Effects of Central or Decentralized Charging Stations for Electric Buses on Route Planning and Travel Time in Public Transport – A Case Study of Aachen, Germany

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1 ABSTRACT

Public buses are well-suited to electrification (Folkesson et. al, 2003). Electric drive systems have advantages over conventional technologies, for example lower travelling costs, a higher level of energy efficiency, and the chance to reduce emissions (Imaseki, 1998; Electric Power Research Institute, 2007a; Electric Power Research Institute, 2007b; Sioshansi and Denholm, 2009; Sioshansi et al., 2010; Doucette and McCulloch, 2011; Sioshansi and Miller, 2011; Liu et al., 2013; Brouwer et al., 2013; Paulley et al., 2004). Additionally, their operation is easy to plan. Public buses usually run in urban areas in which diesel-powered buses cause air and noise pollution, thus affecting the local quality of life. Financial support and public visibility help spread the new technology. In order to render the use of electric buses in public service possible, the battery needs to be charged during operation. Setting up charging infrastructure is prerequisite for the successful use of electric vehicles (Boulanger et al., 2009; Hatton et al., 2009; Silvester et al., 2009). Different concepts need to be considered when selecting sites for the charging stations. Installing the infrastructure centrally may yield higher efficiency of the stations but is likely to cause operational problems – using the turning time at a scheduled route's terminal stop is easier to organize but requires more charging infrastructure. The vehicles themselves add further restrictions due to their limited cruising range. But how do the different concepts affect demand or transportation companies' operation planning? Is it even possible to use electric buses in the existing public transport networks using central or decentralized charging and the existing vehicle scheduling without further ado?

This paper analyzes the positioning of charging infrastructure for electric buses. The objective is to study the influence of charging electric buses on the demand for public transport. Therefore we analyze two scenarios in a case study of Aachen by modelling effects of charging in an macroscopic transport model. The first scenario explores a central positioning of the charging infrastructure. The second scenario analyzes a decentralized positioning. The analysis of the scenarios has shown that charging time is critical. A longer travel time significantly impacts demand. Extending the dwell time at the central bus station negatively affects public transport use: Use declines from 9.2% to 2.3% and is mainly shifted to private transport. In order to keep up the current level of quality, the transport companies would have to adapt their planning. That way, passengers could, for example, change from an empty electric bus to a charged one. Waiting for the buses to charge has proved to have a much stronger negative impact on demand than having to change to another bus. Aside from affecting demand, central charging would require an adaption of the schedules and would thus also impact the timetable and vehicle scheduling of transport companies. In addition, central charging would pose a logistic challenge and would require an improvement of the queuing policies (De Filippo et al., 2014).

The analysis of the timetable and vehicle scheduling has shown that decentralized charging is easier to integrate into the existing structures of local public transport. Decentralized charging using the buses' turning time comes with the advantage that the charging process does not affect the travel time provided the cycle plan is adapted accordingly and a sufficiently high charging speed is achieved. For example, the minimum turning time in Aachen is 3 minutes on average. In order to operate the charging infrastructure at maximum capacity, the ends of routes could be combined. In Aachen, radial routes are especially suited to the use of electric buses and to combining the terminal stops. When it comes to network planning in Aachen, this type of route, at an average 8.66 km, a duration of 34:34 mm:ss, and a turning time of 09:03 mm:ss, should be preferred to the other types. In addition, radial routes often have a common origin so that some of the routes already share a terminal stop.

The concepts need to be adapted and reviewed individually for each city. Whether the infrastructure can be integrated into each urban design needs to be verified as well. We may conclude that successfully integrating

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the charging process into the existing structures of public transport requires a complex and holistic concept that takes numerous aspects into account.

Keywords: public transport, electric mobility, charging, scheduling, Aachen

2 INTRODUCTION

Public buses are well-suited to electrification (Folkesson et. al, 2003). Electric drive systems have advantages over conventional technologies, for example lower travelling costs, a higher level of energy efficiency, and the chance to reduce emissions (Imaseki, 1998; Electric Power Research Institute, 2007a; Electric Power Research Institute, 2007b; Sioshansi and Denholm, 2009; Sioshansi et al., 2010; Doucette and McCulloch, 2011; Sioshansi and Miller, 2011; Liu et al., 2013; Brouwer et al., 2013; Paulley et al., 2004). Additionally, their operation is easy to plan. Public buses usually run in urban areas in which diesel-powered buses cause air and noise pollution, thus affecting the local quality of life. Financial support and public visibility help spread the new technology. In order to render the use of electric buses in public service possible, the battery needs to be charged during operation. Setting up charging infrastructure is prerequisite for the successful use of electric vehicles (Boulanger et al., 2009; Hatton et al., 2009; Silvester et al., 2009).

Different concepts need to be considered when selecting sites for the charging stations. Installing the infrastructure centrally may yield higher efficiency of the stations but is likely to cause operational problems – using the turning time at a scheduled route's terminal stop is easier to organize but requires more charging infrastructure. Site selection is determined by a number of factors. The vehicles themselves add further restrictions due to their limited cruising range. In addition, factors of urban development may restrict the planning as well.

But how do the different concepts affect demand or transportation companies' operation planning? Is it even possible to use electric buses in the existing public transport networks using central or decentralized charging and the existing vehicle scheduling without further ado? And are there certain types of routes that are more suitable for the use of electric buses than others? With this paper we seek to address these questions.

In the following sections, we present the theoretical background (Section 2), our methods including the scenario development and the analysis of the routes in public transport networks (Section 3), the results from our scenario simulation (Section 4) and, finally, a discussion and our conclusions (Section 5).

3 BACKGROUND

The main difference between private and public electric vehicles is that public electric buses have to keep to a schedule. This comes with the advantage that the routes and energy consumption are easily predictable. However, it also necessitates high-speed charging during the vehicles' operation so as not to interfere with the schedule (Ding et al., 2015). In addition to the advantages, e.g. low pollutant emission and reduced noise pollution, electric buses differ from diesel buses in disadvantages such as their low range and long charging times. The mileage constraints of electric buses are there-fore stricter than those of diesel buses.

The range of electric buses is so far not enough to replace conventional diesel-powered public buses without limitations. A conventional bus can operate throughout its entire deployment without needing to refuel. In contrast, electric buses may need to be charged several times a day. As they run on a schedule, installing fast-charging stations is thus prerequisite for using electric buses successfully. For electric buses to be able to compete with diesel buses, an innovative electric bus system is necessary (Rohlfs, Mareev, Rogge, 2015). A simulation of an electric transportation system at the Ohio State University has already shown that employing 22 electric buses on six lines using one 500 kW or two 250 kW charging stations at appropriate service rates is unproblematic (De Filippo et al., 2014).

Public transport planning consists of a number of interconnected components: First of all routes are planned (1). Subsequently, a schedule is developed (2) and vehicles are assigned to trips (3) and drivers to vehicles (4) (Chao and Xiaohong, 2013). The location of the charging stations and the integration of the charging process into the operating schedule may already cause problems for the planning of the route and the development of the schedule.

Central charging comes with the advantage that the routes would not need to be adapted provided that the bus system in question has a central hub already used by most bus routes, which would then be selected as the charging location. This would also allow for the charging stations to be used at maximum capacity. However, it is questionable whether this concept could provide an acceptable level of service: On some of the routes, central charging would mean longer travel times for passengers as it would require a longer dwell time at an intermediate stop. Travel time is an important criterion for the choice of transport mode (Balcombe et al., 2004; Bhat, 1997; Van de Walle and Steen-berghen, 2006). Especially in public transport, a longer travel time results in a decrease of usage (Vasconcellos, 2005). This would create tension between the required charging time and the available charging time. In addition, a solution would need to be found for those lines for which the central hub is not en route.

For decentralized charging, the charging infrastructure would be located at the ends of the routes. Positioning the charging stations there would not require a change of route planning either. It might, however, cause problems with the schedule as the vehicles need enough time to charge their battery before continuing their route. This, too, would create tension between the required and the available charging time. For this concept, the available charging time would hinge on the respective turning time..

4 METHOD

Using the example of Aachen, we have answered the questions of how different charging locations for electric buses affects route planning and travel time for public transport and how these concepts can be integrated into existing public transport structures from the point of view of transportation companies by analyzing two scenarios. The scenarios contain concepts that differ in where the charging infrastructure is located and offer possible visions of the future. In addition we analyzed whether there are differences in, for example, turning times or the length of routes to determine which types of routes are more suitable for the use of electric buses than others.

The two scenarios' impact on the demand is studied using the cross-border transport model of the Aachen region. The transport model simulates a weekday outside of school holidays in October and is based on the four-step algorithm. In addition to the StädteRegion Aachen, the transport model includes the surrounding communities as well as parts of the Dutch province of Limburg and parts of the German-speaking community in Belgium. The planning area for our analysis is the city of Aachen. It is divided into 178 zones. Demand is calculated based on structural data of the planning area from 2010, which is available for the zones. The impact on the operation is studied by means of an analysis of the vehicle scheduling of the urban transport company ASEAG..

4.1 Development of the scenarios

In order to come to a substantiated conclusion about how charging an electric bus affects public transport demand for each of the concepts, we first studied factors that influence the choice of transport mode. This choice is determined by numerous factors. The criteria come from different are-as such as economics, transport geography, and social psychology, and can be divided into socio-demographic, journey characteristic, and space-related indicators (De Witte et al., 2013).

Depending on how well the charging process is integrated into the schedule, charging electric buses may affect travel time and interchange. For example, charging infrastructure located centrally may extend travel time when charging would require a longer dwell time at an intermediate stop. Alternatively, passengers could change to another bus that has already been charged, immediately continuing their journey.

Interchange as a determinant is rarely studied in papers and infrequently found significant for the choice of transport mode (De Witte et al., 2013). The criterion interchange is a journey characteristic indicator. Interchange depends on how the public transport networks are scheduled (Litman, 2008; Wardman and Hine, 2000). Ideally, passengers should not have to change vehicles between their origin and destination.

The determinant travel time has been studied in a number of papers and labeled as a significant contributor (De Witte et al., 2013). In our analysis we therefore focus on the influence of an extended travel time on the demand for public transport. Travel time is a journey characteristic indicator and can be described as the time a person needs from door to door (De Witte et al., 2008). In this paper, we define travel time by public transport with the "door-to-door approach" as follows (Fig. 1): (1) walking from origin to the appropriate stop; (2) waiting for the bus; (3) sitting on the bus; and (4) walking from the final stop to the destination

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(Wardman, 2004; Salonen and Toivonen, 2013). Furthermore, the trav-el time by public transport could include transfers from one route to another including walking and waiting times (Benenson et al., 2011).

Exactly how much demand will decrease when the travel time in public transport is extended by 15 min to charge the electric buses central is examined in Scenario I (cf. chapter 3.1.1). Central charging of electric buses means that the vehicles would be charged at one central station. The buses on routes starting or ending at this station could charge during their turning times. On routes for which this station is not on the way, electric buses could not be used in our example. The buses stopping at the charging station as part of their route would then wait there until their battery is charged. The charging process would extend passengers' travel time. Alternatively, passengers could change to another bus that has already been charged. However, this means that transport companies would have to adapt their timetable and vehicle scheduling and would likely have to deploy additional vehicles. Central charging comes with the advantage that infrastructure costs would be low and the charging stations could be used at maximum capacity. It is, however, questionable whether an appropriate level of service can be achieved using this concept.

In contrast to Scenario I, we study the effects of decentralized charging in Scenario II (cf. chapter 3.1.2), which means that the buses would be charged at the terminal stops of their respective routes using their turning times. If the turning time is sufficient, this would be unproblematic. Turning times exists because buses on the same route that are compatible in terms of location and time are scheduled to form a consecutive cycle (Scholz, 2012). One cycle thus covers the use of a vehicle from when it is deployed to the finish of its shift. Aside from allowing for turning, turning times are meant to make up for delays and to allow drivers to take the breaks required by law. For an optimal schedule, turning times should be minimal since they mean a pause in transport service (Köhler, 2001). However, when the turning time can be used to recharge an electric bus, a long turning time already existing for operational reasons is particularly convenient.

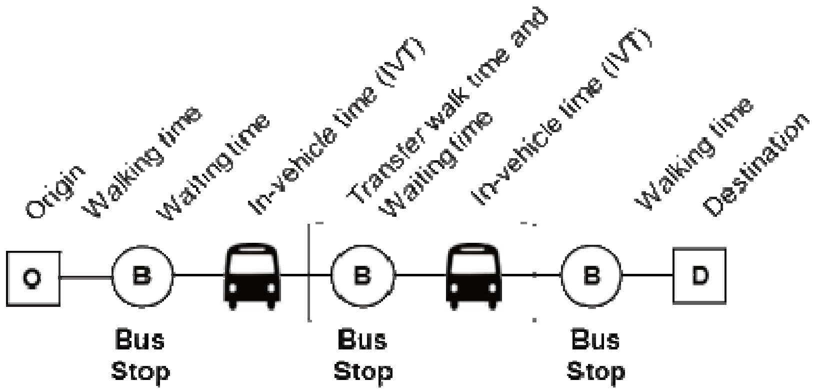

Fig. 1: Example of the door-to-door approach in public transport journeys. (Own depiction according to Salonen and Toivonen, 2013)

4.1.1 Method Scenario I: Central charging infrastructure

Scenario I explores the effects of central charging infrastructure for electric buses using the example of Aachen. The charging infrastructure is located at the central bus station Bushof in Aachen. This stop and the main inner-city bus station Elisenbrunnen constitute a central transport hub in the Aachen bus network. At a total of 65,000 passengers a day, these two stops are the most frequently used ones in Aachen (Planungskooperation "Busnetz 2015+", 2013). As Bushof is located on the standard route of the Aachen bus network, the charging infrastructure will be installed at this stop by way of example in scenario I.

In the analysis of the schedules, the journeys there and back of each route are examined, totaling 138 trips. Of these 138 trips, 18% (25 trips) already start or end at Bushof. Charging electric buses on these routes with otherwise unchanged conditions would not affect the passengers at all. Therefore, demand would not change. The transport company would, however, need to check whether charging the buses is possible without changes in the current cycle plan, i.e. whether or not the turning time is sufficient or whether the plan would need to be adapted and more vehicles used.

Bushof station is not on the way of 32% of the trips (44 trips). In this scenario, electric buses could not be used on these routes as they would require a large-scale adaption of the schedule and the business plan. For

50% of the trips (69 trips), Bushof is an intermediate stop. In order to study the impact of charging on the demand on these routes, we adapted their schedules in the transport model accordingly. In order to simulate the charging process, the dwell time of the buses at Bushof was extended by 15 minutes based on the assumption that at worst, an electric bus needs 15 min charging time per hour of operation (Falzeder, 2013) (Sinhuber, Rohlfs, Sauer, 2010).

Adapting the schedule results in a change of passengers' travel time. The impact of the longer travel time on demand is explored using the cross-border transport model of the Aachen region. The changed schedule is an input variable of the model. Longer travel times change the resistance on the routes of public transport, which directly leads to a changed relation of the resistance between public transport and motor-driven private transport on origin-destination routes. This in turn influences the choice of transportation mode on these routes and therefore the result of the modal split.

In addition, the changed route resistances also influence the result of the trip distribution. The new route resistances change the resistance relations in public transport between different relations. In the transport model, decision makers choose the fastest route. Changing the schedule extends travel time in public transport, causing a shift from public to private transport.

4.1.2 Method Scenario II: Charging at the end of the route

Scenario II explores the effects of a decentralized charging infrastructure for electric buses using the example of Aachen. Decentralized means that the charging stations are installed at the end of a scheduled route or in the bus depot. This comes with the advantage that the buses' turning time could be used for charging.

In order to answer to what extent this concept can be integrated into existing structures, we studied the timetable and vehicle scheduling in Aachen. One bus is rarely used on only one route, which means that buses change between routes and have different terminal stops. For charging buses at the end of their route, this means that the length of the cycle is relevant rather than the length of the route. One cycle covers the use of a vehicle from when it is deployed to the finish of its shift, during which one bus may be used on several routes. On single-route cycles, a vehicle stays on one route for the entire shift. The advantage of single-route cycles is that they have fixed terminal stops that could be used to charge electric buses. However, changing the cycle plan and introducing single-route cycles may make the schedule less efficient. Currently only 31% (162) of the cycles in the Aachen network are single-route cycles.

4.2 Analysis of the types of routes in public transport

We analyzed whether the types of routes of the public transport network in Aachen differ in their turning times, length, and duration in order to come to a conclusion regarding whether there is a route type which is more suitable for the use of electric buses and should be favored accordingly in future network planning.

There are four basic types of routes (Steierwald, Künne and Vogt, 2005): Radial routes, cross-city routes, tangential routes, and circle routes (cf. figure 3). For our case study in Aachen, we analyzed 74 bus routes operated by the urban transport company ASEAG on a workday Tuesday. The bus routes were allocated to the respective route types based on ASEAG's network plan. The results of the analysis can be found in chapter 4.3.

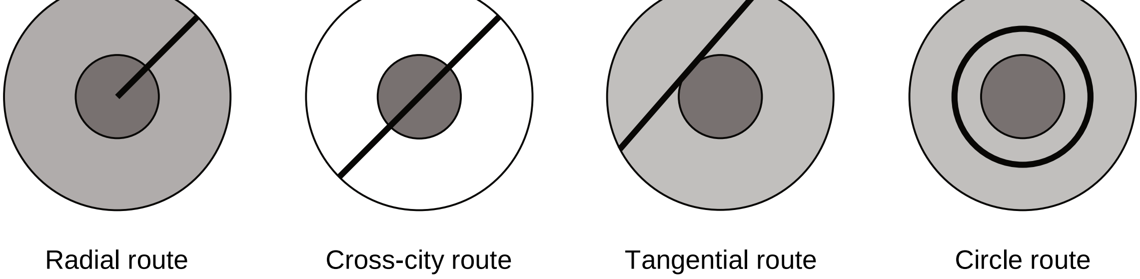

Fig. 2: Basic patterns of the route types (Source: Steierwald, Künne and Vogt, 2005)

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5 RESULTS

This chapter presents the results of the analyses of the two scenarios and the types of routes. Scenario I describes the installation of a central charging station. In contrast, Scenario II describes the effects of a decentralized charging station for the transport company.

5.1 Scenario I: Central charging infrastructure

Table 1 shows the change of the modal split due to the charging time at Bushof station in Aachen. Extending the dwell time at Bushof negatively affects public transport use: Use declines from 9.2% to 2.3% and is mainly shifted to private transport. The increase of private transport from 56.0% to 62.7% will lead to a higher load on roads, which will also come with economic effects.

To summarize, the charging infrastructure cannot be located centrally without changing the cycle plan because of the impact on demand alone. In order to avoid longer travel times, passengers could change to a fully charged electric bus at the central charging station. The effects of additional changing would therefore not have as negative an impact as longer travel times (De Witte et al., 2013), but would come with a significant need for additional vehicles at the transport company. Furthermore, the charging infrastructure requirements and the space needed for both charging and changing would be immense. Adapting the cycle plan would be out of all proportion to the resulting costs and benefits and is therefore no viable solution for Aachen.

Purpose of the journey	Analysis			Scenario I "Bushof"			Difference	
	non-MIT	MIT	PT	non-MIT	MIT	PT	MIT	PT
1 Home - Work	17,6%	69,1%	13,4%	17,9%	80,6%	1,6%	11,5%	-11,8%
2 Home - Primary school	59,6%	26,8%	13,5%	58,0%	34,9%	7,1%	8,1%	-6,4%
3 Home - Secondary school	43,6%	18,9%	37,6%	42,9%	24,1%	33,1%	5,2%	-4,5%
4 Home - Higher education	40,6%	23,3%	36,1%	40,1%	29,8%	30,2%	6,5%	-5,9%
5 Home - Shopping	30,5%	63,3%	6,2%	30,8%	68,4%	0,8%	5,1%	-5,3%
6 Home - Recreation	32,1%	59,8%	8,1%	32,4%	66,8%	0,8%	7,0%	-7,3%
7 Recreation - Recreation	25,8%	67,3%	6,9%	25,9%	73,9%	0,2%	6,5%	-6,7%
8 Work - Work	4,6%	83,3%	12,2%	4,9%	93,9%	1,3%	10,6%	-10,9%
9 Shopping - Shopping	34,0%	62,1%	3,9%	34,5%	65,5%	0,1%	3,4%	-3,8%
Total	34,9%	56,0%	9,2%	35,1%	62,7%	2,3%	6,7%	-6,9%

non-MIT: non-motorized individual transport
MIT: motorized individual transport
PT: public transport

Table 1: Modal split in the planning area (Own calculation, data source: transport model AC region)

5.2 Scenario II: Charging at the end of the route

Decentralized charging does not necessarily cause changes for the passengers. Therefore, charging the vehicles with otherwise unchanged conditions would not affect demand. If the turning times are too short, however, the charging could necessitate adapting the vehicle scheduling and would therefore affect the transport companies' planning.

Table 2 shows the cycle lengths in Aachen according to the current cycle plan. Assuming that a typical inner city electric bus has a range of 150 km (e.g. Rampini), cycles shorter than 150 km could be covered by electric buses without intermittent charging. On these cycles, the buses could be charged at the depot provided that they, once returned, have a long enough layover to fully charge their battery before the next cycle begins. In order to do so, another study would need to explore the vehicle deployment. 72% (378 cycles) of the cycles in Aachen are shorter than 150 km and could therefore already be covered by electric buses with no intermittent charging

En-route charging needs to be made possible for the cycles longer than 150 km. This could happen at the terminal stops using the turning time. Table 3 shows the distribution of turning times on the long cycles (<150 km). However, the turning times are average times scheduled by the cycle plan. The actual turning times may differ, e.g. because of the traffic situation. Only 11% of the cycles have a scheduled turning time of less than 5 minutes.

Cycle length	Cycles	
km	%	n
200 +	19	100
150 to < 200	10	53
100 to < 150	12	63
50 to < 100	21	110
< 50	39	205

Table 2: Cycle lengths in Aachen (Own calculation, data source: ASEAG)

The charging duration of electric buses using fast charging systems depends on the boundary condition (weight, fuel economy) and the charging capacity. It is, for example, possible to charge a 12 m bus (avg. load) consuming 30 kW on average in 5 minutes for an hour's journey at a charging capacity of 350 kW (Sinhuber, Rohlfs, Sauer, 2010) (Rohlfs, Mareev, Rogge, 2015). Even a charging capacity of 500 kW is possible for the electric bus system (Sinhuber, Rohlfs, Sauer, 2010) (Rohlfs, Mareev, Rogge, 2015). This means that at a required charging time of 5 minutes, 89% of the cycles (turning time > 5 minutes) could currently be charged using the turning time at the terminal stops.

Turning time accoding to schedule	Cycles (> 150 km)	
min	%	n
00:15:00 +	3	4
00:10:00 to < 00:15:00	29	43
00:05:00 to < 00:10:00	57	86
< 00:05:00	11	17

Table 3: Average turning time of cycles longer than 150 km according to schedule (Own calculation, data source: ASEAG)

The compromise between the required and the available charging time is an operational and technological challenge. The available charging time is restricted by the public transport schedule. The required charging time can be adapted by increasing the charging speed. In Aachen, all bus routes have a turning time of at least 3 minutes (cf. Figure 3, Table 4). However, we must consider that the turning time cannot be used for charging in its entirety. There must still be padding to make up for delays and to allow the vehicle to turn. Depending on the charging technology, the driver could take their break during the charging process. Therefore, a high charging speed and an optimized queuing policy are necessary for decentralized charging in Aachen to keep the charging time as low as possible

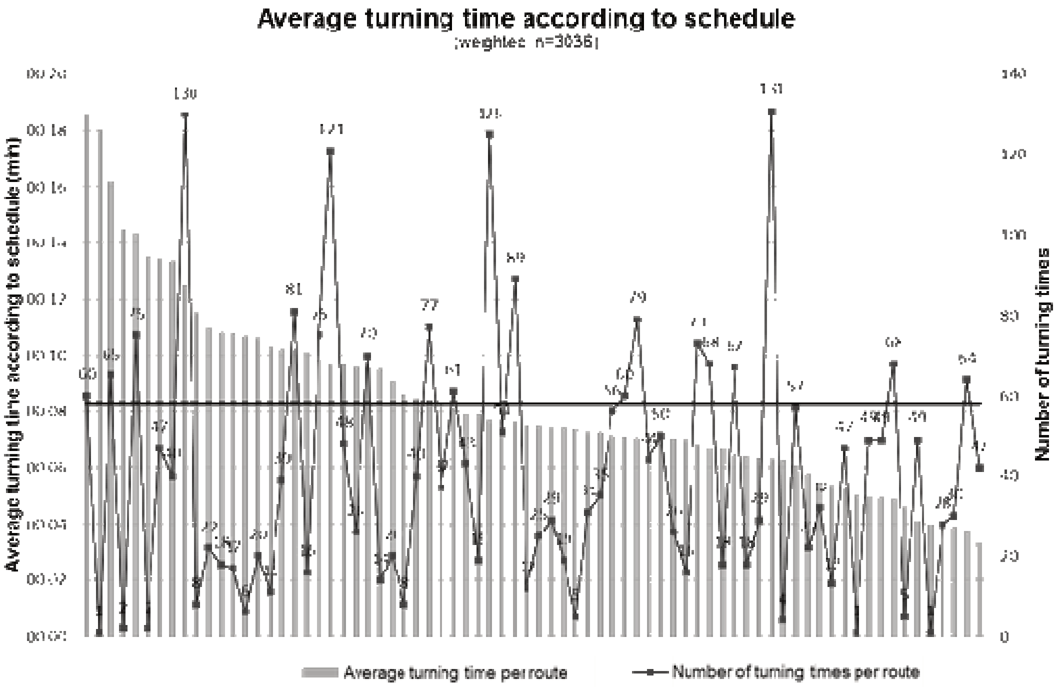

Fig. 3: Average turning times in public transport in Aachen (Own calculation, data source: ASEAG)

In order to operate the charging stations at maximum capacity, the terminal stops of routes could be combined. Additionally, we should consider an interdisciplinary cooperation of different stakeholders: The charging infrastructure might also be used by urban electric vehicles.

Average turning time* (min)	Number of routes	
> 3	74	100%
> 4	69	93 %
> 5	63	85 %
> 6	59	80 %
> 7	49	66 %
> 8	31	42 %
> 9	26	35 %
> 10	19	26 %
> 15	3	4 %

Table 4: Distribution of the turning times(Own calculation, data source: ASEAG)

5.3 Results of the analysis of the types of routes in public transport

The distribution of the analyzed routes by route type is illustrated in Figure 4. In addition to route types such as cross-city, radial, circle, and tangential routes, Figure 4 distinguishes between routes outside of Aachen, school routes, and extra buses deployed during rush hour. School routes are buses used during the peak times of student traffic. Routes outside of Aachen have no connective function within the city. Extra buses are deployed during rush hour on partial routes and only stop at select stations. Bus transport in Aachen consists primarily of cross-city and radial routes. However, circle and tangential routes are used as well. Especially the five circle routes are scheduled tightly so that the overall network shape of the city of Aachen is a radial circle network.

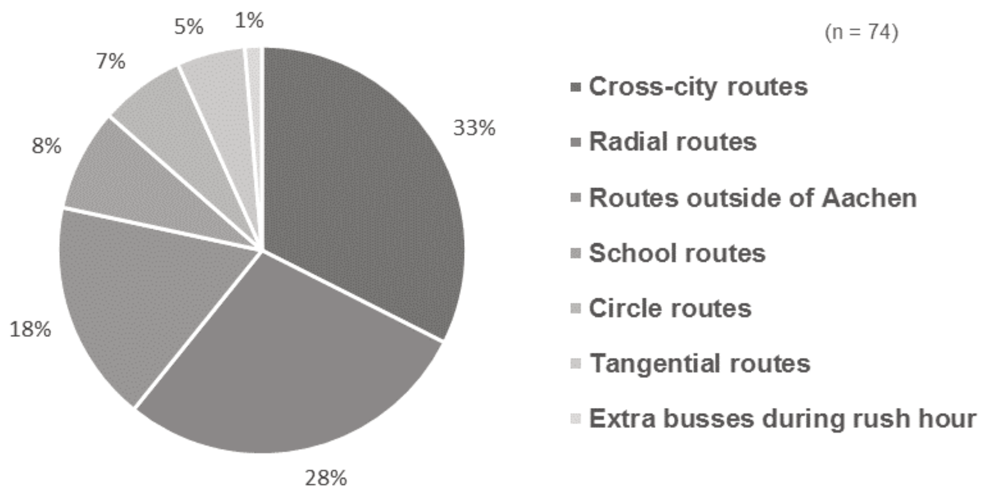

Fig. 4: Distribution of the bus routes in Aachen by type of route (Own calculation, data source: ASEAG)

The average route length, duration, and turning time are summarized in table 5 by type of route. The route length describes the distance between the terminal stops of a route. Turning time is the vehicle's scheduled dwell time at the first or last stop of a route before the next route begins. The turning time is necessary padding to make up for delays. The route duration is the time span between the terminal stops.

At 13.75 km the cross-city routes are the longest average routes. The circle and tangential routes are also longer than 12 km on average. The routes outside of Aachen, school routes, and radial routes are 8 to 10 km long. At 3.92 km, extra buses partially supporting busy routes during rush hour have the lowest average route length. The average length of all bus routes is 10.91 km.

The route duration and the route length correspond since the average speed of public buses in urban areas is virtually constant regardless of the type of route. Extra bus routes are the shortest both in length and duration. Cross-city routes are the longest at an average duration of 48:18 mm:ss. Circle routes are unique in that their first and last stop are identical. Cross-city routes also have the highest average turning time as they are the longest and are at a higher risk of delays.

In Aachen, radial routes are particularly suited to electric buses: At an average 8.66 km, radial routes are short and at the same time exhibit the second longest turning times in Aachen at 09:03 mm:ss on average.

	Number of routes	ø Length of route* [km]	ø Duration of route* [mm:ss]	ø Turning time* [mm:ss]
Cross-city route	24	13.75	48:18	09:11
Radial route	21	8.66	34:34	09:03
Routes outside of Aachen	13	9.48	29:42	06:13
School routes	6	8.93	24:50	09:03
Circle routes	5	12.96	32:07	05:31
Tangential routes	4	12.42	32:56	08:49
Extra buses	1	3.92	13:26	07:54
Total	74	10.91	36:50	08:20

Table 5: Summary of the types of routes (Own calculation, data source: ASEAG)

6 CONCLUSION

This paper explores the effects of the location of charging infrastructure for electric buses on route planning and travel time in public transport using the example of Aachen, distinguishing between central and decentral charging locations. For this purpose, the timetable and vehicle scheduling of local public transport in Aachen were analyzed. The aim was to study the impact of the two charging concepts on public transport demand and to analyze the possibilities of integrating these concepts into the existing public transport structures and the current vehicle scheduling. Additionally, the study analyzed if the types of routes in the public transport network in Aachen differ in e.g. turning times or length of routes, so that some types are better suited to the use of electric buses than others.

The analysis of the scenarios has shown that charging time is critical. Charging electric buses must not affect the passengers. A longer travel time significantly impacts demand. In order to keep up the current level of quality, the transport companies would have to adapt their planning. That way, passengers could, for example, change from an empty electric bus to a charged one. Waiting for the buses to charge has proved to have a much stronger negative impact on demand than having to change to another bus.

Aside from affecting demand, central charging would require an adaption of the schedules and would thus also impact the timetable and vehicle scheduling of transport companies. In addition, central charging would pose a logistic challenge and would require an improvement of the queuing policies (De Filippo et al., 2014).

The analysis of the timetable and vehicle scheduling has shown that decentralized charging is easier to integrate into the existing structures of local public transport. Decentralized charging using the buses' turning time comes with the advantage that the charging process does not affect the travel time provided the cycle plan is adapted accordingly and a sufficiently high charging speed is achieved. For example, the minimum turning time in Aachen is 3 minutes on average. In order to operate the charging infrastructure at maximum capacity, the ends of routes could be combined. In Aachen, radial routes are especially suited to the use of electric buses and to combining the terminal stops. When it comes to network planning in Aachen, this type of route, at an average 8.66 km, a duration of 34:34 mm:ss, and a turning time of 09:03 mm:ss, should be preferred to the other types. In addition, radial routes often have a common origin so that some of the routes already share a terminal stop.

The concepts need to be adapted and reviewed individually for each city. Especially the necessary network infrastructure should already exist in order to install a charging station. Whether the infrastructure can be integrated into each urban design needs to be verified as well. In order to come to a general conclusion regarding which type of route is particularly suited to electric buses, an analysis of the routes in other cities' public transport networks is necessary. We may conclude that successfully integrating the charging process into the existing structures of public transport requires a complex and holistic concept that takes numerous aspects into account. Finally, it is important to note that electrifying public transport significantly contributes to the solution of future challenges and to the improvement of quality of life.

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8 REFERENCES

Balcombe R, Mackett R, Paulley N, Preston J, Shires J, Titheridge H, Wardman M, White P.: The Demand for Public Transport: A Practical Guide. TRL Report 593. Available online: http://www.demandforpublictransport.co.uk/TRL593.pdf. Last accessed: 07/17/2015. 2004.

Benenson, Itzhak, Martens, Karel, Rofé, Yodan, Kwartler, Ariela: Public transport versus private car GIS-based estimation of accessibility applied to the Tel Aviv metropolitan area. Annals of Regional Science 47, 499-515. 2011.

Bhat, Chandra R.: Work travel mode choice and number of non-work commute stops. Transpor-tation Research Part B: Methodological 31 (1), 41-54. 1997.

Boulanger, Albert G., Chu, Andrew C., Maxx, Suzanne, Waltz, David L.: Vehicle electrification: Status and issues. P. IEEE, 99(6), 1116-1138. 2011.

Brouwer, Anne Sjoerd, Kuramochi, Takeshi, van den Broek, Machteld, Faaij, André: Fulfilling the electricity demand of electric vehicles in the long term future: an evaluation of centralized and de-centralized power supply systems. Applied Energy 107, 33-51. 2013.

Chao, Zhu, Xiaohong, Chen: Optimizing Battery Electric Bus Transit Vehicle Scheduling with Battery Exchanging: Model and Case Study. Procedia – Social and Behavioral Sciences 96, 2725-2736. 2013.

De Filippo, Giovanni, Marano, Vincenzo, Sioshansi, Ramteen: Simulation of an electric trans-portation system at The Ohio State University. Applied Energy 113, 1686-1691. 2014.

De Witte, Astrid; Macharis, Cathy; Mairesse, Olivier: How persuasive is 'free' public transport? A survey among commuters in the Brussels Capital Region. Transport Policy 15, 216-224. 2008.

De Witte, Astrid; Hollevoet, Joachim; Dobruszkes, Fréderic; Hubert, Michel; Macharis, Cathy: Linking modal choice to motility: A comprehensive review. Transportation Research Part A 49, 329-341. 2013.

Ding, Huajie; Hu, Zechun; Song Yonghua: Value of the energy storage system in an electric bus fast charging station. Applied Energy (2015), http://dx.doi.org/10.1016/j.apenergy.2015.01.058 (in press). 2015.

Doucette, Reed T., McCulloch, Malcolm D.: Modeling the prospects of plug-in hybrid electric vehicles to reduce CO2 emissions. Applied Energy 88, 2315-2323. 2011.

Electric Power Research Institute: Environmental Assessment of Plug-In Hybrid Electric Vehi-cles, Volume 1: Nationwide Greenhouse gas Emissions. Tech. rep. 1015325, Palo Alto, CA, USA. 2007a.

Electric Power Research Institute: Environmental Assessment of Plug-In Hybrid Electric Vehi-cles, Volume 2: United States air quality analysis based on aeo-2006 assumptions for 2030. Tech. rep. 1015325, Palo Alto, CA, USA. 2007b.

Falzeder, Florian: Charging into the Future. Pictures of the Future | Spring 2013, 106-107.

Folkesson, Anders, Andersson, Christian, Alvfors, Per, Alaküla, Mats, Overgaard, Lars, 2003, Real life testing of a Hybrid PEM Fuel Cell Bus. Journal of Power Sources 118, 349-357. 2013.

Hatton, C., S. K. Beella, J. C. Brezet and Y. Wijnia: Charging stations for urban settings: the design of a Productplatform for electric vehicle infrastructure in Dutch cities. World Electric Vehi-cle J., 3, http://repository.tudelft.nl/view/ir/uuid%3A6e209248-7741-4743-bf7c-b59d1e1323d8/ (ac-cessed July 23, 2015). 2009.

Imaseki, Takashi: Japanese automotive transportation sector's impact upon Global warming. Applied Energy 59, 175-185. 1998.

Köhler, Uwe: Verkehr. Straße, Schiene, Luft. Kap. A-8, A-9, Abschn. B-3.1, B-5.2, C-2.5, Kap. F-3, Berlin: Ernst & Sohn Verlag. 2001.

Liu, Wen, Hu, Weihao, Lund, Henrik, Chen, Zhe: Electric vehicles and large-scale integration of wind power—the case of Inner Mongolia in China. Applied Energy 104, 445-456. 2013.

Litman, Todd: Valuing transit service quality improvements. Journal of Public Transportation 11 (2), 43-63. 2008.

Paulley, Neil, Balcombe, Richard, Mackett, Roger, Titheridge, Helena, Preston, John, Wardman, Mark, Shires, Jeremy, White, Peter: The Demand for Public Transport: A Practical Guide. TRL Re-port 593. Available online: http://www.demandforpublictransport.co.uk/TRL593.pdf. Last ac-cessed: 07/17/2015. 2004.

Rohlfs, Werner, Mareev, Ivan, Rogge, Matthias: Innovative Schnellladung von E-Bussen im Pro-jekt SEB e-ÖPNV. In: Der Nahverkehr, Heft 5. S. 11-16. 2015.

Salonen, Maria, Toivonen, Tuuli: Modelling travel time in urban networks: comparable measures for private car and public transport. Journal of transport Geography 31, 143-153. 2013.

Schmechtig, Mathias, NahverkehrsConsult; plan:mobil Frank Büsch; Ingenieurbüro Helmert (Planungs-kooperation „Busnetz 2015+"): Projekt „Busnetz 2015+". Überarbeitung des Busliniennetzes in Aachen. Ergebnisbericht. Aachen. 2013.

Scholz, Gero: IT-Systeme für Verkehrsunternehmen. Informationstechnik im öffentlichen Perso-nennahverkehr. Heidelberg, dpunkt.verlag GmbH. 2012.

Silvester, Sacha, Beella, Satish, Quist, Jaco: Advent of electric vehicle: A research agenda, in Joint Actions on Climate Change (eds. A. Remmen and H. Riisgaard). University of Aalborg, Aal-borg. 2009.

Sinhuber, Philipp, Rohlfs, Werner, Sauer, Uwe: Conceptional considerations for electrification of public city buses. Emobility - Electrical Power Train. IEEE. 2010.

Sioshansi, Ramteen, Denholm, Paul: Emissions impacts and benefits of plug-in hybrid electric vehicles and vehicle to grid services. Environ Sci Technol 43, 1199–204. 2009.
Sioshansi, Ramteen, Fagiani, Riccardo, Marano, Vincenzo: Cost and emissions impacts of plug-in hybrid vehicles on the Ohio power system. Energy Policy 38, 6703-6712. 2010.
Sioshansi, Ramteen, Miller, Jacob: Plug-in hybrid electric vehicles can be clean and economical in dirty power systems. Energy Policy 39, 6151-6161. 2011.
Steierwald, Gerd, Künne, Hans D., Vogt, Walter: Stadtverkehrsplanung – Grundlagen, Methoden, Ziele. Springer-Verlag, Berlin, Heidelberg. 2005.
Van de Walle, Stefaan, Steenberghen, Therese: Space and time related determinants of public transport use in trip chains. Transportation Research Part A 40, 151-162. 2006.
Vasconcellos, Eduardo Alcantara de: Urban change, mobility and transport in São Paulo: three decades, three cities. Transport Policy 12, 91-104. 2005.
Wardman, Mark, Hine, Julian: Costs of Interchange: A Review of the Literature. University of Leeds, Institute of Transport Studies, Leeds. 2000.
Wardman, Mark: Public transport values of time. Transport Policy 11, 363-377. 2004.

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