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Identifying bottlenecks in charging infrastructure of plug-in hybrid electric vehicles through agent-based traffic simulation

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Abstract

The effect of different charging infrastructure configurations on the electric-driven distance of plug-in hybrid electric vehicles (e-mileage) has been investigated, using an agent-based traffic simulation. Our findings suggest that the same e-mileage can be achieved with fewer charging poles if the poles support charging from several parking slots around them, and the charging cable is switched from one vehicle to the next. We also find that the charging power supported by most Finnish charging stations, 3.7 kW, and the cable switching delay of 1 h seem to be sufficient for effective workplace charging.

Keywords: PHEV; charging; infrastructure; agent-based modeling

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1 INTRODUCTION

Plug-in electric vehicles (PEVs) are ground vehicles that can draw their energy from an electrical outlet; a feature that allows the decoupling of transportation and CO_2 emissions. With the ongoing struggle to reduce greenhouse gas emissions to a sustainable level, and with the transportation sector consuming around 27% of energy worldwide [1], it is expected that PEVs will become more prevalent in the near future.

However, lack of EV charging infrastructure is the most critical barrier to successful deployment of EVs at large scale [2]. Thus, the problem of optimally locating and sizing charging stations has been studied rather well. In general, these studies optimize (e.g. maximize social welfare, minimize number of missed trips due to battery running out) a function under budget constraints. In cases with no budget constraint, the objective is usually to minimize the total cost, as in [3–6], although multiobjective approaches exist also [2]. Evaluation of the functions can be computationally demanding, and thus the optimization routine may involve heuristic methods such as genetic algorithms [3, 7–9] or particle swarm optimization [6, 10]. Case studies are often incorporated into these publications [2, 3, 6, 11].

However, relatively few studies examine the low-level interactions where parking slots are physically occupied by vehicles. This is important because if all parking slots near a charging pole are occupied by fully recharged vehicles, that charging pole is effectively out of service and does not contribute to serving the EV power demand [12]. Interactions such as this one may be critical in capturing the true effectiveness of the charging infrastructure.

Some authors, e.g. Xi *et al.* [13], Hess *et al.* [14] and Qin and Zhang [15], have performed this more detailed analysis. Xi *et al.* optimized the location and size of charging stations in central Ohio region. Their two objectives were to maximize the number of EVs that charge and the amount of battery energy recharged. A vehicle charges if and only if there is an unoccupied charger available upon arrival, and a charging EV occupies the charger for entire parking duration. Two different chargers were used, level-1 (1.4 kW) and level-2 (4 kW) [13].

Hess *et al.* used genetic algorithms to optimize the placing of 30 charging plugs and up to 6 charging stations that house them in Vienna. The objective was to minimize the average trip time, including queuing and charging. The article studies full EVs that alter their traffic behavior according to the state of charge (SOC) of their batteries [14].

Qin and Zhang minimized the queuing time for charging in an open road network with 100 charging stations. In their approach, EVs make charging reservations to certain stations. The

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stations then use the reservation data to inform EVs on current and future waiting times at different stations. Each EV may then select the best station to minimize its waiting time, which comprises queuing time and charging time [15].

In the current study, dedicated charging poles are not assumed for each parking slot, i.e. a single charging pole may serve vehicles parked in several slots around the pole. The difference with regard to Xi *et al.*'s approach is that, even if there are no charging sockets available upon arrival, a vehicle may still charge later if a cable becomes available (a nearby vehicle is disconnected).

The major difference in our approach with regard to all three studies is that all the vehicles in the current study are plug-in hybrid electric vehicles (PHEVs) instead of EVs, and can thus leave any node at will, regardless of SOC. Furthermore, only workplace charging is considered in the current study.

2 METHODS

Home charging, with its high accessibility and low power requirement, is widely regarded as a preferred charging mode [16], especially for PHEVs [17]. Consequently, in our analysis, each vehicle has a dedicated charging post at home. In this base scenario, no charging infrastructure exists outside homes. To this base case, we add charging infrastructure to workplaces, in different configurations. Workplaces are selected because commuting vehicles are a major contributor to weekday travel and because these vehicles stay at their destination relatively long periods of time. This approach is in line with the findings of Xi *et al.* [13], who note that the amount of EV energy recharged is maximized when most of the charging stations are built at workplaces [12]. Consequently, only ordinary weekdays (24 h in length, starting at midnight) are simulated.

The parameter that is used to measure the performance of different infrastructure implementations is the electric mileage (*e-mileage*), which is simply the total distance driven by all vehicles in electric-only-mode during the simulated period. By selecting this measure, we focus on the benefits that EVs provide on the society level. When e-mileage is maximized, fuel use in the vehicles is minimized, implying CO_2 emission reductions compared with the base scenario.

We assume that the investment in the charging infrastructure is heavily subsidized by the government. Therefore, problems related to the commercialization of EV charging (e.g. the '6 euro problem') are ignored [18, 19]. Similar public funding assumptions have also been made by, for example, Wang *et al.* [2], Sathaye and Kelley [20] and He *et al.* [21].

PHEV power demand is obtained through an agent-based simulation that relocates vehicles by attracting them toward certain node types at certain times. There are five types of nodes: home, workplace, shopping, leisure and empty nodes. A vehicle is parked at the node for a time that depends on the type of the node in question. The simulator is explained in more detail in [22].

Simulator control functions used here are the same as in our previous work [23]. However, the original node network was modified by adding artificial 'node tails' consisting of work nodes, to account for long-distance commuting (Figure 1). Workplaces were then assigned to the vehicles in such a way that the simulated commute distance distribution would closely resemble the measured commute distance distribution in [24]. Furthermore, in the current work, all vehicle agents travel at a constant speed of 60 km/h.

2.1 Charging infrastructure

The central element in our charging infrastructure implementation is the *charging pole*. A charging pole is a charging access point that can charge one or several EVs at the same time. The number of EVs that can be simultaneously charged at one pole is determined by the number of *cables* at the pole. A cable transfers power from the charging pole to a single EV by conductive means, with a certain maximum supported power. Each cable at one pole can charge a vehicle located in one of the parking *slots* around the same pole. Only one vehicle can occupy a single slot at a time. An example system with one pole, two cables per pole and eight slots per pole is shown in Figure 2.

If there are fewer cables than occupied slots at one pole, a charging *queue* may be formed. Charging order in the queue is based on the arrival times of the vehicles such that vehicles that

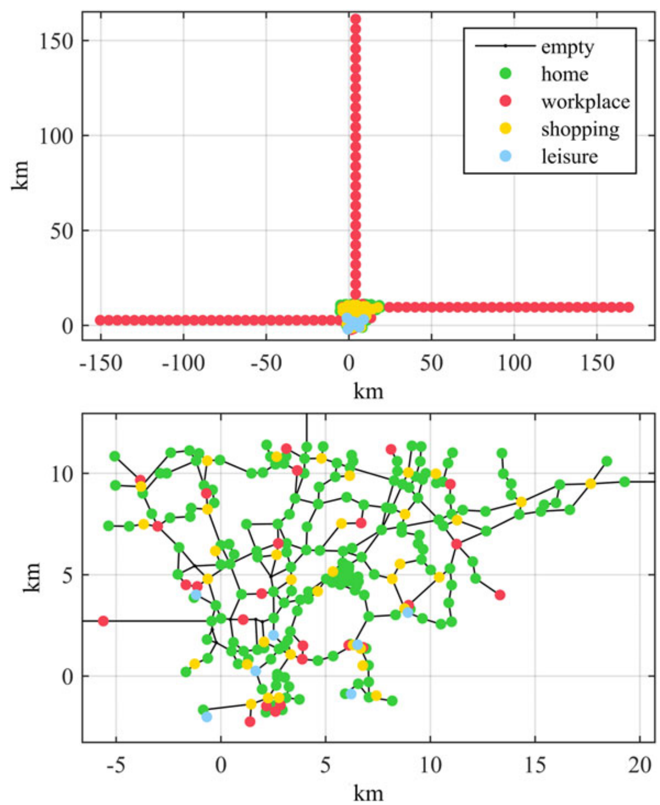

Figure 1. *Node network used in the simulations, representing Helsinki region in Finland.*

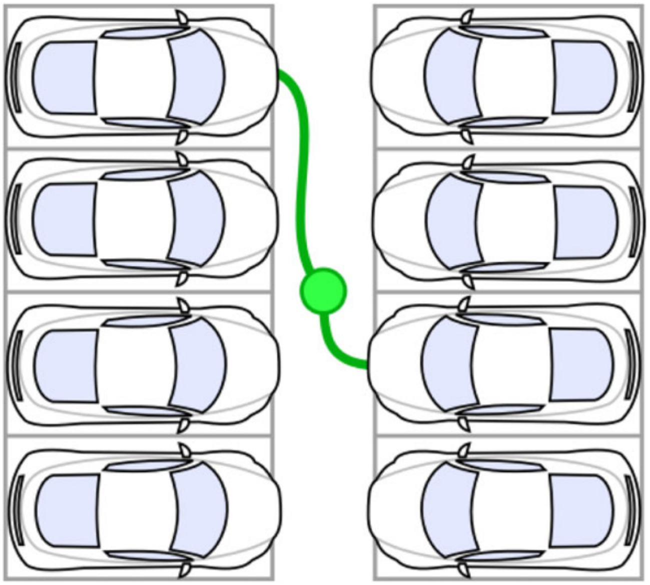

Figure 2. *Example infrastructure at a node: the node has one charging pole, each pole has two cables and each cable can recharge vehicles parked in any of the eight parking slots around the pole.*

arrive first are charged first (*first come, first serve*-principle). When a vehicle is fully charged, the cable is switched to another non-fully charged vehicle which then begins charging. The first vehicle will, however, keep occupying its slot until it is moved by the owner. This means that, if all vehicles in the slots around the pole are fully recharged, that pole is temporarily out of service.

Cable switching takes a certain amount of time, determined by the *cable switching delay*. This delay reflects the amount of time it takes for an entity to physically disconnect the charging cable from one vehicle and connect it to another. Delayed switching occurs when a vehicle becomes fully charged. When vehicles arrive to or leave from the charging pole, there is a person (the driver) present, and thus, the cables connected to that pole are switched immediately. We assume that no driver cheats the system by always connecting the cable to their own vehicle.

Finally, when a new vehicle arrives to the node, it will search for the pole that has the shortest charging queue (the fewest number of vehicles), and parks in one of the slots around that pole (if the shortest queue is tied, the pole with the lowest identification number is selected). If all slots around every charging pole are taken, the vehicle parks in an ordinary parking slot that does not provide charging service. These vehicles are not recharged at all during their stay at the node.

For simplicity, we assume that all work node charging poles are identical. In reality, charging infrastructure can vary considerably between different nodes and even within the same node. Similar symmetry assumptions have been made by, for example, Xi *et al.* [12] and Qin and Zhang [15].

2.2 Battery model

The battery model is a simple linear model which assumes that the energy transferred to the battery of vehicle v, $\Delta E_{\mathrm{batt},v}$, is only dependent on the power of the charging device, ignoring, for example, battery temperature, ambient temperature, battery voltage and the magnitude of the charging current:

$$\Delta E_{\mathrm{batt},v} = \eta \times P_{\mathrm{charg},v} \times \Delta t \tag{1}$$

where η is the charging efficiency (assumed constant 90%) and Δt the length of the time step (5 min). The power a vehicle v is charged with $P_{\mathrm{charg},v}$ is given by the lowest of the two power limitations: the maximum power of the battery $P^{\max}_{\mathrm{batt},v}$ and the charging cable $P^{\max}_{\mathrm{cable}}$:

$$P_{\mathrm{charg},v} = \min(P^{\max}_{\mathrm{batt},v}, P^{\max}_{\mathrm{cable}}) \tag{2}$$

The energy demand of the vehicle for a trip of length d is approximately

$$E_{\mathrm{trip,\,demand}} = d \times k \tag{3}$$

where k is the mean electricity consumption per distance (assumed 0.2 kWh/km). If the battery runs out before the trip is covered ($\mathrm{SOC} < E_{\mathrm{trip,\,demand}}$), the remainder of the trip is spent in fuel-only mode. Thus, the distances driven in electric-only mode d_{el} and fuel-only mode d_{fuel}, are, for this particular trip:

$$\begin{aligned} d_{\mathrm{el}} &= \min\left(d, \frac{\mathrm{SOC}}{k}\right) \\ d_{\mathrm{fuel}} &= d - d_{\mathrm{el}} \end{aligned} \tag{4}$$

These distances are cumulatively tracked for each vehicle separately. The battery is used exclusively for driving and thus air conditioning, radio use, indoor lighting etc. do not affect the battery SOC.

2.3 Infrastructure parameters

The parameters that determine the charging infrastructure at each node are now introduced. These are the *number of poles* (how many charging poles there are), *cables per pole* (how many vehicles can recharge simultaneously at a single charging pole), *slots per pole* (how many slots can a single cable be taken to), *maximum power of cable* (the maximum charging power supported by one cable), *cable switching delay* (how fast the cables are switched between vehicles) and finally the *battery capacity*. The total power at each charging location is not limited, so that no power allocation strategies are required. At high PEV penetrations, this may not hold true due to the risk of overloading the supply grid.

2.3.1 *Number of poles*

As our goal is to study workplace charging instead of home charging, each vehicle has its dedicated charging pole at home. At work nodes, however, the charging poles are distributed so that the total number of poles at work nodes is $N^{\mathrm{work}}_{\mathrm{poles}}$. The number of charging poles assigned to work node n, $N_{\mathrm{poles}}(n)$, is linearly dependent on the number of vehicles assigned to that work node $N_{\text{vehicles}}(n)$:

$$N_{\text{poles}}(n) \approx N_{\text{vehicles}}(n) \times N_{\text{poles}}^{\text{work}} \tag{5}$$

However, this relationship may not hold exactly due to rounding errors. If the sum of the number of work node poles calculated using Equation (5) does not match the total number of poles given by the user, the number of poles at each work node is modified by a randomized process that ensures that there are exactly $N_{\text{poles}}^{\text{work}}$ poles in total at the work nodes. As $N_{\text{poles}}^{\text{work}}$ is increased, more vehicles have the opportunity to recharge at work, and thus e-mileage increases.

2.3.2 *Cables per pole*

This parameter determines the maximum number of vehicles that can be charged at the same time at one pole. Its effect depends strongly on the number of slots per pole. For example, if there are two slots per pole, and two cables per pole, adding more cables has no effect on e-mileage, because a cable can only be taken to a parking slot next to the pole. Thus, in a sensible infrastructure, the number of cables per pole should always be less than or equal to the number of slots per pole.

2.3.3 *Slots per pole*

Slots per pole is the number of parking slots that can be served by one pole, or equivalently, the number of parking slots one cable can be taken to. Because vehicles are not moved when they finish charging, they continue to occupy a parking slot near the charging pole until the driver departs. However, the cable can be disconnected and connected to another vehicle parked at another parking slot. This way multiple cars can be recharged using only one cable and without relocating any vehicles. Increasing the number of slots per pole will therefore increase the e-mileage. As mentioned above, in a sensible system, the number of slots per pole is always greater than or equal to the number of cables.

2.3.4 *Cable maximum power*

In the linear battery model, the cable maximum power $P_{\text{max}}^{\text{cable}}$ simply determines the maximum power for recharging the vehicles connected to the pole. As higher power shortens the charging time and thus queuing time, increasing charging power increases the e-mileage.

2.3.5 *Battery capacity*

In the linear battery model, battery capacity determines the amount of energy that can be stored into the battery at maximum. Increasing this value allows the vehicle to spend a higher amount of time in the electric only-mode, increasing the e-mileage.

2.3.6 *Cable switching delay*

As explained in Section 2.1, this parameter determines the delay for switching the cable between different vehicles parked at the same pole. Lowering this value allows the next vehicle in the queue to be recharged sooner, increasing the e-mileage.

3 RESULTS

For all the following scenarios, the total distance traveled by all simulated vehicles is 34 752 km, and the e-mileage is shown as a fraction of this distance. The base assumptions for the linear battery model are shown in Table 1. These assumptions are always in effect unless mentioned otherwise.

3.1 Cables and slots for a single pole

The e-mileage for a different number of cables and parking slots for a single pole is shown in Figure 3. It can be seen that e-mileage is sensitive to the number of slots that can be served by the pole and relatively insensitive to the number of cables at the pole. When the number of cables is larger than the number of slots, the number of cables has no effect on the e-mileage. This is because a cable can only be taken to an existing parking slot. As mentioned

Table 1. *Base assumptions*

Number of simulated PHEVs	1000
Charging strategy	*First come, first serve*
Charging poles	1000 at home nodes 20 at workplace nodes 0 at other nodes
Max charging power (pole)	3.7 kW at home nodes 3.7 kW at workplace nodes 0 kW at other nodes
Battery capacity	5 kWh
Max charging power (battery)	∞ kW (unlimited)
Charging efficiency	90%
Electricity consumption	0.2 kWh/km
Cable switching delay	15 min
Cables per pole	1
Slots per pole	4
Moving fully charged vehicles away from pole	*Not allowed*

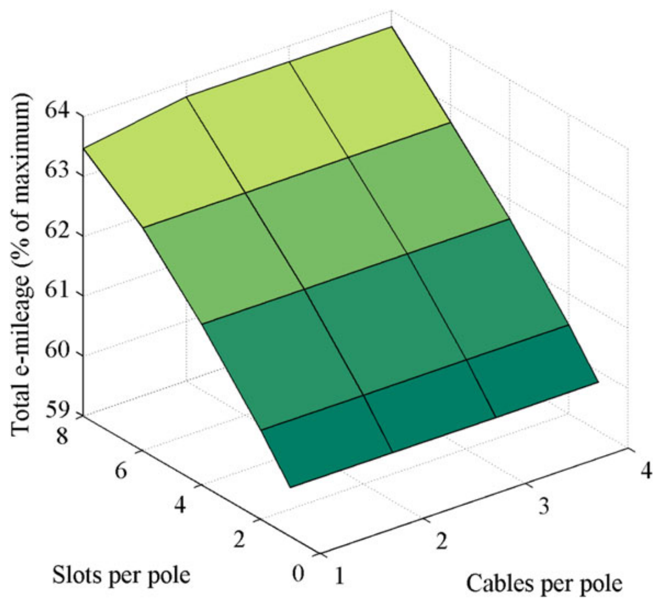

Figure 3. *Sensitivity of e-mileage to slots per pole and cables per pole.*

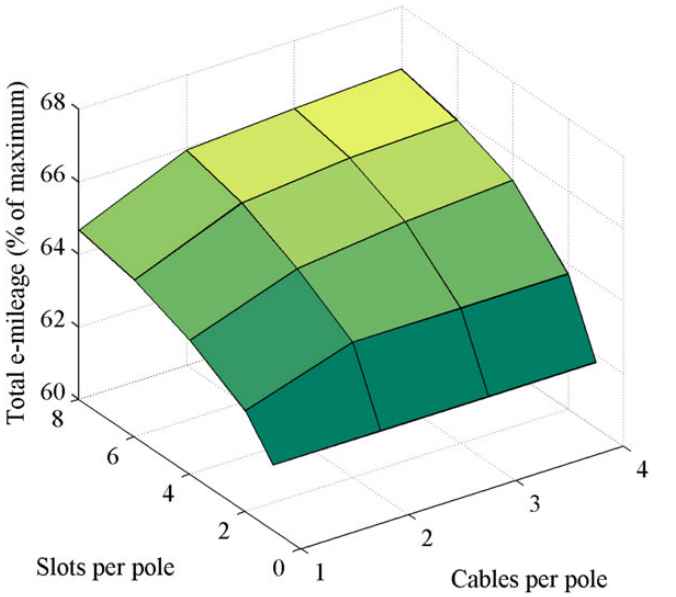

Figure 4. *Sensitivity of e-mileage to slots per pole and cables per pole, when fully charged vehicles can be moved.*

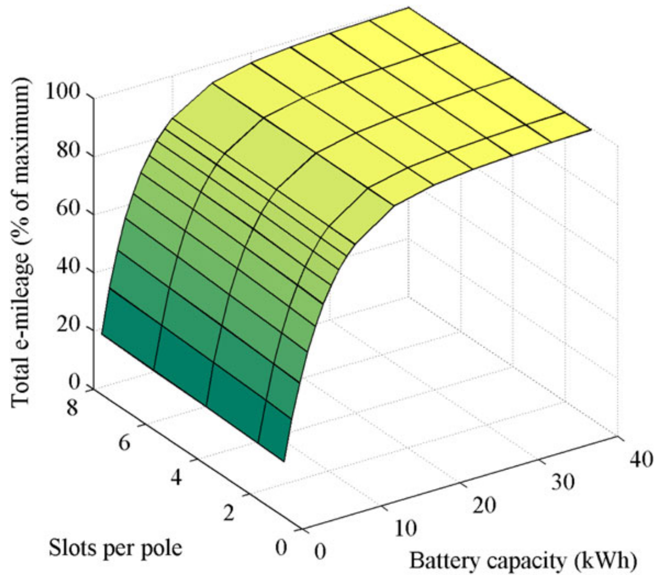

Figure 5. *Sensitivity of e-mileage to slots per pole and battery capacity.*

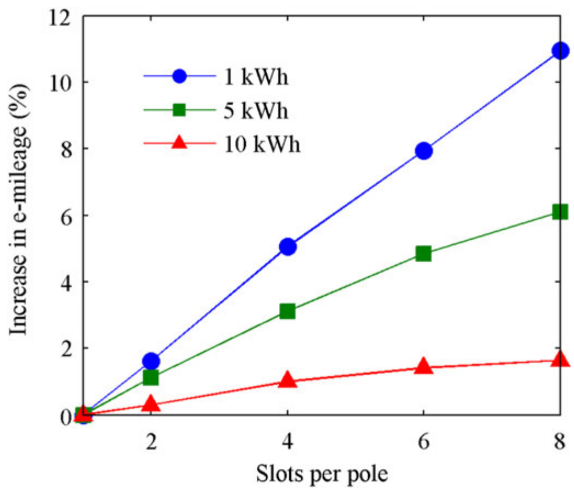

Figure 6. *Relative increase in e-mileage due to increasing the number of slots per pole from 1, for different battery capacities.*

earlier, in a sensible scenario, the number of parking slots should always be greater than or equal to the number of cables. With eight slots per pole and one cable per pole, adding one extra cable slightly increases e-mileage. Nevertheless, it seems that the number of cables per pole is not a bottleneck in this case.

Figure 4 shows the same scenario, but with the added possibility of moving a fully charged vehicle, meaning that an entity (not necessarily the owner) can physically relocate vehicles to make room for others. The moving happens with the same delay as with cable switching, but also with the same logic, i.e. when a vehicle arrives or leaves, the delay is not enforced.

With this modification, e-mileage becomes much more sensitive to the number of cable connected to the pole. This is because a fully charged vehicle can no longer keep occupying a slot, preventing other, depleted vehicles from charging. However, even if vehicles can be moved, a single cable does not have enough time to recharge all vehicles around the pole, unless the charging power is increased. This can be seen in the early saturation of e-mileage with respect to slots per pole in the case with only one cable per pole. When more cables are added, this saturation occurs at higher number of slots per pole, as more vehicles can then be charged simultaneously. As in the case with no moving allowed, increasing the number of cables past the number of slots has no effect on e-mileage. The bottleneck in this scenario is formed by the fully recharged vehicles that continue to physically occupy slots.

3.2 Battery capacity and slots

Figure 5 shows the e-mileage as a function of battery capacity and slots per pole. It is evident that e-mileage is relatively insensitive to the number of slots per pole compared to battery capacity, implying that the battery capacity forms a bottleneck in this case. However, e-mileage still improves as a function of slots per pole. This effect is more pronounced with low battery capacities (Figure 6). This is because PHEVs with higher capacities can travel longer distances in electric-only mode using only the charger at home, and consequently, their e-mileage is less influenced by the public charging infrastructure.

3.3 Battery capacity and power

Figure 7 shows the e-mileage as a function of the maximum power supported by a cable and battery capacity. It is seen that, with a wide range of battery capacities, increasing the power does not improve e-mileage at all. Therefore, charging power of 3.7 kW is already sufficient for workplace charging. This power

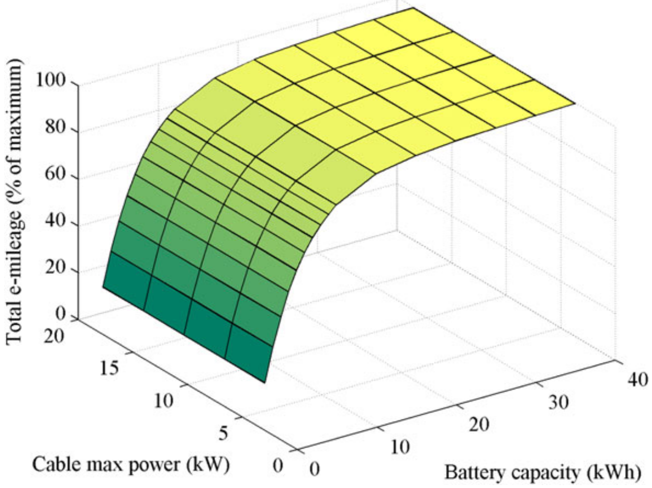

Figure 7. *Sensitivity of e-mileage to cable max power and battery capacity.*

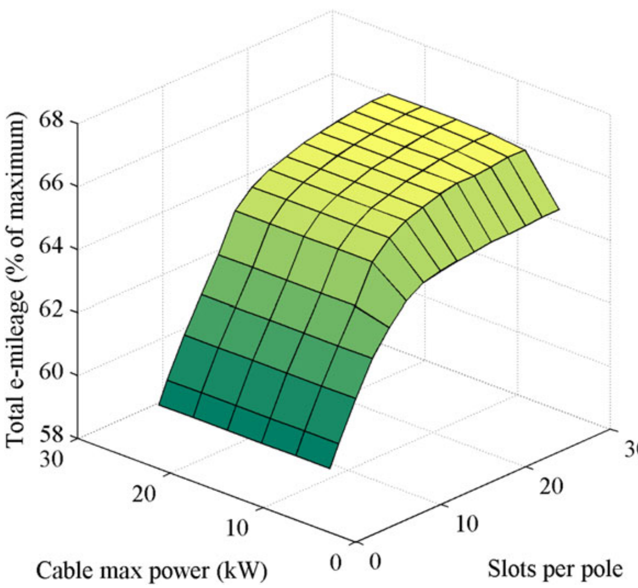

Figure 8. *Sensitivity of e-mileage to cable max power and slots per pole.*

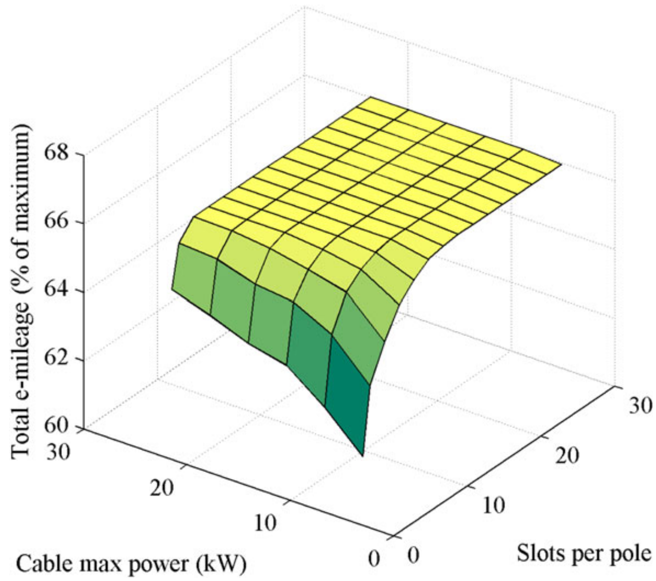

Figure 9. *Sensitivity of e-mileage to cable max power and slots per pole, when fully charged vehicles can be moved.*

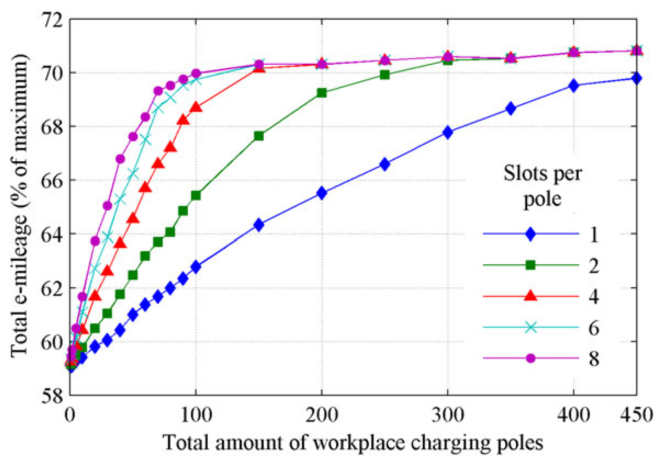

Figure 10. *Sensitivity of e-mileage to slots per pole and number of poles.*

is already supported by the majority of installed charging poles in Finland [25]. The bottleneck is the battery capacity.

3.4 Power and slots

Figure 8 shows e-mileage as a function of the maximum power supported by a cable and slots per pole. It is seen that when the number of slots per pole is small, increasing the power has a negligible effect. This is because the cable cannot be used to charge vehicles that are not parked in the slots near the pole. Even if power is increased, the vehicles that occupy the slots (the first vehicles that arrived to work) recharge faster, but still keep the slot occupied. However, when there are (unrealistically) many slots, power starts to have an effect. Because charging is faster, the single charging cable is moved between different vehicles more frequently.

The situation is remarkably different when vehicle moving is allowed (Figure 9). Now even with a small number of slots, the single cable can recharge a large number of vehicles. When power is increased, recharging is faster and thus the cable is switched more rapidly to the next depleted vehicle. Consequently, power has a strong effect on e-mileage even with only one slot per pole. However, the requirement of physically relocating fully charged vehicles makes this scenario unrealistic.

3.5 Poles and slots

Figure 10 shows e-mileage as a function of the number of workplace charging poles and slots per pole. We see that at low levels of charging infrastructure at work, e-mileage is almost linearly dependent on the number of poles. However, if there is only one slot per pole, increasing traffic electrification by increasing poles

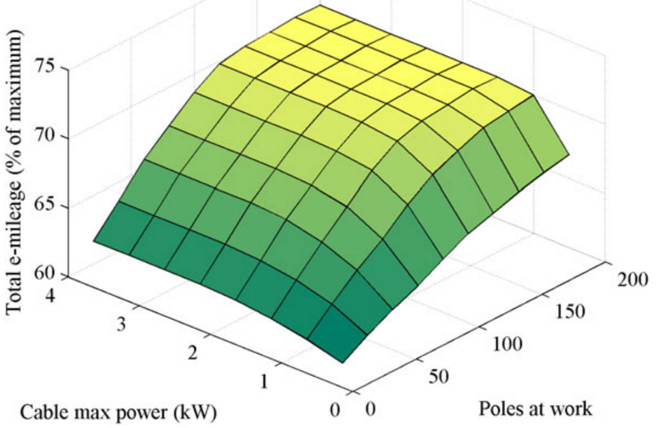

Figure 11. *Sensitivity of e-mileage to maximum power supported by the cable and the total number of charging poles at workplace nodes.*

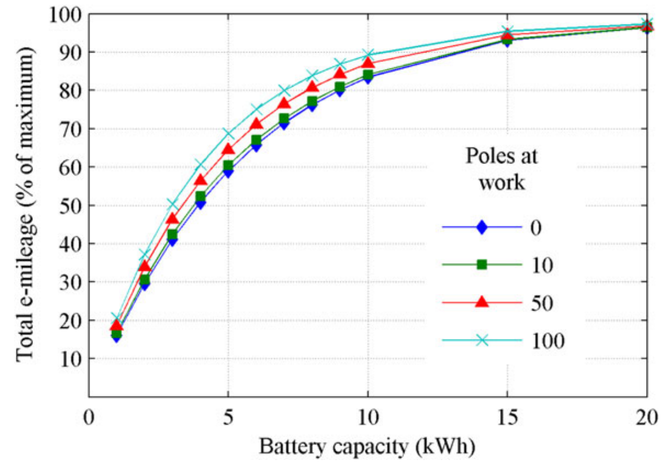

Figure 12. *Sensitivity of e-mileage to the number of poles and battery capacity.*

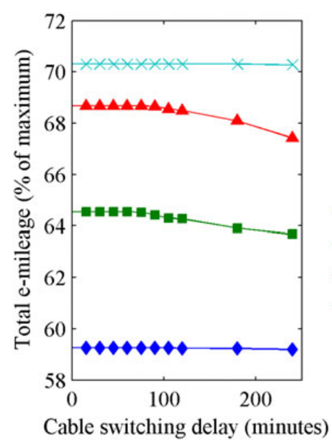

Figure 13. *Sensitivity of e-mileage to cable switching delay and the number of charging poles at workplace nodes.*

is a costly strategy. It would likely be less expensive to allow multiple parking slots to benefit from the same charging pole. For example, almost the same e-mileage can be achieved with either 150 single-slot charging poles or 50 units of four-slot charging poles.

The decrease in e-mileage at 300–350 poles is due to the randomized rounding operation related to Equation (5). This operation may sometimes remove poles from work nodes that have vehicles traveling long distances, reducing total e-mileage slightly.

3.6 Poles and power

Figure 11 shows e-mileage as a function of maximum power supported by the cable and the total number of charging poles at workplace nodes. The number of poles has a strong effect on e-mileage until saturation at around 150 poles. However, the effect of charging power is already saturated at 3.7 kW, and this saturation was also observed for battery capacities 2 and 10 kWh. We again conclude that 3.7 kW is sufficient for workplace charging.

3.7 Poles and battery capacity

Figure 12 shows e-mileage as a function of battery capacity and the number of charging poles at workplace nodes. Workplace charging poles can increase e-mileage by around 10%-units, but this effect is small compared with the effect of increasing battery capacity, which can increase e-mileage all the way to 100%. The highest increase in e-mileage, 12%-units, was observed for the battery capacity of 4 kWh, when there were 1000 poles (implying a dedicated charger for each vehicle at its workplace). With very low ($<$1 kWh) and high ($>$15 kWh) battery capacities, workplace charging infrastructure has less of an impact on e-mileage.

3.8 Poles, switching delay and cables per pole

Figure 13 shows e-mileage as a function of the number of charging poles at workplace nodes and the cable switching delay. Two observations can be made. The first is that the switching delay has a relatively small effect on e-mileage if there is a very small or very large number of poles. This is understandable, as a small number of charging poles has only a minor effect on e-mileage, no matter how fast the cables can be switched. On the other hand, if there is an abundance of charging poles, each vehicle can park next to a vacant pole, rendering switching delay irrelevant.

The second observation is that, in the base case with four slots per pole, one cable per pole and 5 kWh battery capacity, e-mileage is not improved when cable switching delay is reduced below 1 h. Switching delay of around 1 h is not only sufficient, but also manageable in reality.

Figure 14 illustrates the saturation switching delay (the delay below which there is no improvement in e-mileage) for different capacities when there are 50 charging poles at work. The saturation switching delay depends on the battery capacity and is the lowest, 45 min, for capacities in the range 8–12 kWh. For small ($<$4 kWh) and large ($>$15 kWh) batteries, considerably longer delays are acceptable.

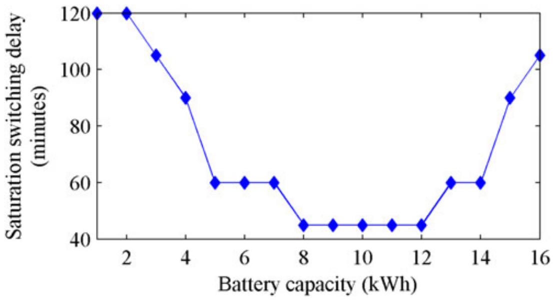

Figure 14. *Saturation switching delay for different battery capacities when the total number of workplace charging poles is 50.*

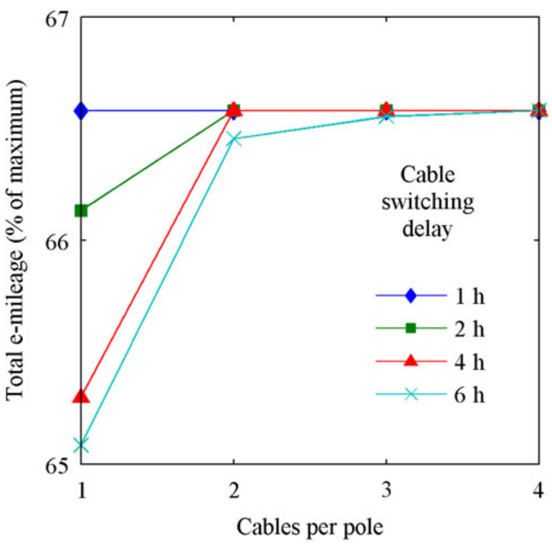

Figure 15. *Sensitivity of e-mileage to the number of cables per charging pole and the cable switching delay, when the total number of charging poles at workplace nodes is 70.*

It is possible to compensate for a long switching delay by adding more cables to the pole, as seen in Figure 15. For example, the same increase in e-mileage can be achieved either by reducing the switching delay from 4 to 1 h or adding one cable to the pole.

4 CONCLUSIONS

Table 2 shows a pairwise comparison of the infrastructure parameters. The parameter with the highest reasonable potential to increase e-mileage from the base scenario (the bottleneck) is shown inside the matrix. For example, if there is an option of increasing PHEV battery capacity from 5 kWh or decreasing cable switching delay from 15 min (both baseline values), increasing battery capacity has the bigger positive effect. When both parameters can be used to increase e-mileage, the one with the highest approximated cost-efficiency is selected. This is the case when comparing the number of poles versus the number of slots per pole. Cursive text indicates a result not based on simulations, but deduced from other results. Notably, switching delay and cable maximum power are deemed low-potential parameters compared with the rest, as their effect is already saturated.

Table 2. *Pairwise comparison of infrastructure parameters*

	Poles	Cables per pole	Slots per pole	Cable max power	Switching delay
Battery capacity	Battery capacity	Battery capacity	Battery capacity	Battery capacity	*Battery capacity*
Poles		Poles	Slots per pole[a]	Poles[b]	Poles[c]
Cables per pole			Slots per pole	*Cables per pole*	*Cables per pole*
Slots per pole				Slots per pole[d]	*Slots per pole*
Cable max power					*Cable max power*[e]

Parameters inside the matrix are the bottlenecks in a comparison scenario.
[a]Increasing slots per pole is more economical than increasing the number of poles.
[b]Provided cable max power is around 2 kW or greater (as in base scenario).
[c]Provided switching delay is around 1 h or less (as in base scenario).
[d]Cable max power starts to matter only at unrealistically high number of slots per pole.
[e]Both are relatively ineffective, but it is presumably easier to upgrade the cables than to reduce switching delay.

We find that battery capacity has the biggest potential in increasing e-mileage. However, it can be argued that battery capacity is not a true charging infrastructure parameter. If this is the case, the highest priority should be given to increasing the number of slots per pole. In practice, this means selecting charging pole locations optimally (not placing it in a corner) and equipping it with longer cables. When there is a sufficient number of slots per pole, more poles can be added. No considerable benefit is found in reducing the maximum switching delay below 1 h or increasing the power beyond 3.7 kW, which is already supported by most Finnish charging stations.

Finally, the optimal number of cables on a multi-slot charging pole is dependent on the cable switching delay. If the node can manage switching in around 45 min or less (a reasonable time), one cable per pole is sufficient. If this is not possible, more cables can be added to compensate for a long switching delay.

Nevertheless, one should note that the general effectiveness of workplace charging infrastructure is dependent on the battery capacity of the vehicles to be charged. For very small ($<$1 kWh) or large ($>$15 kWh) batteries, the infrastructure has less of an impact on e-mileage. Importantly, the above results are only valid for workplace charging where vehicles are parked for around 8 h, and should not be generalized for, for example, shopping center charging, where the parking times are typically much shorter.

5 DIRECTIONS FOR FUTURE STUDIES

Explicit economic analysis was not performed in this study. With knowledge of all the associated costs, such as installation costs of charging poles, and the cost of extending existing charging pole cables to support charging from further away, the approach here could be used to arrive at the cost-optimal workplace charging infrastructure.

The total charging power available at a node was not limited. At high PEV penetrations, this may not be the case, as there is a risk of overloading the supply grid. Introducing power limitations could imply allocation of power between connected vehicles. Depending on the driving schedule of vehicles and the allocation method used, this may lead to lower total e-mileage than reached here.

Charging infrastructure was assumed identical for each workplace, except for the number of poles. In reality, the charging infrastructure parameters can vary considerably between different nodes, or even within the same node. For example, one workplace may have two sets of charging poles, with different maximum power.

Only PHEVs were simulated. The results can be very different when pure EVs are simulated instead, as one must then account for complicated range anxiety effects.

Finally, it is not known if the results can be well generalized to all types of cities. In the future, we aim to modify the road network in order to perform studies on city designs with much longer or much shorter average trip distance.

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