save fuel.

Another approach to capture driver's interaction with the support system is to combine the modelling of the support system and the drivers compliance with the system. This approach was for example used in [30] to study ISA. The combination of the ISA-system and the drivers' compliance with the ISA-system was modelled by adjusting the desired speed of equipped vehicles, i.e. the desired speed of ISA equipped vehicles was drawn from another desired speed distributions than the nonequipped vehicle.

Given the 'discretionary' nature of the eco-driving advice, it is crucial that the microscopic traffic simulation modelling is extended to incorporate not only the simulation of the eco-driving support system in the equipped vehicles but also the drivers' compliance to the advice given by such systems. This can either be done by modelling the behaviour of drivers equipped with the system, without separating modelling of the eco-driving support system and the drivers' interaction with the system (e.g. by adjustments of parameters in the car-following model [as e.g. in 13] or in the desired speed distribution [as e.g. in 30]), or by explicitly using separate models of the support system and the interaction of the driver with the support system [as e.g. in 32, 37]. While the former may be sufficient for investigations of the effects of driver support systems for existing traffic situations, it is not appropriate for use in investigating future traffic scenarios where both penetration and compliance rates are likely to differ from the existing scenario. Therefore, a separate modelling of the FeDS and the driver's compliance to the FeDS is preferable since it allows a more straight forward analysis of effects of different compliance rates for future traffic scenarios.

3. The Investigated Eco-Driving Support System

The eco-driving system investigated in this article is the so-called Full ecoDriver system (FeDS) developed in the ecoDriver project. The FeDS provides advice to drivers on fuel-efficient driving by optimising the driver-powertrain-environment feedback loop. The system uses a vehicle energy and environment estimator (named VE^3), that runs on-line in vehicles utilising on-board (sensor) information and an e-horizon functionality based on digital map data. The energy estimator uses a physics-based energy usage model based on a powertrain model to estimate optimum, from an energy usage perspective, speed and gear configuration considering vehicle factors (powertrain, gear, speed) and roadway factors (gradient and speed limit). An energy usage lookup-table is used to allow for fast estimations of actual and optimal energy usage (see [38–40] for details on the powertrain and energy usage model). With these data on energy usage, a signal is generated for eco-friendly driver guidance, which is relayed to the driver via a human-machine interface. The final advice is not a "hard core" energy saving advice, i.e. the FeDS will e.g. not suggest a speed lower than the speed limit if you are currently driving above the speed limit even if such speed would imply a lower energy usage. Furthermore, the system will take traffic safety into account and it will not give advice that might imply safety issues, e.g. by giving an advice that is higher than the speed limit or the drivers currently preferred speed even if such a speed would decrease the energy usage (see [39, 41] for details).

FeDS provides the driver with a continuous speed and gear advice together with pop-up warnings/advice like lift your foot off the pedal to adapt on upcoming speed limit changes, intersections, sharp curves, etc. The main screen of the FeDS is presented in Figure 1. The speedometer was shown with the current speed and the speed advice (in green). The advised speed was shown continuously. Advice to change the speed was provided for approaching: an intersection; a lower speed limit; a curve; and a preceding vehicle. The current gear was indicated including gear shift advice (in this case the advice is to stay at the current gear). The performance of the driver was indicated through green circles against a background of a tree indicating the eco-driving performance (five filled circles indicated excellent eco-driving performance and none a poor performance).

FeDS was implemented in test vehicles driven in field tests in France, Germany, Spain, and Sweden (see Woldeab et al. [42] and Lai et al. [43] for descriptions of the different test sites). A mix of controlled and naturalistic tests was carried out, with various types of vehicles (e.g. passenger cars, trucks and buses) with different powertrains (ICE (petrol), ICE (diesel), and fully electric vehicles). However, in order to estimate the true potential of FeDS, the results of the field trials needed scaling up to the EU-28 level using a scenario-based approach including three different future scenarios for a 20-year time horizon. This motivates the current study where we focus on the critical step to implement and realistically replicate the FeDS in microscopic traffic simulation environments.

Figure 1: Main screen of the Full ecoDriver System (FeDS).

4. Simulation Framework for Evaluation of the FeDS

As mentioned in Section 2, separate models of the FeDS and compliance is essential to realistically model future years where compliance rate is expected to vary among different scenarios and future years. The proposed framework for achieving this (presented in Figure 2) consists of four main components:

(1) a *Traffic Simulation program (TS)*,
(2) an *External Module (EM)* handling the FeDS and drivers interaction with the systems,
(3) a traffic simulation program specific *Application Program Interface (API)* which handles the connection between the traffic simulation program and the external module, and
(4) a *Performance Indicator calculation module (PI)*.

The external module (*EM*) consists of three sub modules:

(1) the *ecoDriver system (ED)*,
(2) a *Driver Model (DM)*, and
(3) a *Vehicle Model (VM)*.

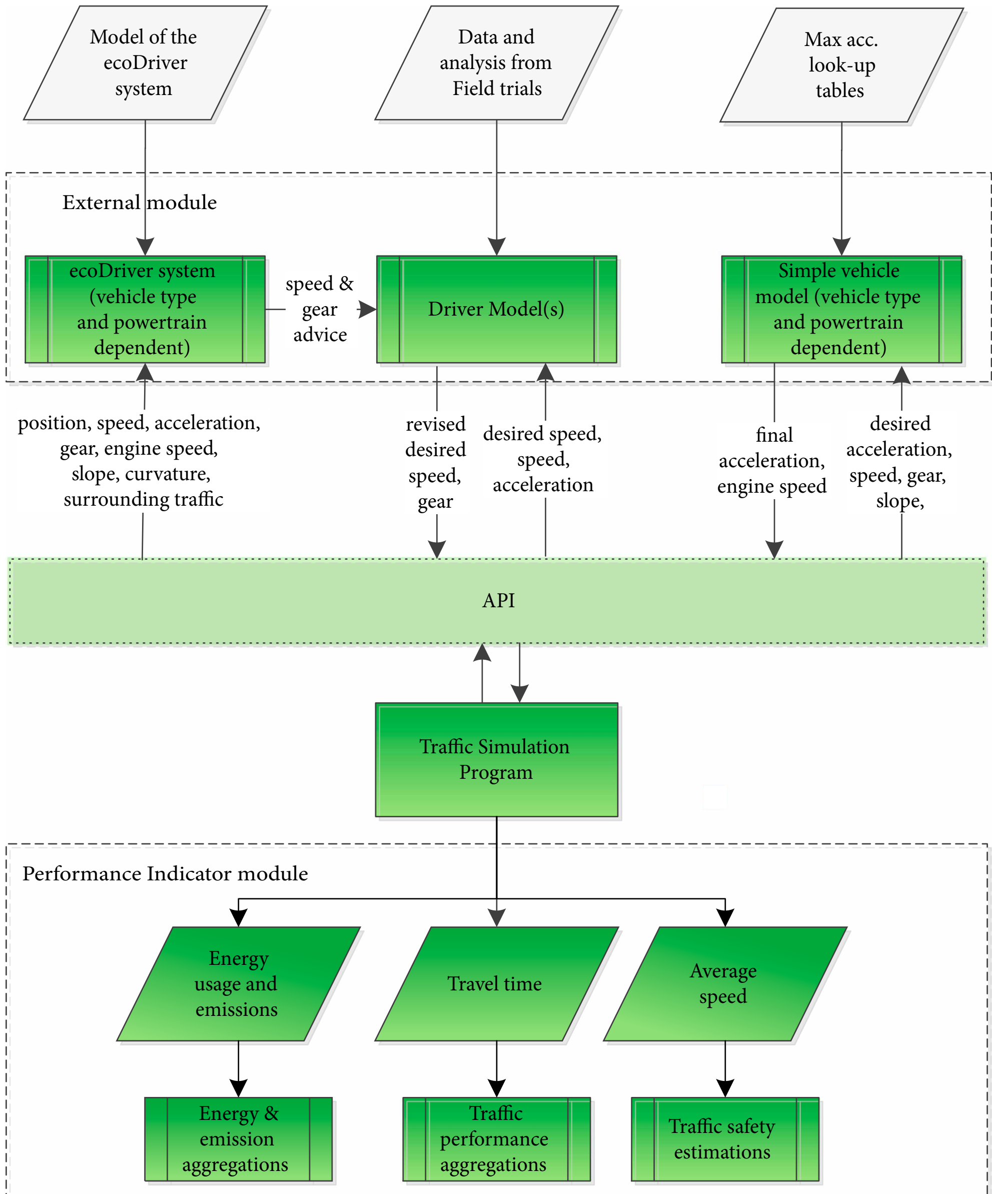

Figure 2: The traffic simulation framework.

The *ecoDriver system module (ED)* are vehicle class (passenger car, van, truck) and powertrain (petrol/diesel, hybrid, electric vehicle) specific models of the ecoDriver system that were developed within the ecoDriver project [39, 41]. The *ecoDriver system module* generates speed and gear advice to the drivers based on the vehicle current state and map data (received from the *Traffic simulation program (TS)* using the *API*). The *Driver model(s) module (DM)* simulate how drivers respond to that advice, in particular, their compliance with the speed and gear advice under different circumstances. These models are based on data collected in the field trials conducted within the ecoDriver project. The drivers' choices (speed, acceleration, gear) are fed into a simple *Vehicle model module (VM)* that determines the engine speed and whether the vehicle can deliver the requested acceleration. The data are then via the *API* fed into the *Traffic simulation program (TS)* which updates the vehicles' positions. This way, vehicle trajectories are fed into the *Performance Indicator module (PI)* in which aggregated statistics are generated. The statistics are used to determine the impacts of the FeDS on traffic performance (i.e. travel times), traffic safety (i.e. relative changes in accidents and fatalities), and the environment (i.e. energy use and emissions). Extracting travel times from microscopic traffic simulation models is straightforward while the estimation of emissions and safety effects requires additional modelling. For the estimation of energy usage and emissions, an external emission model was developed based on Ligterink, Van Zyl [44]. A positive safety effect is expected since the system generally leads to a speed reduction. In order to understand and assess the safety effect (how much is the speed reduction and what is the relation of that with the estimated number of accidents), we use the results of the simulations as input for the speed power model [45, 46], which relates the relative change in e.g. accidents to the relative change in average speed based on real accident statistics.

5. Modelling of Drivers Interaction with the FeDS

As described in Section 4 the traffic simulators have to be complemented with driver models considering the driver's compliance with the advice that the driver support system gives, in the case of the FeDS the following advice was taken into account:

(1) when to start anticipation to a lower speed limit (t_{ED}^{a}),
(2) which speed to drive at (v_{ED}^{a}),
(3) at which engine speeds (r_{ED}^{a+} and r_{ED}^{a-} to shift gear (up and down).

It is reasonable to assume that drivers will not fully comply with, nor totally disregard, the advice given by the system. To represent such situations, a model that revises the driver's desired speed was developed. The revised desired speed was [as in e.g. 36] set up as a linear combination of the driver's desired value and the advice from the system. An important part of the design of the compliance models was that it should be possible to calibrate the compliance parameters using data from field trials. Since the traffic simulators do not model gear shifting while the FeDS gives advice with respect to gear shifting, an additional gear shifting driver model was also developed (to allow calculation of the driver's desired gear and gear shifting behaviour). This section describes these additional driver models, but starts with a description about the field trial data used for the calibration of the models.

5.1. Calibration Data. The data available for calibration were 10 Hz sampled data from controlled drives with the FeDS using a Volvo V70 (Diesel). The controlled trials with the Volvo V70 were carried out in Sweden with 10 participants. Each participant conducted two baseline drives (without the FeDS) and six treatment drives (with the FeDS). Each drive was ~90 km long and included both urban, rural road and motorway driving. For a complete specification of the route see [42].

5.2. Speed and Start of Deceleration Compliance with the FeDS

5.2.1. Compliance Model for Start of Deceleration with respect to Upcoming Speed Limit. The extended driver model includes a start of deceleration compliance model, estimating when the driver desires to start anticipating upcoming lower speed limits. The model estimates the time when the driver desires to start decelerating in order to adapt its speed with respect to the upcoming speed limit. The output of the driver model (DM) is a revised desired start of deceleration time t_{DM}^{des} which is calculated as

$$t_{DM}^{des} = c_{\text{deceleration}} \cdot t_{ED}^{a} + \left(1 - c_{\text{deceleration}}\right) \cdot t_{TS}^{des}, \qquad (1)$$

where t_{TS}^{des} is the original desired time (i.e. the base value in the traffic simulation (TS)) and t_{ED}^{a} is the time advised from the ecoDriver system (ED) and $c_{\text{deceleration}} \in [0,1]$ is to what extent the driver takes the advice into account. A fully compliant driver ($c_{\text{deceleration}} = 1$) will start the deceleration at the advised time t_{ED}^{a} and a noncompliant driver ($c_{\text{deceleration}} = 0$) will start decelerating at t_{TS}^{des}. Driver reaction time to the advice is not explicitly modelled. This is instead implicitly taken into account in the calibration of the time when to start adaptation to a new desired speed, e.g. at a speed limit change.

5.2.2. Compliance Model for Speed Advice. Also, the speed compliance model was designed as a linear combination of the driver's desire and the advice, i.e. the driver's desired speed v_{TS}^{des} and the instantaneous speed advice v_{ED}^{a} given by the FeDS. The output is a modified desired speed v_{DM}^{des} calculated as

$$v_{DM}^{des} = c_{\text{speed}} \cdot v_{ED}^{a} + \left(1 - c_{\text{speed}}\right) \cdot v_{TS}^{des}, \qquad (2)$$

where $c_{\text{speed}} \in [0,1]$ is the parameter representing the driver's compliance with the system advice. This model allows any degree of compliance with the advice from full compliance, $c_{\text{speed}} = 1$ implying $v_{DM}^{des} = v_{ED}^{a}$, to no compliance, $c_{\text{speed}} = 0$ implying $v_{DM}^{des} = v_{TS}^{des}$.

There is though one exception from the calculation in Equation (2) concerning the driver's revised desired speed v_{DM}^{des}. The exception is related to changes in speed advice as a consequence of upcoming lower speed limits. The advice on when to start anticipate upcoming lower speed limits indirectly change the advised speed from the current speed limit to the upcoming lower speed limit. Whether the driver will follow the new speed advice for the upcoming speed limit depends on the driver's compliance with the start of deceleration advice for an upcoming speed limit change. The driver will start to adjust its speed to the new speed advice if the time to reach the position of the upcoming speed limit sign $t_{v_{limnext}}$ (estimated based on the current speed and the distance to the speed limit sign) is shorter than the desired time to start anticipation towards the next speed limit t_{DM}^{des}. If the driver does not accept the new speed advice, the desired speed remains the same as in the previous time step $v_{DM}^{des}(t-dt)$. This implies that Equation (2) has to be extended and v_{DM}^{des} is in the end calculated as

$$v_{DM}^{des} = \begin{cases} c_{\text{speed}} \cdot v_{ED}^{a} + \left(1 - c_{\text{speed}}\right) \cdot v_{TS}^{des} & v_{ED}^{a} = v_{lim} \\ c_{\text{speed}} \cdot v_{ED}^{a} + \left(1 - c_{\text{speed}}\right) \cdot v_{TS}^{des} & v_{ED}^{a} = v_{lim\text{next}} \quad \text{and} \quad t_{v_{limnext}} < t_{DM}^{des} \\ v_{DM}^{des}(t-dt) & \text{otherwise,} \end{cases} \qquad (3)$$

where v_{lim} and $v_{lim\,next}$ is the current and the upcoming next speed limit, respectively. An example of how the driver's decision of applying the advised speed may vary during the deceleration phase, is illustrated in Figure 3. The figure show a 50% compliant driver with a desired speed 10% above the speed limit approaching a speed limit change from 80 to

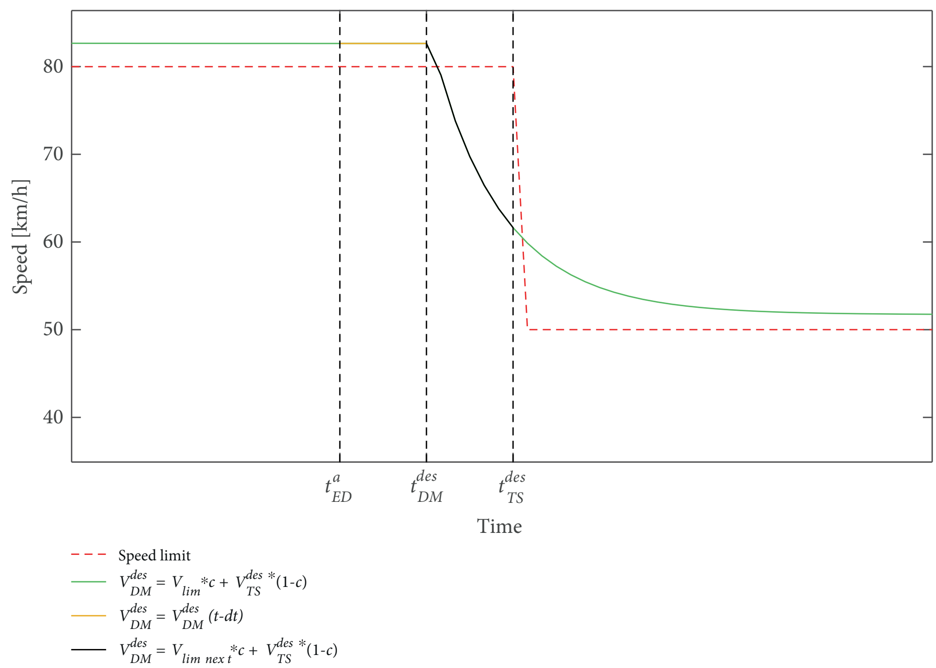

Figure 3: Example of how the desired speed may vary during the deceleration phase for a 50% compliant driver with the desired speed 10% above the speed limit given a speed advice equal to the speed limit. Note that the time is related to the time when the driver is expected to reach the speed limit change.

50 km/h. For time $t < t^a_{ED}$, the driver is 5% above the speed limit. It would have been 10% without the system. The system advises 0% above the speed limit, so 50% compliance means $0.5 \cdot 10\% + 0.5 \cdot 0\% = 5\%$. Time t^a_{ED} is the moment that the system advises to lift the foot of the accelerator pedal. t^{des}_{TS} is the time that an unequipped (or noncompliant) driver will start decelerating, here assumed to be when passing the speed limit sign. Our 50% compliant driver will pick a time exactly in the middle between t^a_{ED} and t^{des}_{TS}, namely at $t^{des}_{TS} = 0.5 \cdot t^a_{ED} + 0.5 \cdot t^a_{TS}$.

5.2.3. Speed Compliance Calibration Using Field Data. The speed compliance model includes one parameter c_{speed}, that needs to be estimated. In order to estimate c_{speed}, data from controlled field trials within the ecoDriver project were used to estimate the participants' desired speed with and without the system (for different sets of situational variables). To estimate the desired speeds, sections of free driving and cruising were extracted from the baseline drives without the FeDS and treatment drives with the FeDS. Free driving was specified by a time headway larger than 6 s and cruising by $|\text{acceleration}| < 0.6\,\text{m/s}^2$. This is the same definition as used in the field trial analysis and was chosen in order to ensure consistency with the field trial analysis [47]. Furthermore this is in line with the findings of e.g. Vogel [48]. Free driving and cruising samples constituted approximately 55% of the total data set. Estimations of desired speeds requires long enough sections of free driving and cruising. Therefore, sections of free driving and cruising shorter than 10 s (which constitutes 62.5% of the epochs) were ignored in the analysis.

Figure 4 presents the distributions of desired speeds estimated from the field trials for the treatment (TR) and baseline (BL) driven with a Volvo V70 equipped with the FeDS during the treatment drives. Each distribution is constructed based on all observations from all drivers for a specific combination of speed limit and case (i.e. BL or TR). The general observation is decreasing desired speed when using the FeDS, i.e. the solid curves for the desired speed distribution in the treatment cases lies in general to the left of the corresponding dotted curve for the desired speed distribution for the baseline case without

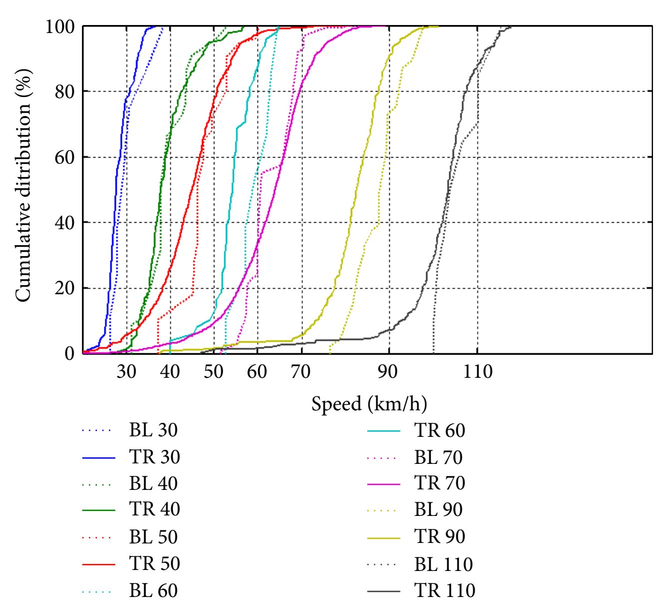

Figure 4: Distributions of desired speeds (cruising and free-driving speed) for the cases without (BL) and with (TR) the FeDS.

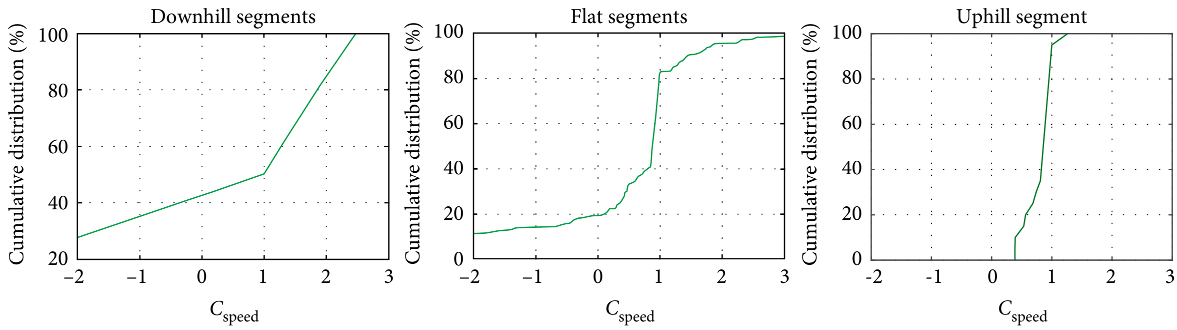

Figure 5: Speed compliance distributions for free and cruising segments in the field trials for drivers with desired speed above the speed limit.

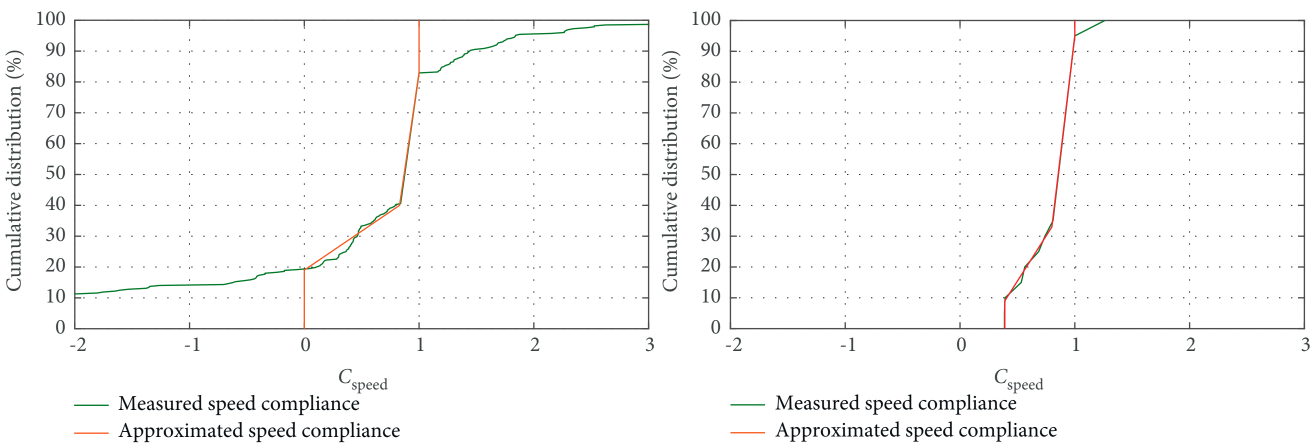

Figure 6: Estimated and approximated speed compliance distributions based on field trial data.

the FeDS. Even if the trials were quite long (~90 km), the two baseline drives with the Volvo V70 resulted in a rather low number of free driving and cruising segments for some speed limits, which can be observed in Figure 4 in form of nonsmooth desired speed distributions for the baseline cases.

The estimated desired speeds from the baseline drivers were used to calculate estimates of the compliance factor c_{speed} by comparing specific driver's desired speed in each free driving and cruising section in the treatment drives with the same driver's average desired speed in the baseline drives and the speed advice by the FeDS. Figure 5 illustrates cumulative distributions of the estimated speed compliance at different slope classes (downhill (<−3%), level (>−3% and <3%) and uphill (>3%)) for drivers with a baseline desired speed above the speed limit. We concluded early that drivers with desired speed below the speed limit almost have 100% compliance due to that the FeDS was designed in such a way that the system adapted the advice towards the driver's desired speed when driving slower than the speed limit. It was assumed that there is no difference between compliance at downhill and flat sections, mostly because of the limited number of observations (only 4) for downhill segments. Separate compliance was estimated for uphill (20 observations) and flat (328 observations) sections since compliance seems to be higher when driving at uphill sections.

Based on the centre and right-hand subfigure in Figure 5, speed compliance distributions were approximated using piecewise linear distribution as illustrated in Figure 6. The piecewise linear distribution was chosen since it is the simplest function that could be fitted well to the data.

Desired speed is a traffic simulation model construction and in reality, drivers desired speed can vary from day to day. This leads to the notion that drivers with an estimated average desired speed above the speed limit sometimes drive faster in the treatment drives than their estimated desired speed from the baseline drives, which yield a compliance less than 0. There were also cases in which the drivers drove even slower than the advised speed (i.e. compliance above 1). It was difficult to distinguish whether this was due to overcompliance with the advice or due to the variation in desired speed over time. The approximated distribution therefore assume only compliance between zero and one meaning all drivers estimated having negative compliance were modelled as having zero compliance (this has the same effect as being unequipped, but is conceptually different) and drivers having more than 100% compliance were treated as if they fully comply but do not drive slower than the advised speed.

5.2.4. Deceleration Compliance Calibration Using Field Data. Analysis of the participants' compliance with the advice on upcoming lower speed limits was not straightforward. The desirable approach is to conduct location specific within participant comparisons of when the participants start to

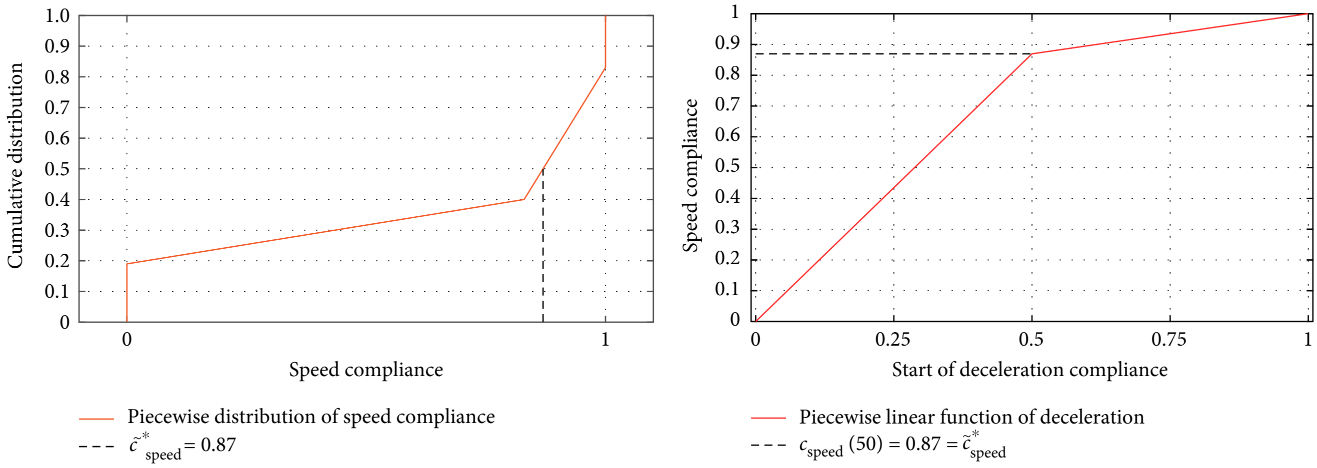

FIGURE 7: Piecewise linear distribution of deceleration compliance $c_{\text{deceleration}}$ (right) and how it is related to the piecewise linear distribution of speed (left).

decelerate in the baseline and treatment drives. Additionally only cases without any constraining leader vehicle should be used to avoid that the start of the deceleration is given by the deceleration of a preceding vehicle. This give a maximum of 2 baseline and 6 treatment observations for each participant and location, which resulted in too few observation and to noise data.

Instead we used a between group analysis and compared average behaviour over all participants in the baseline and the treatment drives. Analysis of the field trials indicate that the average time of anticipation using the FeDS was around 6 s (150 m at speed limit 90 km/h) earlier than in the baseline drives. Furthermore, the data indicated that there were no difference in average deceleration rate levels between the baseline and the treatment drives. The limited number of suitable speed limit change locations and observations per location did not allow for detailed analysis and the calibration were based on the indications found in the data material. Unequipped drivers were by default assigned $t^{des}_{TS} = 0$ seconds based on the current calibration and default settings used in the utilized traffic simulation models. A 6 s earlier response can be interpreted as an average change in compliance with 50 percent since the advice in average was launched 12 s before the speed limit change. So equipped drivers were in average assumed to have a 50% compliance to the advice on when to start decelerate for a lower speed limit.

The limited data did not allow for variance or correlation analysis between the speed compliance and compliance with the advice on when to start anticipation to a lower speed limit. It is reasonable to assume some correlation between speed compliance and distance starting anticipating to a lower speed limit, i.e. that the deceleration compliance is a function of the speed compliance $c_{\text{deceleration}}(c_{\text{speed}})$. Since the only data available was estimations on drivers' average compliance with the advice on when to start anticipation to a lower speed limit we align the $c_{\text{deceleration}}$ and c_{speed} for an average driver, or more precisely a median driver. We assume that also the deceleration compliance function $c_{\text{deceleration}}(c_{\text{speed}})$ is a piecewise linear function and that the speed compliance for the median driver and the deceleration compliance for the median driver deduce the breakpoint in this piece-wise linear function. Thus, the function $c_{\text{deceleration}}(c_{\text{speed}})$ is synchronized so that the $t^a_{ED} \cdot c_{\text{deceleration}}(\tilde{c}^*_{\text{speed}}) = 6 \quad s$ given that $\tilde{c}^*_{\text{speed}}$ represents the optimum median speed compliance estimated according to Equation (4). $\tilde{c}_{\text{speed}}$ represents all points where the median speed compliance is obtained.

$$\tilde{c}^*_{\text{speed}} = \max\left\{\tilde{c}_{\text{speed}} : P\left(\text{speed compliance} \le \tilde{c}_{\text{speed}}\right) \le 0.5\right\} \tag{4}$$

In most cases, there will be a unique value $\tilde{c}_{\text{speed}}$ where $P(\text{speed compliance} \le \tilde{c}_{\text{speed}}) = 0.5$ (namely, this is the case if the cumulative distribution graph has a slope that is not vertical and not horizontal at the point $(\tilde{c}_{\text{speed}}, 0.5)$, which e.g. is the case in Figure 6). If there is a unique value of $\tilde{c}_{\text{speed}}$ Equation (4) may be simplified to $\tilde{c}^*_{\text{speed}} = \tilde{c}_{\text{speed}}$. The value of $c_{\text{deceleration}}$ is in the end calculated as

$$c_{\text{deceleration}}(c_{\text{speed}}) \begin{cases} \dfrac{c_{\text{speed}}}{2\tilde{c}^*_{\text{speed}}}, & c_{\text{speed}} < \tilde{c}^*_{\text{speed}} \\ 1 - \dfrac{1 - c_{\text{speed}}}{2\left(1 - \tilde{c}^*_{\text{speed}}\right)}, & c_{\text{speed}} > \tilde{c}^*_{\text{speed}} \\ 0, & c_{\text{speed}} = \tilde{c}^*_{\text{speed}} = 0 \\ 1, & c_{\text{speed}} = \tilde{c}^*_{\text{speed}} = 1 \\ \dfrac{1}{2} & 0 < c_{\text{speed}} = \tilde{c}^*_{\text{speed}} < 1. \end{cases} \tag{5}$$

The last three rows in Equation (5) handle the exceptional cases where the first two would lead to a division by zero and follow the principle that speed compliance of 0 or 1 corresponds to a deceleration compliance of the same value. Figure 7 illustrates an example of how the piecewise linear distribution of speed and the piecewise linear deceleration compliance function may look like. The median driver have a speed compliance of $\tilde{c}^*_{\text{speed}} = 0.87$. The median driver should have a start of deceleration compliance $c_{\text{deceleration}} = 0.5$ which together with $\tilde{c}^*_{\text{speed}} = 0.87$ is used to deduce the breakpoint in the piecewise linear relationship between the speed compliance and the start of deceleration compliance.

5.3. Gear Shifting Strategy. The driver model also includes a gear shifting strategy model based on Ligterink [49]. The model is mainly based on the engine speed s, which is estimated from gear ratios multiplied with the current speed. Drivers are assumed to be shifting up to the next gear $(g+1)$ when

$$s(t) > RPM_g^{UP} + \Delta RPM_g^{UP} \cdot \max\{a(t), 0\}, \quad (6)$$

where RPM_g^{UP} is the shifting up engine speed threshold for the current gear g. The second term $\Delta RPM_g^{UP} \cdot a(t)$ delays the gear shift at accelerations. Aggressive driving usually imply high accelerations and the model therefore includes a correlation between aggressive driving and higher engine speed shifting points. The delay is given in rpm per 1 m/s^2 acceleration.

The shifting down procedure is only based on engine speed levels. A shift to a lower gear $(g-1)$ is conducted if the current engine speed decreases below the RPM threshold of the current gear (RPM_g^{DOWN}). The engine speed based gear shift model estimates the desired gear to be used by the driver in the next step $g(t+dt)$ as

$$g(t+dt) = \begin{cases} g(t) - 1 & \text{if } s(t) < RPM_g^{DOWN} \\ g(t) + 1 & \text{if } s(t) < RPM_g^{UP} + \Delta RPM_g^{UP} \cdot a(t) \\ g(t) & \text{otherwise.} \end{cases} \quad (7)$$

The gear shift model needs to take into account the desired acceleration in comparison to the acceleration that the engine can deliver at the current gear choice. Else, there may be suboptimal gear choices, where the desired acceleration cannot be met with the current gear choice, but a better choice is available. $a_{\text{physmax}}(v, g)$ represents the maximum acceleration that the engine can deliver at the current speed and gear, taking into account all external forces (rolling resistance, air resistance, and gravity in case of slope). Let $a_{\text{physmax}}(v) = \max_g a_{\text{physmax}}(v, g)$ be this maximum acceleration maximized over all gears. The set of gears for speed v where the maximum acceleration is achieved is denoted $\mathcal{G}(v)$ and obtained as

$$\mathcal{G}(v) = \{g : a_{\text{physmax}}(v, g) = a_{\text{physmax}}(v)\}. \quad (8)$$

A reasonable assumption is to let $\mathcal{G}(v)$ be an interval. Let $g_-(v)$ and $g_+(v)$ be the boundaries of this interval defined as.

$$g_-(v) = \min \mathcal{G}(v) \quad \text{and} \quad g_+(v) = \max \mathcal{G}(v). \quad (9)$$

If the desired acceleration a_{desired} is larger than the maximum acceleration at the desired gear, and a better gear is available, then a gear shift override will be applied. The desired gear g_{desired} is given as

$$g_{\text{desired}} = \begin{cases} g + \Delta g_{\text{combined}}, & 1 \le g + \Delta g_{\text{combined}} \le n \\ g, & \text{otherwise.} \end{cases} \quad (10)$$

Thus a gear shift override is applied if the conditions (11) and (12) are satisfied.

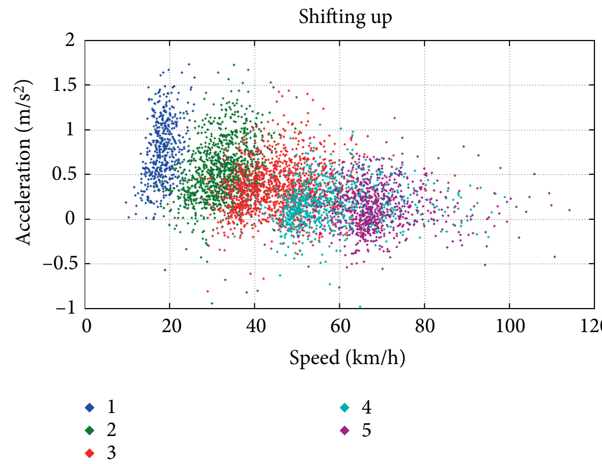

Figure 8: Acceleration and speed at actual gear shifts from different gears from field trials in Sweden using a Volvo V70 (6 gears diesel).

$$a_{\text{desired}} - \Delta a_{min} > a_{\text{physmax}}(v, g_{\text{desired}}), \quad (11)$$

$$a_{\text{physmax}}(v) > a_{\text{physmax}}(v, g_{\text{desired}}). \quad (12)$$

Switching to another gear is helpful if the current gear g cannot deliver the desired acceleration (e.g. acceleration in connection to an overtaking), and there is another gear that can do that, that is if the condition in (13) is satisfied.

$$a_{\text{desired}} > a_{\text{physmax}}(v, g) \text{ and } a_{\text{physmax}}(v) > a_{\text{physmax}}(v, g). \quad (13)$$

In this case, the gear shift should be towards the interval $\mathcal{G}(v)$. Note that g is not in this interval if (13) holds. Thus, the procedure leads to the overridden gear shift $\Delta g_{\text{override}}$ calculated as

$$\Delta g_{\text{override}} = \begin{cases} \Delta g_{\text{combined}} & \text{(11) does not hold} \\ -1 & \text{(11) and (13) hold and } g > g_+(v) \\ +1 & \text{(11) and (13) hold and } g < g_-(v) \\ 0 & \text{otherwise.} \end{cases} \quad (14)$$

5.3.1. Calibration Using Field Trial Data. The gear shift model behaviour has been calibrated using field trial data from the baseline drives without the FeDS. Since the gear shifting behaviour depends on the vehicle model and make the calibration need to be conducted separately for each vehicle model and each gear, identifying RPM values for downshifts, upshifts and delays due to acceleration. Gear shifts were extracted from the 10 Hz data by identified the moment the driver starts to press the clutch pedal and the next moment the clutch pedal is fully released. As described in the previous section gear shift behaviour depend on several aspects as current engine speed, vehicle speed and acceleration. Figure 8 shows that at higher accelerations, gear shifts start at a higher speed (and thereby higher RPM). This effect gets less pronounced at higher gears.

By using linear regression to estimate the effect of acceleration, a gear shifting threshold and a delay factor were

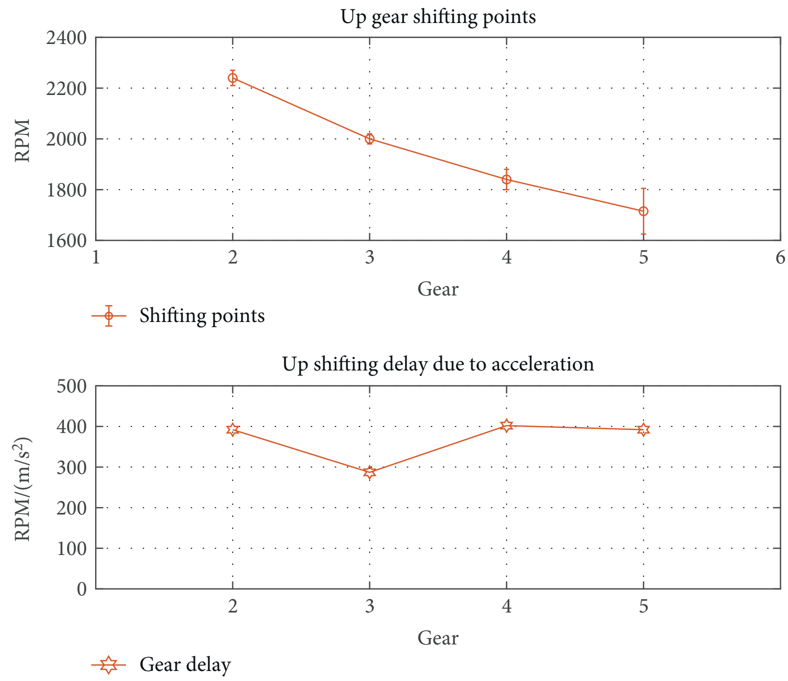

Figure 9: Estimated gear shifting points (RPM_g^{UP}) and how shifting points are delayed by acceleration (ΔRPM_g^{UP}) based on the field trials data for a Volvo V70 (6 gears diesel). Lack of data gives no estimation for 1st gear. The error bars show 95% confidence intervals.

estimated for each gear, see Figure 9 for example of estimated thresholds and delay factors. The same method was also used to estimate downshift thresholds, except no delay factor was adapted since the acceleration is assumed to have no effect on downshifts (and no relation was found in the field trial data). Only sequential gear shifts was investigated (skipping gears is neglected due to the number of observations). The final output is gear shifting points (averaged to the closest 100 RPM).

5.4. Gear Advice Compliance

5.4.1. Model Description. The driver model contains a gear compliance model taking the instantaneous gear advice g_{ED}^{a} provided by the FeDS and combines it with the driver's desired gear g_{TS}^{des}. The output from the model is a modified desired gear g_{DM}^{des} representing the driver's compliance with the advice given.

Modelling drivers' compliance with the gear advice was not as straightforward as for the speed advice. One difficulty is that it is not so much a question whether the driver follows the advice of shifting gear but rather when the gear shift occurs. One aim of the gear advice is, of course, to ensure that the drivers use the most optimal gear from a fuel consumption point of view but also that they shift to the optimal gear as soon as possible. There are several cases which were found to be problematic from an analysis point of view, e.g.:

(1) After some time more or less all drivers end up at the advised gear and it is difficult to judge whether this is an effect of the advice or not.

(2) When shifting down drivers commonly shift down too early (at a higher than advised RPM) and they will then not get any advice or if they shift down much too early they might get an advise to shift up.

Even if this kind of situations make it difficult to evaluate the effect of an advice, the advice clearly affected the RPM levels at which equipped and nonequipped driver changed gear. So instead of modelling the gear advice as an advised gear, we decided to model the gear advice as a recommended RPM level at which to change gear. This is not the direct advice that the driver gets from the FeDS but a suitable representation of it. The gear compliance model is thereby only based on engine speeds and the driver's revised desired shifting point r_{DM}^{des} is calculated as

$$r_{DM}^{des} = c_{gear} \cdot r_{ED}^{a} + \left(1 - c_{gear}\right) \cdot r_{TS}^{des}, \qquad (15)$$

where r_{TS}^{des} is the driver's desired shifting point, r_{ED}^{a} is the advised shifting point and $c_{gear} \in [0,1]$ is a parameter representing the compliance with the system advice. The gear shift model, described in Equation (7), is then applied using the revised gear shifting points (r_{DM}^{des}) instead of the original (r_{TS}^{des}).

5.4.2. Calibration Using Field Data. The gear advice compliance was estimated using data from the field trials within the ecoDriver project. In contrast to speed compliance, gear compliance is not drawn from a distribution but set to a fixed value depending on the gear g and whether it is an up-shift or a down-shift procedure. The main reason was that there were not enough gear shifts for all "from gears" for each driver to estimate individual desired shifting points. This also implied that it was not possible to conduct correlation analysis of drivers speed and gear compliance. The compliance was estimated based on the average observed shifting point at baseline and treatment runs and the advised shifting points Examples of engine speeds for upshifts using the Volvo V70 (6 gears diesel) is given in Figure 10 and the resulting compliance for upshifts

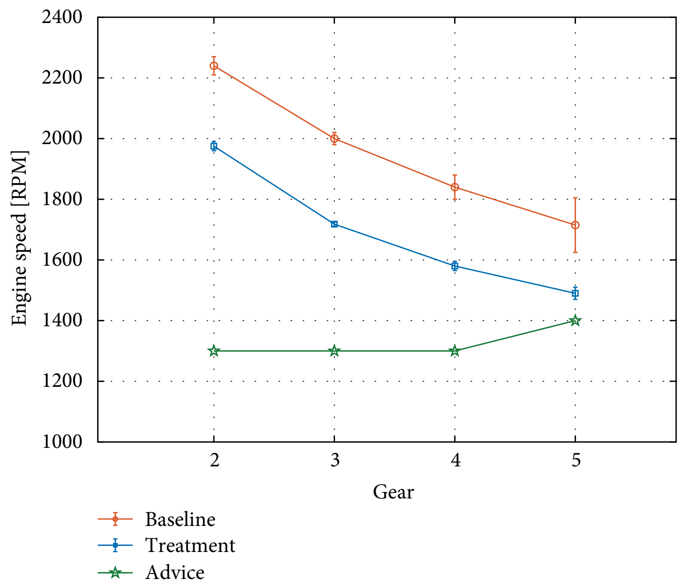

FIGURE 10: Up shifting behaviour Volvo V70 (6 gears diesel) comparing treatment, baseline and optimal gear shifting points.

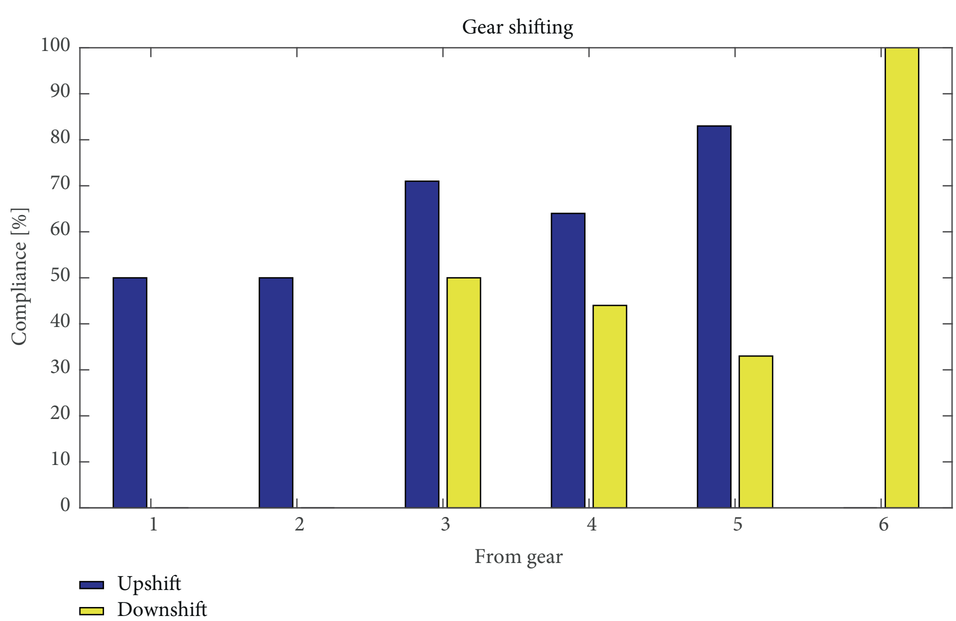

FIGURE 11: Estimated gear shift compliance from the field trials.

and downshifts is illustrated in. Figure 11. There were very few observations for downshifts from gear 2 and the average RPM levels used in the treatment drives were actually higher than in the baseline drives. Therefore the compliance with the gear advice to shift down from gear 2 was assumed to be zero.

6. Vehicle Model

An external vehicle model was required in the simulation framework since none of the traffic simulation tools used in this study supported gear shifting. The vehicle model includes a simple representation of the vehicle behaviour at different gears in different situations. The model estimates the engine speed and the maximum acceleration available at a specific speed and gear.

6.1. Calculation of Maximum Acceleration. The maximum acceleration estimation is based on engine maps developed for each specific vehicle type. It is a look-up table function identifying the maximum acceleration a_m available during current circumstances. Each gear and velocity has its own value and include energy losses caused by air resistance, rolling resistance and engine frictions. An example of how the maximum accelerations available a_m varies at different gears and speeds is given in Figure 12. The only external force affecting the maximum acceleration given from the

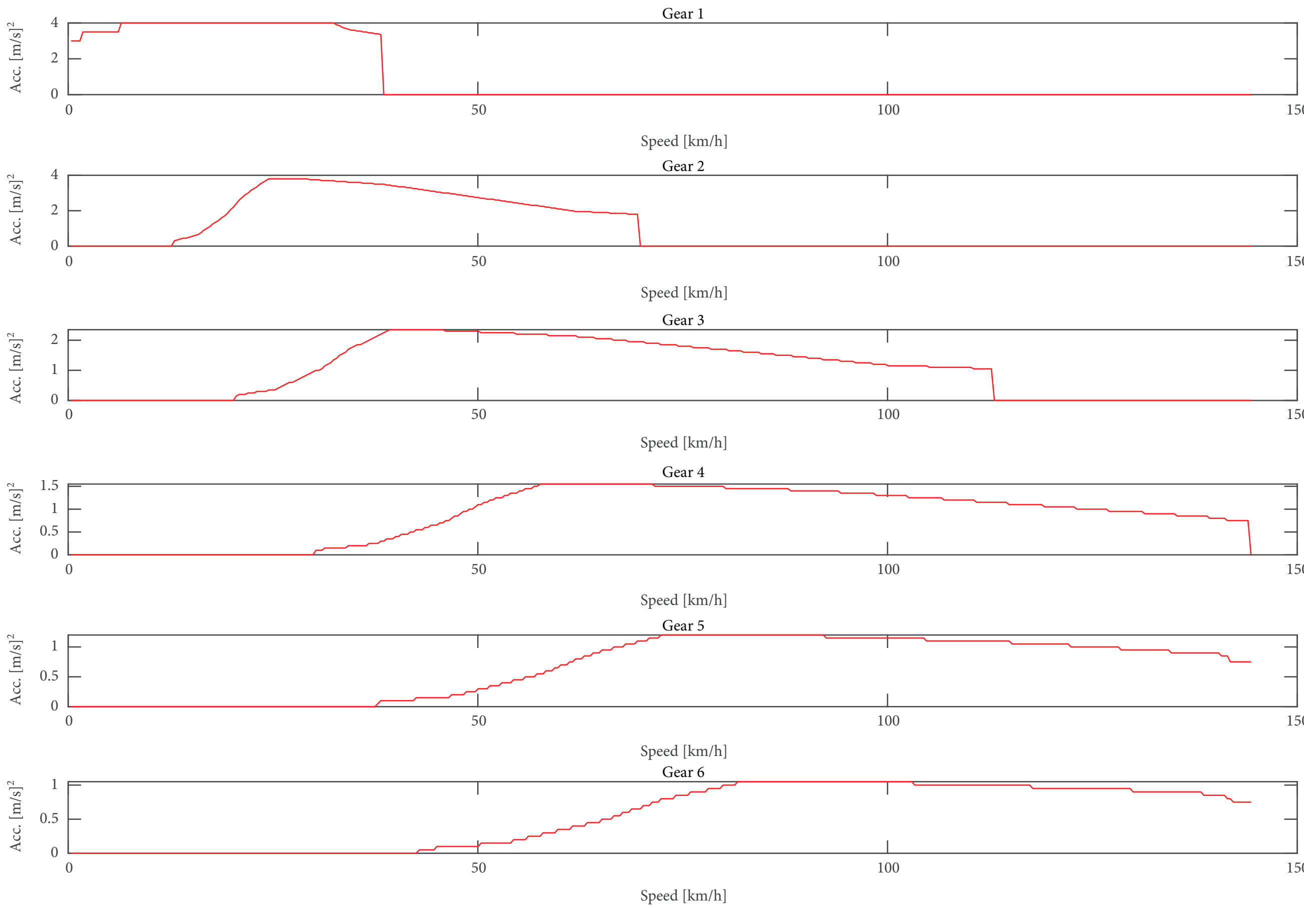

FIGURE 12: Maximum acceleration available [m/s^2] for a 6 gear diesel engine for all possible combinations of speed and gear.

lookup function, is caused by the slope of the road $\theta(x(t))$. The resulting maximum acceleration a_{max} is calculated as

$$a_{max} = a_m(g(t), v(t)) - 9.81 \cdot \theta(x(t)), \tag{16}$$

where $a_m(g(t), v(t))$ is the maximum acceleration with respect to the current gear and speed and $\theta(x(t))$ is the slope of the road.

6.2. Calculation of Engine Speed. Vehicle engine speed is required in order to estimate the driver's gear shift behaviour. The engine speed is utilising the gear ratio for each vehicle type. The unit of the gear ratio is $h/(km \cdot min)$, and the engine speed can be estimated by multiplying the gear ratio with the current speed v in km/h. The engine speed s is calculated as

$$s(t) = GR_g \cdot v(t), \tag{17}$$

where GR_g denotes the gear ratio of the current gear g and $v(t)$ the current speed of the vehicle.

7. Verification Simulation

To illustrate the effect of the combination of the ecoDriver system and drivers' compliance to the advice we conducted a set of verification simulations. The verification simulation has been performed using a basic scenario simulating the driver's anticipation due to six different speed limit changes along a 13 km long single road stretch. It is a flat road without any curves, intersections or obstructions causing decreased visibility. The traffic demand is set to only one single vehicle, a manual gear diesel car, which means there will be no interactions with other vehicles in the simulation. Three different cases were simulated:

(1) Unequipped (or no compliance against the advice provided from the ecoDriver system),
(2) Half compliant (50% compliance against the advice provided from the ecoDriver system),
(3) Fully compliant (100% compliance against the advice provided form the ecoDriver system).

The level of compliance is consistent between gear, speed and start of deceleration. The unequipped driver is assumed to be driving 10% faster than the speed limit and have a more aggressive gear shift strategy (use higher RPM shifting points) compared to a fully compliant driver using the ecoDriver system.

The results from the simulations are presented in Figure 13 containing speed, acceleration, gear and engine speed profiles.

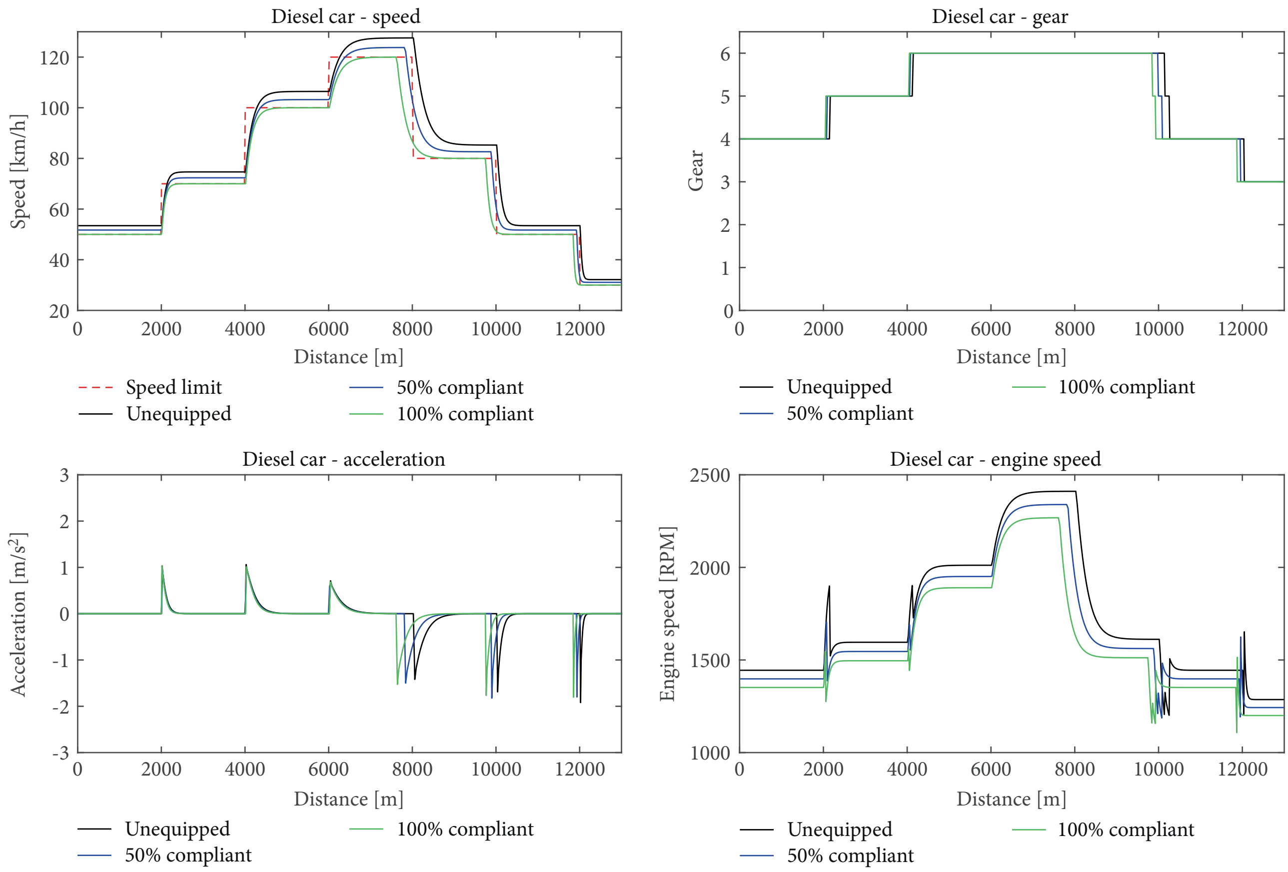

Figure 13: Simulations of a 0%, 50%, and 100% compliant driver equipped with the ecoDriver system.

It can be seen that the level of compliance towards the ecoDriver system affects desired speed, start of deceleration and gear shifting points. The results show the difference in speed limit compliance and the earlier start of deceleration at the decrease in speed limits for the 50% and 100% compliant drivers. The figure also show that the 50% and 100% compliant driver shifts gear earlier than the noncompliant driver. Thus, the framework with the added compliance models and gear and maximum acceleration models enable simulation analysis of different driver compliance to an eco-driving advice system.

8. Conclusions, Recommendations and Future Research

Traffic simulation modelling of the effect of advisory driver support systems requires accurate and realistic modelling of the system as well as the driver's response to the system. In particular, it is important to define and calibrate a good compliance model. In this article, we have shown that it is possible to set up a traffic simulation framework that can be used to extend state-of-the-art traffic simulation tools with models for an eco-driving support system, vehicle dynamics, drivers' gear shifting behaviour and compliance with advice from an eco-driving advisory system.

The developed compliance and gear shift models have been calibrated using field trial data. Calibration of compliance requires data both for estimating the driver's behaviour without system interference as well as the driver's response to the system. Although several field trials were executed within the ecoDriver project it was a challenge to use the data for calibration and estimation of the probability distributions underlying the behavioural models, because the number of baseline drives was limited and/or drives were too short to obtain enough observations for the number of situational variables that needed to be considered. In order to allow for a more comprehensive calibration of compliance models for inclusion in traffic simulation models, field trials have to be designed not only for traditional human factor driver behaviour analysis but also with the traffic simulation modelling in mind. For example, the number of baseline and treatment drives per driver in combination with the length of each drive has to generate enough observations of participant's behaviour without and with the driver support system for specific traffic conditions.

The speed compliance model is based on the notion of desired speeds. The desired speed concept is a traffic simulation construction to represent a driver characteristic that in reality of course shows some variation for a specific driver. A real driver does not always desire to drive at the same speed even at the same road section depending on several things (mood, time of day, weather and road conditions, etc.). Thus, estimating the desired speed of a driver as a single value is therefore difficult. Hence, the difference between observed desired speed without and with a driver support system consists of two parts: the real difference and differences related to the variation in desired speed for a specific driver. However, larger datasets per driver is required to analyse and separate these variations and without the possibilities to do so a linear combination of the simulated driver's desired speed and the speed advice seems to be the most straightforward way to model the speed compliance.

The gear shifting behaviour (i.e. at what engine speeds that driver's change gear) depend on the vehicle model and make (since the gear ratios vary depending on vehicle model and make). It is clear that the inclusion of a gear shifting model and calculations of emissions from traffic simulation models gain from a more detailed disaggregation of the vehicle types, e.g. splitting passenger cars depending on powertrain/fuel type (e.g. petrol, diesel, and electric). Therefore, it is recommended that a representative set of gear shift engine speeds for common powertrains is developed.

For future years vehicles might to a larger extent be equipped with automatic gear boxes. This imply that eco-driving gear advices can be implemented directly instead of given as advises. Whether eco-driving gear switching mode is used or not is still a question of compliance and the trend of higher penetration rates of automatic gear boxes have therefore not been modelled explicitly. However, this can be taken into account implicitly by assuming higher gear compliance rates.

The traffic simulation framework developed have been implemented in three different traffic simulators, one simulator specialised for simulation of ITS (ITS Modeler [50]), one specialised for simulations of rural roads (RuTSim [51]) and one commercial simulator (Aimsun [52]). This shows that the framework and the developed compliance models are flexible and generally applicable and not tied to a specific traffic simulator. The developed framework was used to conduct a scenario-based evaluation of the effects of the FeDS on motorways, rural roads and urban street networks, for different vehicle classes, different policy scenarios and different circumstances, see Olstam et al. [53] for details. The simulations were one part of an approach for scaling up the results from field trials to effects on the EU-28 level including cost-benefit analysis (CBA) for different stakeholders (see Jonkers, Wilmink [54, 55]) for details on the scaling up and the CBA.

Data Availability

Data used for the estimation of the compliance levels and gear shifting points as well as simulation output data are available upon request to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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