Connected strategy for energy-efficient driving of electric vehicle

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Abstract: This paper presents the potential benefits of connected strategies for energy-efficient driving for electric vehicles achieved during the H2020 EU project CEVOLVER.

Two strategies are presented. First solution optimizes the route and the recharge planning such as minimizing the battery energy consumption within a suitable trip time (eco-charging). Second solution, coupled with the first, provide the optimal speed profile using predictive information from the eco-charging and topology and infrastructure data from third party webservices (eco-driving).

The benefits provided by the developed connected strategies are evaluated in simulation. Gains obtained by the eco-driving are validated experimentally with a mixed urban and extra-urban route, showing a significant energy consumption reduction.

Keywords: Connected strategy, electric vehicle

1. Introduction

In the past decade, electric vehicles (EVs) made significant progress in term of range, while charging stations network has been expended all over Europe. EV sales have recently increased showing customers' interest in emission or fuel dependency reduction. However, EVs have still not attained the level of user acceptance needed to support a broader mainstream market uptake. Long charging times and uncertainties in range prediction are still the main obstacles to overcome for a further widespread use.

Connectivity of EV represents a promising way to overcome the range anxiety. Connection to cloud webservices exploiting geographic information system (GIS) and traffic data offers the opportunity to predict the driving range accurately and to minimize the energy consumption. To ensure long trip, crowd-sourced data of existing DC fast-charging stations are useful as well for optimal charge planning. As a result, with the optimization of energy range and fast charging, battery can be right-sized, making EVs affordable.

Within this context, the H2020 European project CEVOLVER [1] aims to develop battery electric vehicles (BEV) that improve user experience over long trips. Project's demonstrator vehicles are designed to take advantage of future improvements of the fast-charging infrastructure, whilst the installed battery is dimensioned for affordability. They also integrate improvements to reduce energy consumption, leveraging connectivity for further optimization of components and system design (right-sizing), as well as vehicle controls (battery pre-conditioning for fast charging, cabin thermal management, powertrain energy management), and driving strategies (eco-charging and eco-driving). The final objective of CEVOLVER is to demonstrate on open road that long-trips are achievable by EVs with limited extra time with respect to conventional vehicles.

The eco-charging algorithm solves the problem of finding a time- and energy-optimal route for an EV requiring multiple battery charging events to complete a long-distance trip. The proposed routing strategy also provides the optimal sequence of charging events, as well as the optimal average speed for each road segment to reduce charging needs and thus save trip time. The route and charging sequence optimizations are based on a predictive model of the Ford Transit. In [2], study shows eco-charging can support trips achieved with small battery capacity and long-distance trips. The eco-driving algorithm provides the driver with instantaneous speed recommendations to minimize energy consumption. The developed real-time strategy bases its calculation on: (1) route topology and infrastructure data from GIS, (2) the predictions made by the eco-charging strategy, in particular the average speed, and (3) the real-time ADAS measurements, if available, to anticipate the surrounding traffic disturbances. For more details about the eco-charging and eco-driving strategies developed during the project, developments have been published in [3] and [4,5] respectively.

Few experimental validations on connected strategy for energy-efficient driving of EVs exist. In [6], predictive eco-driving strategy considering real-world traffic flow has been validated under real-world traffic environment. In [7], the developed eco-driving algorithm has been validated using a driving simulator.

This paper focuses on the potential energy gains provided by the connected eco-charging and eco-driving strategies on a Ford Transit van with a battery electric propulsion system, obtained in simulation and on open road.

The paper is organized as follows. In Section 2, the energy reduction performance provided by the eco-charging and the eco-driving is evaluated in simulation. Simulation of long trip use case with different average speed will confirm the large impact of the average speed on the trip time for the Ford demonstrator vehicle, enforcing the results obtained with the presented connected functions. In Section 3, experimental test results of eco-driving in real traffic conditions on a representative use case are presented and analysed.

2. Potential energy gain from connected strategies

This section presents the simulation results of eco-charging and eco-driving. First, simulations of a long trip with the Ford demonstrator, with different average speed values shows the impact of the speed on energy consumption. This result is then confirmed by simulations of the complete eco-charging strategy, where both the route choice and average speed are optimized. The saved battery energy reduces the charging needs and thus the trip duration. Then, simulations of the eco-driving strategy on repeated trips in Cologne show how optimizing the instantaneous speed profile can further reduce the energy consumption.

2.1 Average speed variation impact on the Ford demonstrator

For the Ford demonstrator, the main benefit of optimal average speed advice is expected for highway traffic where the travel speed can be adapted largely without constraints. In terms of urban applications, it is expected that on the one hand the observance of the speed advice is more disturbed by interactions with the surrounding traffic and on the other hand, dynamic changes of the recommended target speed are more difficult to be considered by the driver. Thus, the focus of the benefit analyses for the demonstrator was placed on the benefits during long distance trips.

For that purpose, the energy demand for a 350 km trip was considered for different vehicle speeds between 70 and 130 km/h assuming for simplicity that the whole trip is driven at constant speed. In addition, the total trip time was evaluated based on the time demand for driving and the time demand for battery charging with 20 to 150 kW just to the state of charge that is required to reach the target destination. The resulting graphs that show the interdependency between available charging power, energy demand and trip time are shown in Figure 1.

It is obvious that the energy demand is increasing strongly with increasing vehicle speed which is due to the huge frontal area of the BEV demonstrator and the resulting air resistance. Comparing the vehicle speed with the total trip time, the graphs indicate that depending on the available charging power an increase of vehicle speed is not always beneficial in terms of trip time. For an average charging power of 20 kW, the trip time demand at 80 km/h is by far less than for 130 km/h. The reason for that is the difference in driving energy demand and the related amount of charging energy that results in heavily increased time demand for charging. This effect is mitigated with the availability of higher charging power but even for 100 kW average the time savings for travelling at 130 km/h instead of 100 km/h are negligible whereas the increase in energy demand is significant.

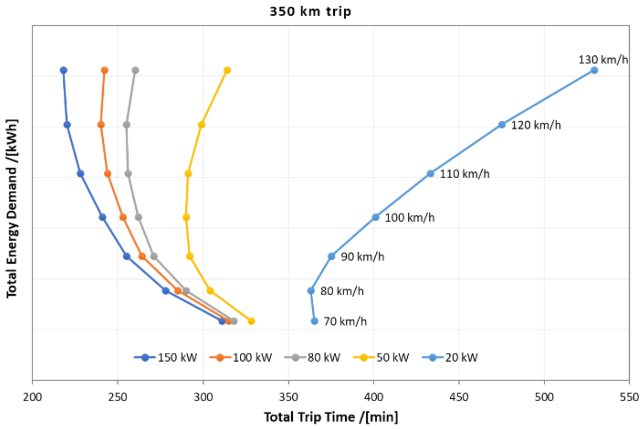

Figure 1: Dependency between available charging power, energy demand and trip time for a long distance trip

2.2 Eco-charging

The performance of the eco-charging strategy is evaluated on a trip between Aachen (Germany) to Deauville (France) of 545 km. Figure 2 shows the trip planned by the eco-charging algorithm with the stop locations. The table 1 shows a comparison of the solutions given by the eco-charging algorithm with the average speed added as a decision variable in the optimization, where “no speed” indicates that average speed is not a decision variable. The indication “with speed” refers to the optimization with average speed v as decision variable with speed varying within a range of $[v - 30, v]$ in km/h.

Using travelling speed as decision variable benefits both on the energy consumption and the recharged energy, with a reduction of 3.9 and 11.1% respectively. Eco-charging changes the charging planning according to the adjusted speed profile, avoiding an additional charging stop leading to reduce the overall trip time.

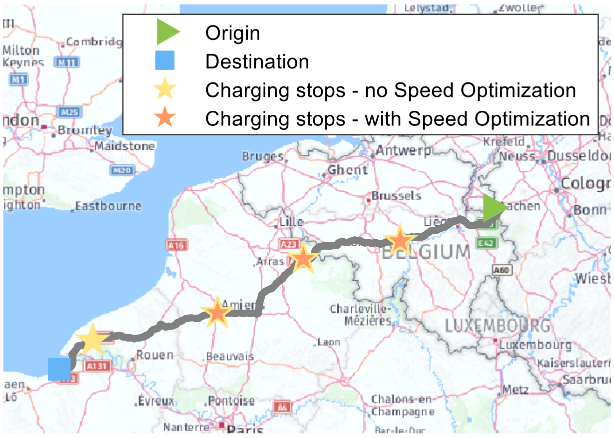

Figure 2: Mission profile between Aachen (Germany) and Deauville (France) (© 2022 HERE)

Table 1: Eco-charging performance with average speed as a decision variable

	No speed	**With average speed**
Trip time difference	7h38	6h54
Number of charging stops	4	3
Energy consumption [kWh]	/	-3.9 %
Recharged energy [kWh]	/	-11.1 %

2.3 Eco-driving

The potential energy gain from the eco-driving strategy is evaluated on a 19 km trip repeated 24 times in Cologne near Ford's facilities at off-peak hours.

The mission profile is divided into three parts: (1) the highway part for routes with $v_{max} \geq 70\ km/h$, (2) the extra-urban part with $50 < v_{max} < 70\ km/h$, and (3) the urban part where $v_{max} \leq 50\ km/h$. The split is detailed in Figure 3.

The eco-speed is computed using information about the average traffic speed and predictive data from eco-charging about the route segment's end speed. The speed optimization only takes into account the route topology, the legal speed limits constraints and the traffic prediction, although the developed approach is able to consider the surrounding traffic in real-time as described in [4].

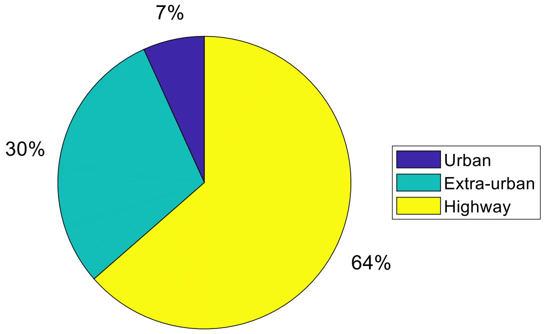

Figure 3: Speed limits split within the trip

The driven and the computed eco speed profiles are represented in Figure 4. The real speed profiles show that the test drives are relatively repeatable but surrounding traffic influences strongly the speed profile, in particular in urban area.

The eco-driving algorithm smooths and adapts the speed to avoid unnecessary acceleration and deceleration between route segments. Deceleration anticipation as segment end approach is possible thanks to the eco-charging predictions. One can notice that predictive information from the eco-charging about the segment ends speed is quite accurate as closed to the real speed transition.

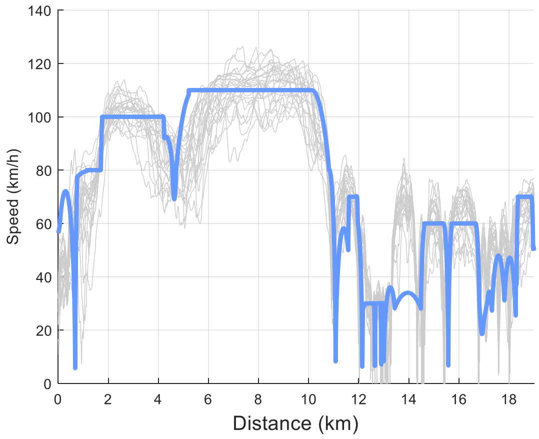

Figure 4: Driven (gray) and eco (blue) speed profile

In Figure 5, the normalized battery energy consumptions against the total trip time for each drives and the computed eco-speed are shown. The impact of the speed profile optimization on the travel time is limited as the strategy takes as a constraint the travel time accordingly to the traffic data obtained from the GIS providers (HERE webservice is used). About the energy gains, eco-driving could reduce the energy consumption of 3.5% in average and up to 13% on the whole trip (Figure 6).

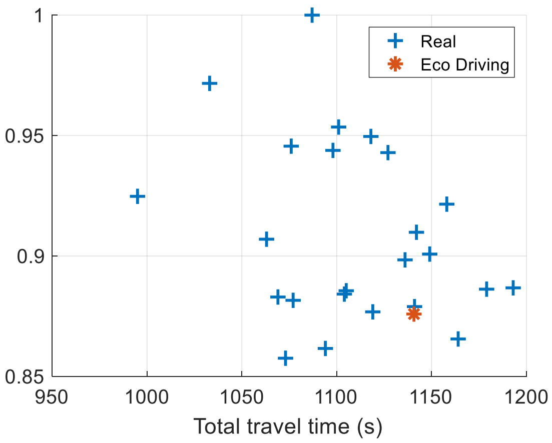

Figure 5: Normalized battery energy consumption according to the total travel time

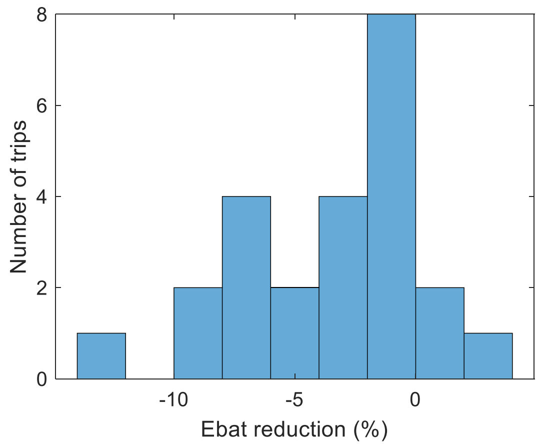

Figure 6: Energy consumption reduction distribution for the whole trip

Focusing on the two main parts of the trip, namely the highway and the extra-urban parts, the energy consumption reduction distribution in Figure 7 shows that reduction will be possible especially in extra-urban parts.

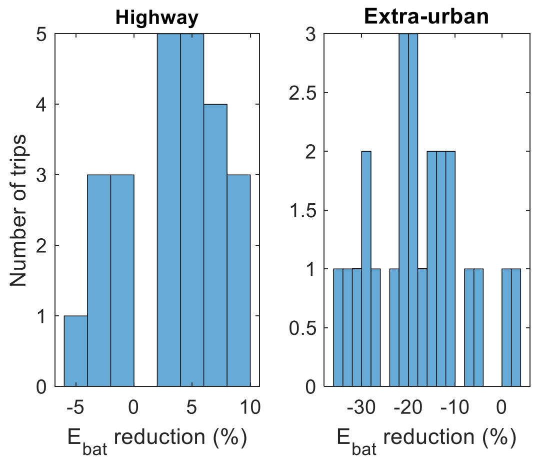

Figure 7: Battery energy reduction distribution according to route type

3. Experimental result of eco-driving on open road

The eco-driving was evaluated on open road in Aachen (Germany) with the Ford BEV demonstrator.

3.1 Demonstrator vehicle

The Ford BEV demonstrator for the CEVOLVER project is a commercial vehicle from the 2T Transit range. The variant used in this project has a short wheelbase and a medium roof. The vehicle's powertrain specification is based on the e-Transit that recently went into production [8]. The battery has a usable capacity of 67 kWh. The vehicle contains an 11.3 kW onboard AC charger. It also supports DC-fast-charging up to 115 kW. The motor-inverter is mounted at the back, behind the battery, where it transmits its forces to the rear wheels. The vehicle's electric motor has a peak output power of 269 hp and delivers 430 Nm of torque. The vehicle is shown in Figure 8.

Figure 8: Ford Transit BEV demonstration vehicle

3.2 On-board implementation of the connected strategies

The implementation of the eco-charging and the eco-driving strategies rely on the connected architecture which is composed of a Brand Independent (BI) cloud and dedicated components hosted on a connected device.

The Figure 9 presents the implementation and dependencies between the components.

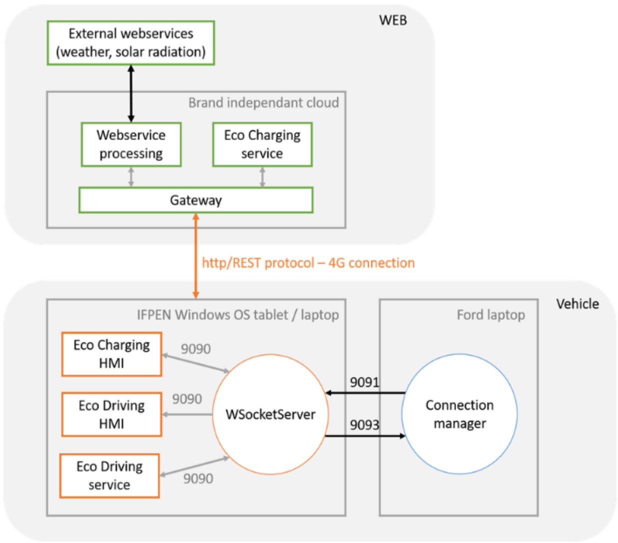

Figure 9: Implementation architecture

The BI cloud serves as a gateway to third party webservices for the connected functions developed during the project (namely eco-charging, powertrain and thermal cabin conditioning optimization, smart fast charging) and hosts the eco-charging webservice. The communication between the connected device and the BI cloud services uses the *http/REST* protocol.

The connected device hosts the eco-driving strategy and serve as HMI for the eco-charging and eco-driving. The device is connected to the BI cloud by 4G connection. on the laptop. A local server, denoted "WSocketServer", handles the *WebSocket* messages between all the implemented components (HMI / Eco-driving / BI Cloud / Ford RCP SW tool) and triggers the eco-driving and eco-charging services.

3.3 Experimental results

The evaluation of the eco-driving strategy on the Ford demo vehicle was performed around the Ford Research Centre in Aachen (Germany). Two routes were selected which represent typical rural and urban routes. The share of the speed limits for the four trips is shown in Figure 10.

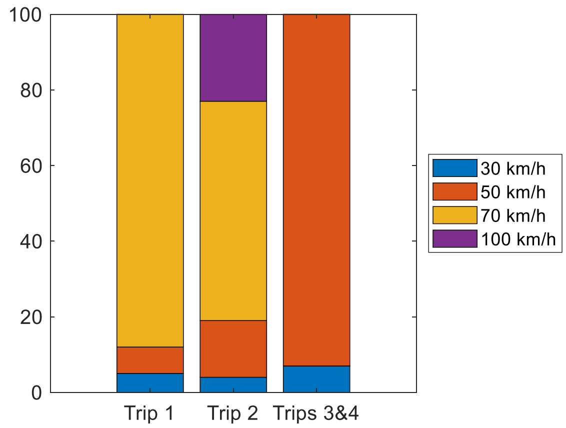

Figure 10: Speed limit share for the two directions of the Ford ECO-driving evaluation route

The rural route is a connection between two urban zones. It has a few stop lights and a rather smooth traffic. The urban route is the main road through a suburb of Aachen. It has more stop lights and crossings. At the time the routes were driven the traffic was moderate, with large shares of the trajectory with no vehicle in front. One could imagine such a route being driven by van drivers, for example from delivery vehicles or craftsmen. The route with the more rural speed profile was driven in both directions, called trip 1 and 2 in the following. The length of the trajectory is 4,25 km for trip 1 and 4,75 km for trip 2. The route starts for less than 100m in a 50 km/h street followed by a ring road where 70 km/h is allowed. At the end, the trajectory turns into a village with a 50 km/h speed limit, to finally find its endpoint in a 30 km/h shopping park zone. On the way back, the ring road contains a share with a speed limit of 100 km/h. After the exit of the ring road, the last part is a 50 km/h street. This part is about 400m longer than in the other direction. The fact that the exit from the ring road is 400m further away from the start point than the entrance explains most of the difference in length for both directions. Further, a second route with a more urban speed profile was added to the evaluation tests. This route was driven in both directions as well which will be called trip 3 and trip 4. The length for both trajectories is 2,97 km. This route has a 50 km/h speed limit, apart from the last part where it ends also in the shopping park zone.

All the trips have been driven repeatedly, whereby the target was three times for each case. The number of drives per case is shown in Figure 11. The repetition of the routes is needed for plausibility of the results, also because the traffic lights influence strongly the speed profile.

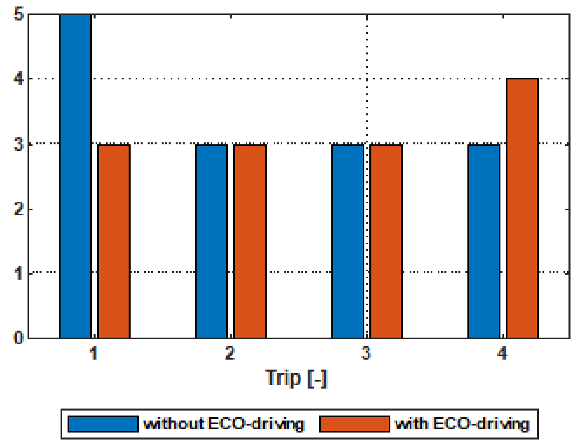

Figure 11: Number of drive repetition with and without ECO-driving

With the advisory function on, the driver attempts to follow the speed advice. No data about the real-time surrounding traffic was available yet as the radar was not active on demonstrator vehicle. A comparison of two randomly selected traces from the urban route is shown in Figure 12.

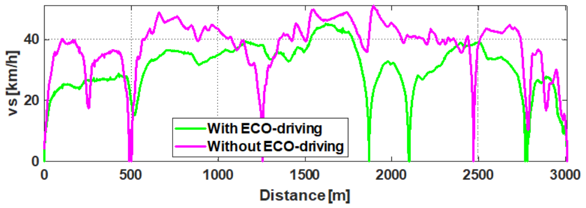

Figure 12: Urban route with and without ECO-driving

In general, the average speed advised is lower than the average speed that would be driven without using the advisory function. One other difference that has been noticed is that the ECO-driving function defines a more economic acceleration profile. A zoom on the speed profile from the mixed rural-urban drive as shown in Figure 13 illustrates this. The acceleration between 70 and 500s, when entering the ring road, is much slower with the ECO-driving speed advice.

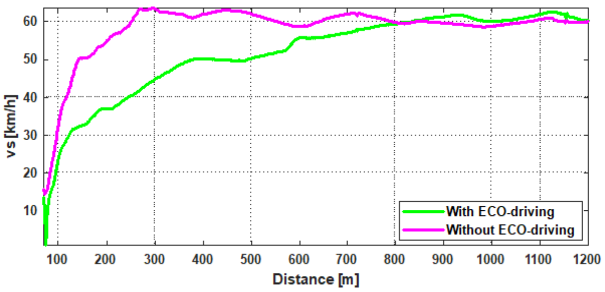

Figure 13: Zoom on an acceleration with and without ECO-driving

The energy savings have been quantified based on the total battery energy consumption over the trip. The Figure 14 compares the averages for the different cases. The Figure 15 reports the average time duration. For all the trips, the average time loss ranges from 65 to 79s. On the other hand, the battery energy consumption is always lower with ECO-driving actively used. The gain is lower for an urban profile (9-10%) than for a more rural type of trip (13-15%). This is also expected, as the urban profile is typically a more dynamic driving profile. The pre-knowledge of the route allows the advisory function to explore opportunities to anticipate stops or, for example, inclinations in the road.

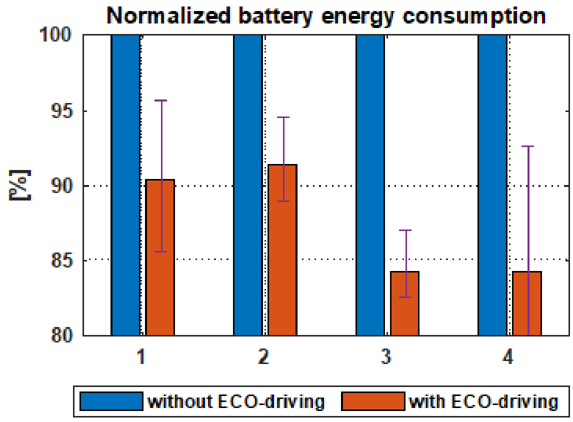

Figure 14: Battery energy consumption with and without ECO-driving for the two directions of the trip

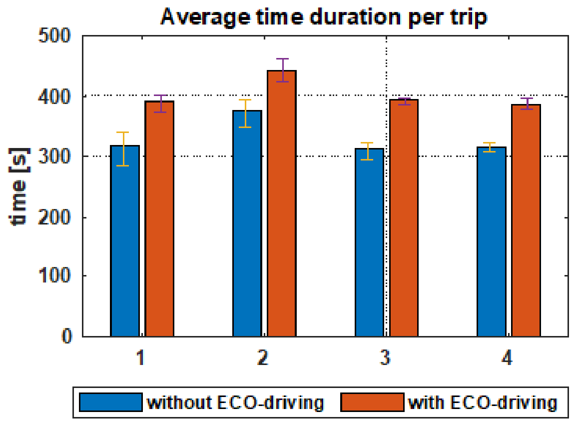

Figure 15: Trip duration with and without ECO-driving for the two directions of the trip

5. Conclusion

This paper has presented a connected strategy for an efficient-energy management of EVs, in particular for the Ford Transit BEV. A comprehensive strategy which optimizes the route, the charge plan and the driven speed provides gains in energy and travel time, thus helps to reduce the range anxiety expressed by EVs users.

Simulation results have shown promising energy gains by optimizing the speed profile. Eco-charging, by both optimizing the charge plan and the average speed, could provide gains up to 5%. Eco-driving by optimizing the instantaneous speed profile could reduce the energy consumption by 3.5% in average up to 13%.

Experimental validation of the developed connected strategy, enhancing the eco-driving feature, shows promising results with average gains of 10% and demonstrate the technical feasibility of the proposed approach.

6. Acknowledgement

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8. Glossary

EV: Electric Vehicle

GIS: Geographic Information System

BEV: Battery Electric Vehicle

BI: Brand-independent

ADAS: Advanced driver-assistance systems