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Dynamic Charging-While-Driving Systems for Freight Delivery Services with Electric Vehicles: Traffic and Energy Modelling

Francesco Deflorio[a], Luca Castello[a,b]

[a]*Department of Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, corso Duca degli Abruzzi 24, 10129 Torino, Italy*
[b] *Currently consultant in Akronos Technologies s.r.l., Torino, Italy*

Abstract

This paper presents a research on traffic modelling developed for assessing traffic and energy performance of electric systems installed along roads for dynamic charging-while-driving (CWD) of fully electric vehicles (FEVs).

The logic adopted by the developed traffic model is derived from a particular simulation scenario of electric charging: a freight distribution service operated using medium-sized vans. In this case, the CWD service is used to recover the state of charge of the FEV batteries to shortly start with further activities after arrival at the depot.

The CWD system is assumed to be implemented in a multilane ring road with several intermediate on-ramp entrances, where the slowest lane is reserved for the dynamic charging of authorized electric vehicles. A specific traffic model is developed and implemented based on a mesoscopic approach, where energy requirements and charging opportunities affect driving and traffic behaviours. Overtaking manoeuvres as well as new entries in the CWD lane of vehicles that need to charge are modelled according to a cooperative driving system, which manages adequate time gaps between consecutive vehicles. Finally, a speed control strategy is simulated at a defined node to create an empty time-space slot in the CWD lane, by delaying the arriving vehicles. This simulated control, implemented to allow maintenance operations for CWD that may require clearing a charging zone for a short time slot, could also be applied to facilitate on-ramp merging manoeuvres.

Keywords

traffic modelling

electric vehicles

dynamic charging

traffic simulation

urban logistics

1 Introduction

Majority of fully electric vehicles (FEVs) currently satisfy the electric energy requirements for their motion with on-board batteries. Extensive literature on FEV limitations focuses on battery problems, particularly on limitations in size and power, battery weight, life and recharge time, and the lack of a wide network of electric charging points. These problems are even more relevant for freight distribution services, where the vehicle masses and daily distances are greater compared with those of passenger cars. In this case, a stationary recharge could require many charging stations not only located at depots, but also distributed in the service area, to provide more charging opportunities during the delivery routes. For this reason, the charging-while-driving (CWD) system could provide a technology to contain the battery sizes and recharging infrastructure costs without impacting on the vehicle autonomy. Wireless charging is based on the principle of inductive coupling. In this type of coupling, a circular magnetic field is generated as a result of the current through a wire coil. If another loop of coil, installed on the electric vehicle (EV), is placed near the first coil, current is induced in it. These coils are regulated to have identical resonant frequency in order to avoid energy leakage and reduce the risk of electrical shock (Bansal, 2015). Dynamic wireless charging (while driving) is implemented to provide energy to equipped vehicles while they are moving over charging pads, which are installed under the road surface. By using this dynamic charge, the idle time owing to possible stops for charging during the journey would decrease and the ratio of range distance over battery size would increase.

In this context, Boulanger et al. (2011) analysed the problems related to battery charging management that may cause range anxiety to drivers: uncertainty surrounding the monitoring of the state of charge (SOC), limited availability of charging infrastructure, and long time required to recharge. The use of intelligent transport systems (ITS), in particular vehicle-to-vehicle or vehicle-to-infrastructure communications, was evaluated to allow drivers to accurately and confidently locate charging stations where they could recharge the battery in the shortest period (Ezell, 2010). Johnson et al. (2013) evaluated how connected vehicle technologies can facilitate the rapid charging of FEVs at charging stations throughout the road network. The market acceptance of FEVs, travel requirements, and consumer choices, particularly for the first car in the household, were also analysed by Kirsch (2000). Moreover, extensive research on overcoming the drawbacks of battery inefficiency and its large space when used in FEVs is being conducted. One of the efforts is devoted to applying the wireless power transfer technology—*Unplugged* (2017), *Fabric* (2017), and *eCo-FEV* (2017) projects are recent examples—where the energy can be transferred to an electric device without any interconnecting media. The *Unplugged* project aims to investigate how the use of smart inductive charging of FEVs in urban environments improves the convenience and sustainability of car-based mobility. In *Fabric*, one of the objectives is the identification of technology requirements that may enable the implementation of wireless charging technology and the diffusion of wireless charging infrastructures. The *eCo-FEV* project aims at achieving an innovation in FEV introduction by proposing a general architecture for FEV integration into different infrastructure systems cooperating with each other, including CWD systems.

Chen et al. (2017) investigated the optimal deployment of charging stations and lanes along a long traffic corridor to serve the charging requirement of EVs as well as the competitiveness of charging lanes. When both charging stations and lanes are deployed along the corridor, EV drivers travelling from one end to the other are assumed to choose charging facilities that minimize their travel costs. A mathematical program is formulated to optimally deploy charging stations and lanes with regard to different operating regimes. The optimal location problem of wireless charging facilities is addressed as well to ensure that the captured traffic flow on these roads is maximized (Riemann et al., 2017). The multinomial logit model stochastic user equilibrium principle is employed to capture the routing choice behaviour of drivers. A case study (Fuller, 2016) evaluated the potential for a dynamic charging infrastructure to address range and recharge issues of FEVs by considering travel to regional destinations in California. Different combinations of wireless charging power (dynamic charging levels from 20 kW to 120 kW) and vehicle range (vehicle ranges between 100 miles and 300 miles) were evaluated using a Geographic Information System (GIS) tool and an optimization model. Dynamic charging, coupled with strategic static charging, proves to be more cost effective than gasoline over a 10-year period. At very low battery prices of $100 per kWh, the research showed that dynamic charging can be a more cost effective approach to extending the range than increasing the battery capacity.

To overcome the FEV range limitation problem, many research activities are focusing also on new electric charging technologies. Ahn et al. (2010) proposed several techniques for the reduction of CWD electromagnetic fields from the power line and the vehicle itself by applying a metallic plate shield. Suh (2011) presented an application of the shaped magnetic field in resonance technology for future urban transportation. Finally, another important element that supports a battery charging modality with frequent and low energy transfer while driving is that the SOC must be managed carefully and the batteries should never be fully discharged to avoid excessive shortening of the battery life cycle.

The aim of this research is to support preliminary studies on one of the possible future technologies that could enhance FEV use in freight transport. One of the goals of the European white paper is to achieve essentially CO2-free city logistics in major urban centres by 2030, and CWD technology could be one of the possible ways to meet this target. Beginning with an EV supply equipment (EVSE) layout defined and analysed in previous studies (Deflorio et al., 2013, 2015), a model for the traffic flow simulation is implemented to quantify and describe the traffic performance (useful for both drivers and fleet operators), SOC variations for the fleet, and also the electric power that should be provided by an energy supplier for the proper management of the charging system.

With respect to the model described in the aforementioned studies, in the simulation model presented here, the relationships between the simulated traffic and the charging operations have been extended, enabling the model to simulate even critical situations in high traffic conditions. Specific improvements related to the functional requirements defined for the CWD system have been introduced to increase the reliability and efficiency of the simulation model. Finally, the model has been adapted to simulate a realistic road scenario with intermediate entrances, where traffic interruptions can also be generated for short time intervals. This paper provides extended analyses of the simulation scenarios previously presented by Deflorio and Castello (2015), including more details on the mathematical model approach (section 3) on the simulation model and algorithms (section 4).

2 CWD service requirements for freight vehicles

Generally, freight distribution services have complicated logistic structures in large cities, for both depots and delivery locations. However, owing to the enhanced typology of this charging service, we could assume that in the near future, urban freight distribution services operated by EVs could be supplied mainly in a city logistics approach. In this context, only few peripheral depots (urban consolidation centres) can generally be used as hubs for urban freight distribution (Taniguchi, 2014) and a subset can be equipped for EVs.

In Turin (Italy), where the case study is located, there is only one logistic centre near the city, connected with railways and motorways (our depot in the simulation). It would then be a possible depot for electric urban freight distribution. In this specific scenario, one destination for all the FEVs can be set.

Charging requirements in this case are not related to driver preference or constraints similar to passenger cars travelling to a desired destination. Indeed, for freight distribution services, the charging and energy management decisions should be selected by the fleet manager according to service configuration and requirements. The consequence of this logic is that vehicle motion, related to the use of the CWD lane, could be less affected by driver decisions. In addition, the rules that control the vehicle behaviour are developed here according to a cooperative driving system where advanced driver assistance systems (ADAS) operate both on longitudinal vehicle behaviour (by speed control functions) and lateral vehicle position (by lane selection functions). This assumption is justified according to the time horizon of possible implementations of these CWD services, which is comparable to the deployment of cooperative driving systems.

To provide a brief overview on the system operations, the primary requirements of the CWD service are presented in the following list, according to the assumptions and system requirements defined in the eCo-FEV project (2013):

1. A driver who wants to use the CWD service should send a request to the charging station operator through an on-board unit (OBU).
2. After verification of the operational requirements, the charging station operator returns a confirmation message to the user and updates the list of authorized vehicles, where the driver receives the authentication on the OBU.
3. The CWD system should include some enforcement functions to prevent unauthorized vehicles from occupying the reserved lane.
4. The position of each authorized vehicle is monitored along the CWD lane to switch on only the coils under the vehicle, thus avoiding energy wastage.
5. The correct position monitoring is important also for vehicles outside the CWD lane because they affect overtaking manoeuvres.
6. The service should consider different vehicle classes, according to their energy requirements: different speeds should be admitted in the CWD lane.
7. Overtaking manoeuvres should be managed according to a cooperative system among vehicles to improve both safety and traffic performance: ADAS guide drivers during their manoeuvres and the cooperative system eventually intervenes on vehicle speeds to maintain the required gaps in the vehicle flow.

3 Simulation scenario and traffic modelling approach

Extensive review on traffic modelling approaches can be found in scientific literature (see for example, Hoogendoorn and Bovy, 2001). The choice of the traffic model is derived from two primary requirements of the CWD system (eCo-FEV, 2013):

	CWD Requirement	**Impact on traffic modelling**
1	CWD is installed along the right-hand lane of the ring road because, according to Italian driving rules, it is used by slower vehicles	⇨ *the traffic model must consider the disaggregation of traffic data per lane*
2	CWD can be used by vehicles with different charging requirements and speeds	⇨ *the traffic model must consider different vehicle classes, related to their SOC*

Considering the well-known approaches available in traffic modelling, a brief discussion is presented to justify the chosen approach. The macroscopic traffic models describe the mean behaviour of the traffic flow on road sections. Therefore, they are not adequate to describe this type of problem because of the lack of single vehicle information such as its energy state. Microsimulation could be one possible approach to effectively model multilane and multiclass problems because single vehicle trajectories and interactions are modelled with a small time step resolution (Barceló et al., 2005). However, microsimulation is oriented to model vehicle behaviour according to traffic parameters and not to energy requirements. In the proposed model, the current SOC of the vehicles may influence drivers' decisions concerning lane changing behaviour, i.e. vehicles try to enter or exit the CWD lane according to their charging requirements. Therefore, specific rules must be defined to obtain useful results for the CWD simulation from the traffic model. In addition, the detailed rules implemented in a microsimulation model usually require an accurate calibration process, aimed at replicating the actual driver behaviour in traffic, as observable in a real case scenario. However, the CWD system currently has been installed only in small test sites and, unfortunately, there are no opportunities to observe driver behaviour using CWD in large-scale systems. Furthermore, even cooperative driving systems are not completely deployed in real and observable cases. The most similar case is the traffic observable along critical road tunnels (e.g. the Mont Blanc tunnel) in which

- minimum vehicle spacing or headway should be maintained;
- all vehicles travel in a predefined speed range for safety reasons.

In such systems, the vehicle motion is controlled by safety constraints, as in the CWD model, although there are no interactions between vehicles, because overtaking manoeuvres and new entries along the lane are not permitted. Furthermore, the CWD technological environment may expand only in the future, involving another generation of vehicles in which vehicle-to-vehicle technology will be used and many cooperative functions will be activated to facilitate the driving activities.

In such a system, observation of the driving behaviour in a real case scenario is not relevant to model the traffic, because vehicle motions and interactions depend more on the activated automated functions of the ADAS and cooperative systems than on drivers' decisions. A calibration process based on empirical observations of the current traffic would be compromised whenever ADAS and cooperative driving systems are considered, because they surely affect driving and traffic performance.

For the reasons aforementioned, a simplified mesoscopic approach would be more appropriate to model the problem, because it represents a good compromise between the detailed resolution of the microscopic simulation and the current preliminary stage of development of the CWD technology, where no deployment is available in large scale. A framework of mesoscopic traffic models can be found in Cascetta (2001), whereas a recent application is proposed by Ben-Akiva et al. (2012). Mesoscopic models usually analyse traffic elements in small groups, within which elements are considered as homogeneous. A typical approach is based on vehicle platoon dynamics, for instance. In this study, the approach to introduce the time-dependent traffic behaviour is similar to Aimsun mesoscopic traffic modelling (TSS, 2014). Each vehicle is modelled as an individual entity, as with the microscopic approach, but the rules that model the state of vehicles (i.e. lane position, speed, SOC, and arrival time) are simplified with respect to microsimulation, because they do not simulate the state at each simulation time step, but take into account, at each node, only those vehicle features that are relevant for our problem, as described in the following section.

4 Simulation model of CWD

This section describes the developed simulation model: the first part reports the variables used and the main logic, whereas the second one details the functions implemented to process the dynamic evolution of the system state.

4.1 Logic of the model and definition of main variables

The road infrastructure is modelled as a sequence of road segments indicated as “sections”, delimited by “nodes” or “detection points”. Detailed traffic information related to each vehicle is updated only at nodes, based on traffic information determined at upstream nodes. Therefore, the iterative algorithm assumes that traffic conditions along the infrastructure can be described knowing only the data related to consecutive nodes, whose spacing, typically in hundreds of metres, can be set according to the specific requirements of the analysis resolution or related to the infrastructure features. The vehicle time information is defined only at nodes, also with respect to new entries of vehicles in the infrastructure. The model reproduces single vehicle trajectories, without introducing a detailed time-space resolution of the driving behaviour and it determines aggregated traffic information, such as vehicle count, average headways, delays, and the number of overtaking manoeuvres along the CWD lane for any road section. The logic scheme adopted and the main variables managed for two consecutive nodes are shown in Fig. 1.

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Fig. 1. Modelling of vehicle trajectories and possible interactions for two nodes.

Initially, the model estimates the arrival time of each vehicle at node (i) based on its arrival time at node (i-1) and its speed that depends on the vehicle class. Then, it manages the interactions between vehicles resulting from new entries in the CWD lane or by overtaking manoeuvres.

Overtaking manoeuvres that occur on the node are identified in the model, because a faster vehicle is not physically in the CWD lane and an erroneous vehicle count would lead to an overestimation of the energy required by the charging zone (CZ) on the same node. These manoeuvres are managed according to a cooperative driving model at constant speed and vehicles do not recharge their battery while they are outside the dynamic charging lane.

New vehicles in the CWD lane are caused by new entries in the infrastructure or by “out” vehicles that move into the CWD lane. New entries may cause unfeasible relative positioning between vehicles if the headway between two vehicles is less than the minimum acceptable headway (headway min); the algorithm corrects the arrival time of the following vehicle by slowing it down. In fact, because of safety and maybe technical reasons, headways less than a threshold value between two vehicles in the CWD lane may not be allowed. Moreover, the entries in the CWD lane are managed according to a cooperative behaviour: each vehicle that needs to recharge its battery is moved into the CWD lane at a node, adjusting its gap in the vehicle flow by slowing down the following vehicles if necessary. The headway verification and correction is therefore performed only at discrete space steps, according to the mesoscopic modelling of traffic. In an actual scenario, this process can be managed by drivers or by a cooperative system adapting the vehicle speed along the entire section before the node where the headway adjustment is performed.

The battery SOC for each vehicle, monitored along the road at each node, plays a crucial role because it influences the drivers’ decisions on whether to use the CWD service or not according to their destinations. For the analysed freight distribution service, this process can be simplified, because all the vehicles have identical destinations and the decision about charging does not depend on drivers but on the fleet operator. Vehicle

SOC is also the parameter used to divide vehicles into different speed classes, according to their charging requirements.

Finally, the algorithm allows the implementation of a speed control strategy, in which vehicles can be slowed down to create an empty time-space slot in the CWD lane at a defined node. An example of this application is described by Sun and Chen (2013). This type of control could be applied to support operations that require a free CZ for a given time slot, for maintenance activities of the coils, for example. This strategy could be applied even to facilitate merging manoeuvres for vehicles entering from secondary accesses, as an on-ramp access control in case of high traffic levels in the CWD lane.

4.2 *Functions of the simulation model*

The traffic simulator has been implemented as a laboratory prototype, using Visual Basic for Applications (VBA). It is composed of several subroutines that will be described in the following paragraphs. The algorithm operates according to the functional scheme shown in Fig. 2: it generates an initial traffic state, modelled by a set of vehicles, and then it iteratively analyses their individual travel times and energy parameters node by node. The routine "Strategy detection" runs only if the closure of the CWD lane is activated for a given time slot. Table 1 and Table 2 list all the input parameters required by the algorithm.

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Fig. 2. Block diagram of the algorithm structure with the sequence of functions.

4.2.1 *Initial traffic state*

The "Initial traffic state" routine defines the initial conditions, in terms of traffic arrivals and vehicle SOC, for both the initial node (node 0) and the secondary accesses. A large number of statistical time headway models have been proposed to describe the distribution of vehicle arrivals for a given road section. An observed distribution of time headways is generally included within negative exponential and normal distribution. A recent study (Moridpour, 2014) confirmed that a shifted lognormal distribution fits well with observed data for congested highways. However, the traffic data used do not refer to a single lane and many parameters are required to apply the proper model to the related traffic level and composition. On the other hand, at very short headways, the negative exponential distribution cannot describe the smaller variability in headways as observed in platoons. For these reasons and to simplify the process according to the scenarios explored, during the experiments presented in the following sections, a truncated normal distribution is used for the sequence generation of vehicle arrivals. The same sampling method is also used to generate the initial SOC. Nevertheless, different random distributions (e.g. negative exponential or lognormal) can be also applied for this function if required to simulate a specific traffic scenario during experiments.

At node 0, the vehicle flow is estimated according to a random algorithm (1) (Daganzo, 1997) used to define the headway h_f for each generated FEV *f* with respect to the previous one:

$$h_f = h_{av} + \sqrt{3} \cdot h_{av} \cdot c_{v,h} \cdot (Rnd + Rnd + Rnd + Rnd - 2) \geq h_{min}, \tag{1}$$

where h_{av} is the average traffic headway, $c_{v,h}$ is the coefficient of variation of the headway distribution, *Rnd* is a random value uniformly sampled in the range [0,1], and h_{min} is the minimum traffic headway. h_{av} is estimated from the average density (k) and the average speed (v_{av}) of traffic flow according to (2).

$$h_{av} = \frac{3600}{q_{av}} = \frac{3600}{k \cdot v_{av}} \tag{2}$$

v_{av} is estimated according to the Northwestern speed-density model (3) (Drake et al., 1967). Although more enhanced models have been proposed in the literature, its reliability is adequate for this application within the density range used (Wang et al., 2011).

$$v_{av} = v_0 \cdot exp\left[-\frac{1}{2}\left(\frac{k}{k_0}\right)^2\right], \tag{3}$$

where k_0 is the optimum density, whereas v_0 is the FEV free flow speed, which is estimated according to an iterative process that progressively reduces the vehicle speed v_f from the street speed limit, until condition (4) is met.

$$\left[\frac{R_{tot} \cdot v_f}{\eta_d} + P_{aux}\right] \leq P_{max,FEV}, \tag{4}$$

where the first term estimates the electric power required to run the engine ($P_{electric}$), which depends on the total resistance to motion (R_{tot}), the driveline efficiency (η_d), and the auxiliary power P_{aux}, which is the power that includes all consumption not related to the vehicle motion such as for lights and air conditioning; $P_{max,FEV}$ is the maximum engine power.

The headways obtained using (1) are then summed up to individuate the vehicle entering times. Using a random algorithm similar to (1), the routine assigns each vehicle its SOC; the SOC random distribution is limited at the lower end by a minimum value and at the upper end by the battery size. According to the generated SOC and to the introduced SOC thresholds, the routine defines the position (“out” or “in”), the status (“no charge”, “charge”, or “emer”), and the speed of each vehicle.

Concerning the on-ramps along the ring road, the routine operates in a simplified mode: given the node in which each access is located, i.e. the number of entering vehicles and the time window in which the entries are included as inputs, an entering time included in the time window is generated for each vehicle. This sampling procedure is performed through a uniform distribution, whereas the initial SOC for these entering vehicles is assigned according to the same random algorithm used for vehicles at node 0.

4.2.2 Strategy management

The “Strategy management” routine operates when the strategy is active and only at the iteration corresponding to the node in which the strategy is planned (briefly indicated as strategy node). It follows the following steps:

1. Sorting the vehicle arrival times in ascending order.
2. Selection of the first vehicle whose arrival time is included in the strategy time window (*strategy leader*).
3. Setting the *strategy leader* arrival time as equal to the strategy end time.
4. Estimation of the average speed of the *strategy leader* along the section approaching the strategy node.
5. Estimation of the new *safety headway* (h_s) that prevents unsafe gaps or even overlapping, according to (5).

$$\mathrm{h_s} = \frac{\mathrm{s_{min}} \cdot \mathrm{t}}{\mathrm{L_{section}}}, \tag{5}$$

where s_{min} is the minimum space allowed between two vehicles to avoid vehicle overlapping, which is set as the vehicle length plus an assumed safety margin (2 m), whereas t and $L_{section}$ are respectively the *strategy leader* travel time and the length of the approaching section.

After defining the *strategy leader* new arrival time, the following vehicles are managed by “Headway correction” and “Time estimation next” routines, as explained in the next paragraphs.

4.2.3 Headway correction

The “Headway correction” routine receives as input the arrival order and the predicted time of all the vehicles in the CWD lane at the investigated node. It progressively calculates the headways between two vehicles: if the calculated headway is less than the minimum headway, the routine delays the arrival time of the following vehicle at the detection point to satisfy the minimum headway requirement. The minimum allowed headway is the higher of the minimum technical headway for CWD operations and h_s. Indeed, when the strategy activation causes relevant speed reductions, the time a vehicle takes to cover its length and the safety spacing could be higher than the technical headway defined for CWD operations. In this case, this specific headway regulation is applied to the time window between the initial time of the strategy and the *end* *queue time*. This value is the time in which the propagation of the strategy effects, in terms of vehicle platooning, is supposed to be ended. The *end queue time* is estimated by the “Time estimation next” procedure, as described in section 4.2.8.

For each simulated vehicle, the “Headway correction” routine also records other parameters that can be used for internal checks, such as the identification code (ID) of the preceding and following vehicles and the headway of the following vehicle.

4.2.4 Overtaking at node

The “Overtaking at node” routine identifies those vehicles that are overtaking just on the detection points. This procedure works following two simple steps:

1. Detection of two consecutive vehicles with different speeds.
2. If the headway between these vehicles is less than half of the overtaking manoeuvre duration, then the faster vehicle is identified as overtaking.

This function is useful to detect FEVs only when they actually cross a detection point in the CWD lane. In this way, more realistic time profiles of the energy provided by the electric line on CZs are obtained. The implemented overtaking model (Fig. 3) refers to an overtaking manoeuvre at constant speed and the overtaking time ($t_{overtaking}$) is defined by (6).

$$t_{overtaking} = t_1 + \frac{2 \cdot L}{v_1 - v_2} + t_3, \tag{6}$$

where t_1 and t_3 are respectively the lane changing time from and to the CWD lane, *L* is the FEV length, and v_1 and v_2 are respectively the speeds of the overtaking and overtaken vehicles. t_1 and t_3 are assumed equal to 4 s, according to the prescriptions of the Italian technical standards for the design of road infrastructures (DM 6792/2001). This value is also supported by the studies of Farah (2010, 2013).

4.2.5 SOC estimation

The “SOC estimation” routine first calculates the actual average speed of each vehicle along the last section after slowdowns generated by headway corrections. The actual average speed is used to update the SOC level of each vehicle by estimating the energy balance between the consumption related to motion and the energy provided by the coils for the vehicles in the CWD lane.

The implemented model for estimating the vehicle energy consumption is based on the resistance to motion approach. The total resistance (R_{tot}) is given by (7).

$$R_{tot} = R_{drag} + R_{rolling} + R_{acceleration} + R_{slope}, \tag{7}$$

where

$$R_{drag} = \frac{1}{2} \cdot \rho \cdot c_x \cdot A \cdot s^2 \tag{8}$$

$$R_{rolling} = m \cdot (f_0 + f_2 \cdot v^2) \tag{9}$$

$$\mathrm{R}_{\mathrm{acceleration}} = \mathrm{m} \cdot \mathrm{a} \tag{10}$$

$$R_{slope} = m \cdot g \cdot p. \tag{11}$$

Therefore, the total resistance depends on the following parameters: air density (ρ) [kg/m^3], drag coefficient of the vehicle (c_x), cross-sectional area of the vehicle (A) [m^2], vehicle speed relative to air (S) [m/s], vehicle mass (m) [kg], rolling coefficients (f_0, f_2) [m/s^2, 1/m], vehicle average speed (v) [m/s], vehicle acceleration (a) [m/s^2], and average slope of the road (p). For simplicity, the speed relative to air will be taken as equal to the vehicle average speed. Finally, the energy consumed by the vehicle along a section is obtained by multiplying the power required to run the engine because of the resistance to motion to the time necessary to cross the section (12).

$$E_{consumed} = P_{electric} \cdot t = \left[\frac{R_{tot} \cdot v}{\eta_d} + P_{aux}\right] \cdot \frac{L_{section}}{V} \tag{12}$$

The energy received from the coils for the vehicles in the CWD lane is strictly related to the system element dimensions (EVSE layout and on-board devices), the power provided by the coils (P_{CZ}) [kW/m], and the occupancy time of the CZ (t_{CZ}), according to (13).

$$E_{received} = P \cdot n_{CZ} \cdot t_{CZ} = \left(P_{cz} \cdot LCD \cdot \eta_s\right) \cdot \left(\frac{L_{section}}{LCZ+I}\right) \cdot \left(\frac{LCZ_{eff}}{V}\right), \tag{13}$$

where LCD [m] is the on-board device length, η_s is the system efficiency that depends on the distance between the coil(s) of the on-board device and the coil(s) of the CZ installed in the road pavement, LCZ [km] is the length of CZs, I [km] is the inter-distance between CZs, and LCZ_{eff} [km] is the CZ length in which vehicles effectively recharge. LCZ_{eff} is calculated according to (14).

$$LCZ_{eff} = LCZ - Trk \cdot LCD \tag{14}$$

The coefficient *Trk* is introduced to take into account the initial and final partial overlaps between coils on the vehicle and in the pavement that reduce vehicle electric recharges.

4.2.6 SOC update for overtaking

For each road section and for each vehicle in the CWD lane, the "SOC update for overtaking" routine operates according to the following scheme:

1. It calculates the number of overtaking manoeuvres by comparing the arrival time of the considered vehicle with all the vehicles in the CWD lane. Considering two sample vehicles (*A* and *B*), an overtaking manoeuvre along section *i* is detected by the conditions presented in (15).

   $$t_A(node_{i-1}) < t_B(node_{i-1}) \ \& \ t_A(node_i) > t_B(node_i) \tag{15}$$

2. It selects and orders the arrival time of the overtaken vehicles ($t_{overtaken,1}$, ..., $t_{overtaken,\ N}$).

3. It calculates the time in which vehicles cannot recharge because they are overtaking t_{out}. Considering two overtaken vehicles (*A* and *B*) and the overtaking vehicle (*C*), the overtaking time is individuated by (16).

$$t_{out} = min\left(2 \cdot t_{overtaking};\ t_1 + (t_B - t_A) + t_3\right) \tag{16}$$

4. It updates the vehicle SOC according to (17).

$$SOC_{new} = SOC - E_{received} \cdot \frac{\mathrm{t_{out} \cdot v}}{\mathrm{(LCZ+l)}} \tag{17}$$

Fig. 3. Two examples of overtaking manoeuvres.

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4.2.7 *Speed test*

"Speed test" is a checking routine for traffic conditions next to saturation. It verifies the consistency between vehicle actual average speeds, headways, and the minimum spacing for two consecutive vehicles. The routine returns an error message if an incoherent spacing case is detected (e.g. overlapped vehicles). During the experimental simulations, this incident has never occurred.

4.2.8 *Status estimation next*

The "Status estimation next" routine returns the lane position ("in" or "out" the CWD lane) and the status ("emer", "charge", and "no charge") of each vehicle in the downstream section, according to the updated SOC on the node. By defining its status, the routine assigns each vehicle its free flow speed, according to the recharging speeds set in the CWD lane.

If the strategy is active at a certain node, the routine excludes that "out" vehicles may enter in the CWD lane during its activation period by keeping their position and status as "out" and "no charge".

4.2.9 *Time estimation next*

The “Time estimation next” routine estimates the arrival times of the vehicles at the next section, based on the free flow speeds assigned by their status.

If the strategy is active, its effects on the traffic are not only limited to the lane closure duration, but also extend to a wider period (*recovery period*). The propagation end time (*end queue time*) can be estimated according to the cumulative plot diagram shown in Fig. 4, where

$$end\ queue\ time = t_{s,1} + \left(t_{s,1} - t_{s,0}\right) \cdot \frac{\lambda}{\mu-\lambda}. \tag{18}$$

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Fig. 4. End queue estimation during the strategy.

The rate of arrivals (λ) and departures (μ) are estimated respectively based on the number of arrivals at the node, scheduled during the lane closure period (N), and the minimum feasible headway (h_{min}) for the vehicle flow before the node involved in the lane closure, according to (19) and (20).

$$\lambda = \frac{3600 \cdot N}{\left(t_{s,1} - t_{s,0}\right)}, \tag{19}$$

$$\mu = \frac{3600}{h_{min}}, \tag{20}$$

where h_{min} is estimated by applying equation (21), assuming that during the period necessary for *emer* vehicles to cover the section length (extended for the lane closure time), vehicles can be uniformly spaced with s_{min}:

$$h_{min} = \left[\frac{L_{section}}{v_{emer}} + \left(t_{s,1} - t_{s,0}\right)\right] \cdot \frac{s_{min}}{L_{section}}. \tag{21}$$

For those vehicles whose scheduled time is included between the initial time of the strategy and the *end queue time*, the routine can operate according to two different approaches. The first one defines the vehicle relative positions at the *strategy node* according to the scheduled arrival times based on two operational speeds in the CWD lane. The second approach performs a standardization of vehicle speeds: all vehicles are projected according to the faster speed class. This implies that overtaking manoeuvres are not performed along the road section approaching the *strategy node*. Long strategy durations lead to very low average speeds in the approaching section. Therefore, overtaking manoeuvres would involve very slow vehicles, causing safety problems because of the dangerous interactions between slow and fast vehicles in "out" lanes. The first approach is suggested only for very short time windows. For slow vehicle classes, the second approach may have another impact: slow vehicles arriving at the *strategy* node shortly after the initial time of the strategy can anticipate lane closure because their speeds are set the same as those of fast vehicle classes.

4.3 Verification and validation processes

An extensive verification process has been performed by analysing, testing, and reviewing the activities, according to the concepts defined in the ECSS (2009) standards. In particular, a technical verification of the model response is performed based on the following four consecutive test case approaches, each one aimed at verifying different aspects:

- *Single vehicle*. This first stage is devoted to ascertain if the single vehicle motion is correctly simulated, as well as the relationship between its behaviour and its energy requirements. First, a verification of the correspondence between the estimated SOC and the vehicle position, status, and speed is performed. Then, a verification of the accuracy of the travel time based on the vehicle speeds is conducted. Finally, a verification of the coherence between the implemented energy model and the vehicle SOC trend at each node is carried out.
- *Uniform vehicle flow without overtaking*. This second stage of the consistency verification of the model is developed to assess if the model is able to correctly manage the headways between vehicles, even in the case of new entries.

- *Complex traffic interaction with overtaking manoeuvres*. The third stage aims to assess the global interaction between vehicles by introducing overtaking manoeuvres. The model has been tested in a scenario in which overtaking manoeuvres are feasible. The number of overtaking manoeuvres per section, the identification of vehicles that are overtaking on the nodes, and the time required for the manoeuvres and its influence on the SOC trend because of the missed recharge have been verified.
- *Strategy activation*. The last stage checks the consistency of the strategy simulation results in case of incidents. A general case of traffic is simulated and vehicle trajectories in the space-time diagram are verified in the neighbourhood of the *strategy node*.

At this stage of the CWD development, the presented model has been validated by checking the satisfaction of the established technical requirements based on a system engineering approach (INCOSE, 2011). The primary functional requirements used for the validation of the model are the following:

1. the model shall estimate the number of vehicles in the CWD lane for any detection point;
2. the model shall consider possible random effects of input flows;
3. the model shall represent the traffic flow at any detection point and determine if concentration of traffic and congestion occur along the lane;
4. the model shall take into account different values of the minimum headway allowed in the CWD to estimate possible effects on traffic and energy for the various CZs over time;
5. the model shall consider also on-ramp input flows along the CWD lane to assess possible interactions over time;
6. the model shall consider the effects of different scheduling plans on the SOC of the vehicle fleet during arrival at the depot;
7. the model shall determine the possibility of a temporary closure of the CWD lane, without interrupting the service to FEVs.

In the following chapters, the model testing results are presented in an "ideal case", in which all of the subsystems and applications involved, such as the CWD booking and authorization functions, or the cooperative ADAS, which enable the vehicle cruise control or the cooperative overtaking, work properly. In this scenario, all related system information, such as the vehicle position and its SOC, is accurately known. This validation approach could be considered as a "best-case" testing and it is consistent with the test-case-design methods applied to test software, such as boundary value analysis (Myers et al., 2004), or distributed real-time systems (Gutiérrez et al., 1998).

5 CWD scenario and experimental results

The model is applied to simulate the CWD activities, traffic, and energy states for a hypothetical freight distribution service operated with EVs starting from a single depot. After completing their routes, vehicles have to come back to the depot to start a new delivery task in the same day. All vehicles that arrive at the depot must have a minimum SOC level to restart further activities without exceeding the wasted time during the stationary recharge. In this way, the fleet operator could maintain its level of service, saving the resources required to install additional electric infrastructures for vehicle stationary recharges.

5.1 General description of simulated scenarios and setting of parameters

The CWD system is assumed to be implemented on the ring road of Turin in Italy (Fig. 5) and the infrastructure is modelled with 1 km road sections, for an overall distance of 18 km. The first section in the road model, between nodes 0 and 1, is used to split the traffic flow between "in" and "out" vehicles and it is not equipped with coils. The input flow is composed of the main stream and four secondary on-ramp flows.

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Fig. 5. Turin ring road with main secondary accesses.

Table 1 lists all the algorithm input parameters, whereas on-ramp input flows are presented inTable 2. The average slope of the road is assumed as negligible, because the ring road is generally flat.

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Table 1. Input parameters related to the different types of data

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Table 2. Demand data: FEV arrivals at each access

Deliveries are supposed to be handled by an electric medium-sized van. Therefore, for a given CWD system and considering one vehicle type, the key parameter that can affect the CWD performance is the vehicle speed. Two operational speed values are implemented, based on previous experiments (Deflorio et al., 2013). The first one allows vehicles to maintain their SOCs: it is the speed adopted by vehicles with an adequate SOC based on the fleet operator requirement. The range of SOC that satisfies the fleet operator requirement is the one comprised between “charge” and “emer” thresholds. These vehicles are in “charge” status and their speeds are set to 60 km/h. The second speed (30 km/h) guarantees a proper recharge—1 kWh after approximately 2.7 km—and it is adopted by vehicles in “emer” status, whose SOC is low and lower than the “emer” threshold.

5.2 Reference scenarios in two scheduling cases

The CWD system model has been tested in several traffic scenarios to determine its capability of simulating effects that are relevant to CWD operations. The traffic along the CWD lane depends also on the demand structure and therefore on the input flows entering at the various on-ramps of the ring road. For this reason, we have assumed two reference-scheduling plans of the freight distribution service, which may represent the worst and best cases of traffic conditions on different possible fleet management strategies:

- Scenario 1 (*Simultaneous end of service in the city centre*) refers to the case where all vehicles distributing or picking parcels complete their services almost simultaneously. In this case, interactions along the ring road will be less relevant and arrivals to the depot will be distributed over a wide time range, because vehicles start to enter into the ring road almost simultaneously but in different spaced nodes. This strategy may be representative of vehicle delivery missions with almost identical durations for the various zones of the city.
- Scenario 2 (*Simultaneous arrival at depot*) concentrates all the arrival times to the depot in a small time window. In this case, vehicles coming from farther zones enter into the ring road earlier than nearer vehicles. By adopting this fleet strategy, vehicle delivery missions are on average longer for the nearer zones of the city, because FEVs can come back to the depot in a shorter time.

The effect of FEVs on the road traffic in the charging lane can be observed by comparing the set of trajectories of all FEVs in the two time-space diagrams related to the two scenarios (Fig. 6). The concentration phenomena of FEVs along the ring road, as expected, are more relevant in the second scenario and occur in the final sections after 10 min from the beginning of the simulation.

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Fig. 6. Space-time relationship for "in" vehicles in scenario 1 (left) and scenario 2 (right) for a sampled replication.

As usual in traffic analyses, the results depend on many random factors, which can be included in the model rules at different levels. In the simulated cases, the focus of random phenomena is related to the features of input flows at various entries, according to their energy level and time of arrival sequence. The scenario variability is simulated in this analysis by 50 replications.

The average time headway and average delay of the vehicles in the CWD lane are shown in the following charts (Fig. 7 and Fig. 8) for a time resolution of 1 min at each node of the ring road modelled. The delay is estimated as the difference between the simulated travel time and the travel time as predicted using the planned speed. The average values are obtained by taking into account all the 50 replications of the experiments.

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Fig. 7. Average time headway of "in" vehicles, node by node, with a 1 min time resolution in (a) scenario 1 and (b) scenario 2.

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Fig. 8. Average delay [s] for "in" vehicles, node by node, with a 1 min time resolution in (a) scenario 1 and (b) scenario 2.

These charts show where and when relevant congestion events, i.e. contemporary low headway values and high delays, are detected by the model. In the first scenario, only few slowdowns occur and they are quite limited and observable only in the final part of the ring road, i.e. after node 12. The minimum headway in CWD (2 s) is never reached in scenario 1, whereas it is frequently observed in scenario 2, which shows more congestion problems for users during the charging operations on CWD.

The effect of vehicle concentration in a smaller period due to s*imultaneous arrival at the depot* is evident by comparing scenario 2 and scenario 1. The effect on congestion is confirmed by the average delays shown in Fig. 8, which are even higher than 1 min. The higher values are detected at nodes 13 and 14 in the time interval [13,18]. The low congestion level for the first scenario is described also by the delay: the maximum value (6 s) is observed at node 14, only during the first minute of the simulation period.

5.3 Incident simulation in CWD lane: simultaneous arrivals at depot (Scenario 3)

The conditions of scenario 2, which are critical for congestion phenomena, can also be monitored in the case of an incident in the CWD lane. For various reasons, such as maintenance, cleaning, or inspection of the coils, the CWD lane could be out of service in a particular node and it should be kept free from traffic for a certain period. This vehicle-free time window can be obtained by reducing the vehicle speeds in the CWD lane along the section approaching the node involved in the incident. The strategy is modelled by “Headway correction” and “Time estimation next” routines and is applied by avoiding overtaking manoeuvres in the approaching section.

In the experiments performed, the CWD lane closure lasts for two minutes, starting from the 18th minute, i.e. 1080 s from the beginning of the simulation.

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Fig. 9. Space-time relationship for "in" vehicles in the case of the strategy application.

Fig. 9 depicts the trajectories of all the charging vehicles for the selected replication (#48) to show the effect on traffic flow of the temporary closure of CWD at node 16. The trajectory of vehicle #247, represented by black dots, shows that, if it was travelling at 30 km/h, it would have been involved in the lane closure at node 16. However, because of the speed control action, it increases its speed and it crosses node 16 before the incident. After node 16, its speed is set again to 30 km/h based on its charging requirements and is then maintained until the final node. In this case, negative values of delay are detected.

The impact of the incident on the SOC is shown in Fig. 10(a) in which the missing simulation data for minutes 18 and 19 confirm the CWD lane closure for that period at node 16. The energy results of traffic flow are averaged on 50 replications to provide reliable estimates.

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Fig. 10. Average SOC [kWh] of "in" vehicles, node by node, with a 1 min time resolution for (a) scenario 3 and (b) scenario 2.

The data also show that vehicles arriving at the depot after the temporary closure have a higher SOC than those in scenario 2 (see Fig. 10(b)). The lower SOC values in the “zone” of lane closure, i.e. 7.7 and 5.7 kWh, refer to the contribution of “emer” vehicles that have avoided the lane closure because of the speed regulation. Indeed, their charging time has been reduced because their speed has been set to 60 km/h. The propagation of the strategy effects on the average travelling speed reduction can be analysed by observing the delay of the vehicles. As expected, the higher delays occur in average in the section before node 16, during the *recovery period*.

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Fig. 11. Average delays [s] of "in" vehicles, node by node, with a 1 min time resolution for scenario 3.

The speed reduction effect on the different sections of the ring road can be observed over time also by analysing the maximum delay values, which provide useful information on the worst traffic condition for vehicles. During the 50 replications, some vehicles are delayed by more than 2 min (Fig. 12(a)) and the more affected vehicles are at node 16 from minutes 20 to 25, in case of incident, whereas in scenario 2 (normal condition) the higher delay values (less than 1.5 min) are detected at node 13 (Fig. 12(b)).

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Fig. 12. Maximum delays [s] of "in" vehicles, node by node, with a 1 min time resolution for (a) scenario 3 and (b) scenario 2.

In the incident node (16), no vehicle is delayed by less than 53 s after the incident is solved (Fig. 13), during the minutes 20 and 21. In the same figure, the negative delay values occurring just before the lane closure and from two minutes after confirm the phenomenon described in Fig. 9.

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Fig. 13. Minimum delays [s] of "in" vehicles, node by node, with a 1 min time resolution for scenario 3.

A detailed delay analysis at node 16 can be performed on the extreme values, counting the vehicles with a delay equal to or greater than 2 min for the various replications during the critical intervals (from minutes 20 to 25). Fig. 14 shows that extreme values that do not always occur for all the replications, even if they are less frequent in minute 25, with a high variability. The maximum value observed is 30 vehicles, which means that all the vehicles are delayed by more than 2 min, given that the maximum number of vehicles crossing the node during 1 min is 30 (minimum technical headway in CWD lane = 2 s).

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Fig. 14. Number of vehicles with delays [s] greater than 2 min at node 16 for scenario 3.

Finally, the worst cases of the SOC for the vehicles arriving at the depot (node 18) have been detected among the fleet. They can be observed by monitoring the 50 replications for the minimum SOC evolution over time (Fig. 15). In this case, the incident and the implemented strategy (scenario 3) affect the possibility of charging the vehicles involved. In particular, some vehicles before the incident arrive at the depot with a low SOC (less than 4 kWh instead of 6 kWh], but the other vehicles (arriving at the depot in the time slot 22–24) recover a higher SOC level with respect to the normal conditions (scenario 2).

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Fig. 15. Minimum SOC [kWh] of "in" vehicles at node 18 (depot) with a 1 min time resolution for scenarios 3 and 2.

5.4 Variation of FEV demand using the CWD service

To explore the effects of different FEV penetration rates on the quality of the CWD service, some relevant results on two further scenarios are presented in this section. Based on scenario 2, scenarios 4 ad 5 are simulated respectively with demand D = 10 and D = 100 FEVs entering from each access (for scenario 2 the value was D = 50; see Tab. 2). Although many combinations are possible for the traffic demand, a homogeneous structure has been assumed to easily compare the results. For simplicity, average delay results are presented aggregated over space (place about here

Fig. 16) and over time (Fig. 17). As the demand increases, a longer congestion time is observed:

- for D = 10 congestion has a low intensity (less than 10 s) and lasts less than 10 min;
- for D = 50 the congestion period is over 20 min, with a maximum delay value of 35 s;
- for D = 100 the congestion period, with a delay peak of 50 s, is almost 30 min.

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Fig. 16. Average delay [s] over time [min] along the entire ring road.

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Fig. 17. Average delay [s] over space [km] along the entire simulation period.

The demand increase generates different delay levels, but if they are averaged over time, the peaks remain at the same nodes (Fig. 17) as expected because of the on-ramp positions.

6 Conclusions and further research

This paper presented a method of assessing the performance of electric power systems to dynamically charge EVs while driving, taking into account both traffic and energy dynamics. The reference scenario involves a freight distribution service in an urban area operated using electric medium-sized vans. The CWD lane has been modelled in a realistic layout, assumed to be installed on a ring road, with secondary on-ramps, for supporting electric charging operations during the return part of vehicle trips. The set of speeds for CWD operations is relatively low because, for the assumed electric power and test vehicle considered, it is most appropriate to satisfy the fleet operator requirement to guarantee a minimum SOC at vehicle arrivals to the depot. The traffic and energy models are then based on assumptions related to this particular simulation scenario.

The implemented dynamic traffic simulator adopts a mesoscopic approach by updating traffic and energy data only for the simulated vehicles at defined nodes along the road, generally spaced in hundreds of metres. The traffic simulator operates according to a cooperative driving behaviour among vehicles, for both the overtaking manoeuvres and the entries management, and it is able to simulate different traffic conditions. From single vehicle data, primary traffic parameters can be estimated in the CWD lane, such as vehicle count, average speeds, and delays, which are time dependent and significantly changed along the road. The model also allows the implementation of a speed control strategy to manage temporary incidents, for example due to extraordinary maintenance operations. This strategy could also be applied in the case of high traffic volumes to facilitate the entries of vehicles from on-ramps. The traffic model is able to manage even queuing conditions and delays caused by the strategy, when headways in the CWD lane are required to be higher than an established value. With respect to conventional dynamic traffic models, in the proposal presented here, the current vehicle energy requirements affect the drivers' behaviour: according to their SOC along the road, vehicles are simulated inside or outside the charging lane and their speeds are set consequently.

The implemented dynamic traffic simulator has an approximation compatible with the stage of development of the CWD technology and the deployment of cooperative driving systems. For this reason, in our idea, the presented model should be considered as a support methodology to feasibility studies of a promising future technology, in ex ante evaluations. When the CWD technology and full cooperative system are available in large-scale applications, more investigations could be required and then the model could be empirically calibrated, also according to the observed driving behaviour.

The main achievements of this study can be outlined as follows:

- To provide a method of measuring the impact on the quality of the defined CWD service (delay, speed) as well as on energy requirements (SOC for vehicles, energy provided at CZs).

- To apply the method in detecting where and when the worst conditions would occur in relevant demand scenarios according to possible timing requirements of the distribution service (worst and best cases in traffic impact) and for different traffic levels.

- To apply the method and verify (in the incident scenario) how much the performance of the CWD can decrease for a short service interruption at a specific node, with a proper management strategy acting on the speed control of the vehicles on the CWD lane.

More developments can be carried out to improve the practicality of the traffic simulator. For example, the speed in the other lanes is estimated according to the initial traffic density. For further enhancement in very high FEV traffic levels, the model could also consider that during the period, the density in the other lanes may change for both FEV lane changing manoeuvres and fluctuations of conventional “non-electric” traffic. Even more complex scenarios with different vehicle types and related traffic flows could be analysed. Furthermore, the model could be extended to flows of passenger cars, where the recharging requirements should be related to vehicle destinations, thus requiring the estimated demand data of detailed origin/destination matrices.

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