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Cool but dirty food? – Estimating the impact of grocery home delivery on transport and CO_2 emissions including cooling

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Recent studies have found that grocery home deliveries are partially replacing consumers' private shopping trips thereby decreasing total vehicle kilometers traveled (VKT) and CO_2 emissions. To our knowledge, such studies do not explicitly consider emissions caused by cooling. To assess the impact of home deliveries, we applied a framework consisting of passenger travel demand and delivery tour generation. Applying the models to the city of Berlin, Germany, we compare impacts in scenarios with home delivery from points of sale in the year 2030, assuming two different market shares for e-food and hot and mild air temperatures. The results show that home delivery decreases VKT and emissions, but total CO_2 emissions are much higher when food cooling is included in hot scenarios and moderately higher or decreasing in mild scenarios as refrigerator units increase fuel consumption and, thus, freight transport emissions by factor two to five as compared to driving. Urban areas are more affected by adverse effects while remote and less dense areas benefit. These findings show the need for considering cooling in analyses of the effects of grocery home delivery and call for the use of more energy-efficient and less polluting technologies in delivery vehicles for driving and chilling.

1. Introduction

The global increase of online shopping has led to a rising number of parcels in freight transport and, therefore, to higher pressure on urban transport. Online grocery shopping[1] is very likely fueling arising congestion or air pollution problems, since grocery shopping induces a considerable share of 9% of total urban freight transport (Durand & Gonzalez-Feliu, 2012), which does not even include private shopping trips. Obviously, ordering goods online allows consumers to purchase special products that probably are not available in the stores nearby and this produces more transport. An even higher effect can be expected from changes in daily grocery shopping. Replacing such trips with home deliveries[2] is expected to aggravate urban transport problems even more due to the high number of grocery shopping activities. This work focuses on finding out the implications of a change in this type of shopping.

In general, online shopping leads to a shift in the responsibility for the last leg of the transport chain, that is to the home of the customer. This differs for home delivery and the pick-up of goods (Edwards, Halldórsson, McKinnon, & Cullinane, 2010). In the latter case, consumers pick up the goods by themselves either at the store or at some intermediate pick-up point, while in the former case the retailer or an intermediate delivery company transports the goods to the consumer. One might think that private daily shopping trips can thus possibly be replaced by commercial delivery trips, thereby decreasing VKT and CO_2 emissions. Recent research has confirmed this, finding that e-groceries have substantially reduced the distances driven (cf. Chapter 2). However, the net effect on transport-related CO_2 emissions, when balancing private shopping trips and commercial home deliveries, remains underinvestigated. Furthermore, the transport of groceries such as fresh or frozen food requires cooling[3] which is associated with further energy

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[1] Throughout the paper, we use the terms online grocery shopping, e-groceries, and e-food interchangeably to refer to all food items purchased online which one could buy in a conventional grocery store such as dry products, produce, frozen food, etc.

[2] By home deliveries, we mean service providers who transport goods to the customers, be it the retailer or an intermediate company. We explicitly excluded the exclusive delivery of prepared or cooked food such as pizza from this. Home delivery in the realm of our analysis refers only to the transport from the point of sale to the consumer.

[3] Throughout the paper we use the terms refrigeration, cooling and chilling interchangeably to refer to the fact that food must be cooled down and kept cool during transport and loading/unloading.

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consumption and the production of CO_2 emissions. This has not been explicitly considered in recent studies. Thus, another question involves determining the balance of emissions from transport changes once food cooling is included.[4]

In Germany, online grocery shopping is much less developed than in many other countries, with only a market share of 1.1% of total grocery retail sales in 2017 (HDE, 2018). However, this form of retail has shown high growth rates. Furthermore, studies (Ernst & Young, 2017) show that consumers of online groceries live in rather urban contexts where transport is already a problem due to high population density. Thus, the growing city of Berlin, Germany, provides an interesting case for application and analysis. Home delivery can occur both from depots or points of sales (POS). A brief desktop review showed that relevant retail operators with outlets such as 'rewe' deliver from both depots and supermarkets while online-only companies use depots (see Appendix B). For the sake of simplicity and its high relevance for urban mobility we focus on POS-based home delivery in our analyses.

This work therefore pursues the following objectives:

1. Develop a simulation-based methodology in order to calculate the balance of vehicle kilometers traveled and CO_2 emissions for both private shopping trips and home delivery tours from POS to the consumer.
2. Calculate emissions generated by transport and cooling of food during delivery tours for different air temperatures.
3. Apply the model to the city of Berlin, Germany, in order to find out the impact home delivery has on transport performance and emissions in passenger and freight transport in general but also to determine how this impact differs spatially.

The paper is structured as follows: First, an analysis of recent studies on transport and the environmental effects of online shopping in general as well as of groceries helps us to identify research gaps and derive the requirements and presuppositions for the models. Next, we present the case study and main assumptions for the analysis, before describing the model framework and the prediction and disaggregation of locations, travel demand model, delivery tour planning, and emissions calculation. Subsequently, we set out the separate and combined results for passenger travel demand, including shopping trips and delivery tours, for vehicle kilometers traveled, emissions from driving, and total emissions including those generated by cooling. In this step, we also compare the results for hot and mild air temperatures. Finally, we discuss the results, limitations and future research, policy implications and conclude with our main findings.

2. Background

Many studies have analyzed shopping transport and logistics or freight transport in general. However, only a limited number have investigated passenger transport in the form of private shopping trips – in conjunction with freight transport, i.e. delivery tours. Another stream of research has looked at the application of simulation models in order to assess the effects of online shopping on transport and the environment. In the following, we give an overview of the state of research regarding the effects of online shopping in general and, more specifically, the effects of e-groceries.

Several studies analyzing the impact of e-commerce on transport and the environment use survey data to predict and, in some cases, simulate resulting transport. Focusing on passenger transport and products such as clothing, books, or electronics and other small non-food items, research by Carling, Han, Håkansson, Meng, and Rudholm (2015), Edwards et al. (2010), Laghaei, Faghri, and Li (2015), and Wiese, Toporowski, and Zielke (2012) mostly found a reduction in CO_2 emissions resulting from the replacement of private shopping trips by home deliveries. For e-groceries, a meta-study by Rotem-Mindali and Weltevreden (2013) report different trip length reduction rates, ranging as high as 93%, when home delivery replaces personal shopping trips. However, most of the cited articles, such as the one by Siikavirta (2002), assume that all trips are made in cars.

Analyzing consumer behavior, Suel and Polak (2017) drew implications from the effects of home delivery on passenger transport. They analyzed the joint choice of retail channel, store location, and mode, applying different discrete choice models. According to their findings, online shopping is an attractive alternative to large-basket in-store shopping for affluent consumers, which ultimately could fuel closures of large stores in the future. Furthermore walking to the shops is more attractive for small-basket shopping. Thus, they conclude that home deliveries rather replace shopping trips conducted in cars and, thus, have a high potential to reduce emissions.

A limited number of studies have considered passenger and freight transport at the same time in a modeling or simulation framework (Gonzalez-Feliu, Ambrosini, & Routhier, 2012; Goodchild, Wygonik, & Mayes, 2017; Laghaei et al., 2015; Wygonik, 2014). The work by Gonzalez-Feliu et al. (2012) employed an explicit substitution procedure to different distribution channels such as traditional shopping, drive (pick up at the store), home delivery, and proximity delivery. The authors determined the channels that have replaced traditional shopping trips based on spatial structure and mode shares. After that they estimated the related quantity of goods to be substituted proportional to the number of trips and orders and applied a model to calculate the routes to delivery points and estimate trip distances for all channels. Simulating scenarios for the city of Lyon, the authors found that home deliveries are less optimized than pick-up point logistics. This is, however, mainly due to the type of engine used in vehicles since small trucks and B2B flows are more efficient. A combination of 50% traditional shopping, 15% home deliveries, and 35% proximity depots leads to a reduction in vehicle kilometers traveled (VKT) by 13% as compared to traditional shopping only. These results potentially support arguments in favor of home delivery as a means to reduce traffic.

Other simulation studies draw further implications for the environment in terms of CO_2 emissions (Gonzalez-Feliu et al., 2012; Goodchild et al., 2017; Siikavirta, Punakivi, Kärkkäinen, & Linnanen, 2002; Wygonik, 2014; Wygonik & Goodchild, 2011). In the very first of these studies, Siikaviarta et al. (2002) analyzed different home delivery strategies and found a substantial reduction potential for distance and emissions, with the highest decrease caused by the use of reception boxes. Goodchild et al. (2017) applied an analytical model that measures distances between two points for the delivery of generic goods. Their objective was to find out which of three different scenarios (consumer pick-up at local depots, home delivery from local depots, and home delivery from warehouses) produces the lowest emissions, and under which circumstances. They concluded that delivery is more efficient than private transport in urban areas with high customer density. Their approach, like that of Siikavirta et al. (2002), did not consider the effect of congestion. Based on a calculation of routes for similar scenarios in the latter study, Wygonik (2014) reported that traveled distances are higher in passenger vehicle scenarios than in local depot scenarios, but that emissions are lower in the former case, depending on the type of vehicle used for delivery. While showing which distribution strategy has the lowest negative impact, all of the mentioned studies seem to miss a crucial component in the calculation of emissions: Groceries also comprise products that have to be refrigerated during the whole tour and thus CO_2 calculations should include emissions caused by cooling. The articles we reviewed did not reveal whether the energy consumed by cooling was included in the factors for calculating CO_2 emissions; none of the studies explicitly reported such factors. This problem was not even addressed in the paper by Edwards, McKinnon,

[4] Note that this study considers only the transport sector, but not the energy sector, e.g., cooling in the supermarket, as this is beyond the scope and focus of the paper.

and Cullinane (2011) as a 'methodological issue' for calculating emissions for e-commerce. These emissions can, however, be substantial: According to a study by Tassou, De-Lille, and Ge (2009), up to 40% of emissions from the diesel engine can be attributed to the cooling activities of the engine.

Summarizing the discussion, we have found that many studies assume that grocery home delivery has the power to reduce VMT and emissions. But we also see the following research gaps:

1. None of the studies mentioned here consider the requirement of food cooling when estimating the emissions resulting from home delivery.
2. Few studies include both passenger and freight transport in one framework and thus do not derive the net effects based on both.
3. Several studies consider only shopping trips by private cars, although in many cities grocery shoppers walk to the store. Thus, interactions between different modes have been neglected.

Taking into account these research needs, we need a comprehensive framework consisting of simulations of both types of transport – passenger transport and freight transport – to understand the impact of increasing online grocery shopping on the movement of passengers and freight. Furthermore, food cooling should be considered when estimating emissions in order to obtain the complete picture. Hence, we introduce a framework of several interlinked simulation models and emissions calculations for both private shopping trips and delivery tours. This model and the test application are described in more detail in the following section.

3. Modeling the effects of home delivery services

In order to understand and predict the impact of increasing online grocery shopping, it is necessary to consider passenger and freight transport together. Against this background, a chain of connected models is proposed. This includes data processing models to determine the probability of locations of grocery stores, their spatial disaggregation as well as shopping trip simulation using an agent-based transport demand model and delivery tour planning. From this, the transport and emissions balance is derived by comparing the different market shares of online shopping. In the review process it turned out that it is also important to compare different weather conditions (hot and mild) as they trigger different levels of emissions which we therefore also included in the analyses. The modeling assumptions and detailed descriptions are provided in the following.

3.1. Model assumptions

A case study for the city of Berlin in 2030 provides the basis for the analysis of the research questions.

For the sake of simplicity, the city consists of the following essential elements: persons and households, locations for activities (e.g., workplaces, education, and shopping facilities, including grocery markets) as well as distribution centers. Exchange between agents takes place within a transport network which links the demand and supply of activities. In the case of online grocery shopping, distribution centers, stores, and private households are the most important actors. The majority of the studies cited in Chapter 2 examined the increase in the use of home delivery services as the primary distribution channel. Because this is also the case in Germany, it is assumed that this is the only distribution channel besides shopping directly at the grocery store. The case study is based on the following assumptions:

- Groceries are transported from distribution centers to grocery stores.
- Home delivery starts at the grocery store (POS), where the delivery is preassembled, and private households are the destinations.
- Some of the groceries have to be kept cool during transport.
- People assigned to households travel to grocery stores with different modes of transport.
- The number of home deliveries corresponds to the number of shopping trips replaced. This means that households that no longer buy groceries in brick-and-mortar stores receive grocery deliveries instead.
- With the increasing turnover of online grocery shopping and decreasing private shopping trips, the number of brick-and-mortar grocery stores decreases due to competition.

In order to analyze the effects of the increasing use of home delivery services, three scenarios were developed with varying percentages of private shopping trips to be replaced: no e-commerce (NOEC), realistic (REAL), and extreme (EXTR). The business-as-usual scenario (no e-commerce - NOEC) is based on the assumption that the share of the online grocery sales and, thus, the replacement rate is 0; i.e., grocery purchases are made exclusively in the form of private shopping trips. The realistic scenario (REAL) is based on the assumption that grocery delivery services replace 3% of private short-term[5] shopping trips. Based on forecasts by different experts such as (BBSR, 2017), who expect a growth of Germany's short-term online grocery sales to about 7% of total retail sales by 2025, we assumed that the share of online grocery shopping in total sales will rise to 10% by 2030. However, only 3% of shopping trips are made through home delivery, which is not the only sales channel. There are also shipments to parcel boxes as well as pick-ups in the grocery stores, which continue to cause private passenger traffic. Furthermore, not every purchase on the Internet replaces a purchase in a store. In fact, the new distribution channel allows for additional purchases that would not otherwise be made. Online shopping nevertheless constitutes competition for the brick-and-mortar grocery stores. Due to the low margins in German grocery retail, it is assumed that if the online shopping segment grows to 10%, the number of stores will decrease by 10% by 2030. For the extreme scenario, (EXTR) a rather high replacement value of 10% of all private short-term shopping trips was considered in order to determine whether the effects increase less intensively due to delivery in bulk to clusters of households. The percentage of grocery stores presupposed to close in this scenario was 15%, assuming a non-linear and flattening increase with higher online sales. Finally, emissions for each of the scenarios were calculated assuming two different sets of temperatures in the delivery truck. The first set (hot) assumes that temperatures are according to DIN8959 (see Appendix A) with an air temperature of 30 °C and further zones with temperatures of 0 °C and −20 °C. In the second set (mild) we tested more realistic weather conditions and temperature zones within in the truck: 13 °C ambient temperature and compartments with temperatures of 5 °C and −20 °C (see Section 3.6). Table 1 gives an overview of the assumptions used in the scenarios.

3.2. Model framework

A framework of four models was used to reflect the trends considered for the case study described above. The location prediction as well as the store disaggregation model generated the data required for the subsequent transport models whereas the transport models simulated the private shopping trips and home delivery tours.

Based on the population forecast for 2030, the location model first determined the number of small and large grocery stores per zone for the NOEC scenario (Heldt, Matteis, Frenzel, & Blechschmidt, 2019). In a second step, the aggregates of the predicted stores per zone and size were disaggregated by the SYNTHESIZER (von Schmidt, Cyganski, & Krajzewicz, 2017) into single locations. The resulting locations of the grocery stores were used in the next step in the agent-based transport

[5] 'Short-term' refers to products that are bought at a high frequency, such as groceries, beverages, or toilet paper.

Table 1
Scenario assumptions.

	NOEC	REAL		EXTR	
	no e-commerce	realistic growth		extreme growth	
e-groceries market share	0	10%		15%	
reduction in # stores	0	10%		15%	
reduction in # grocery shopping trips	0	3%		10%	
number of stores considered for delivery	0	5		5	
		Hot	Mild	Hot	Mild
Air temperature	–	30 °C	13 °C	30 °C	13 °C
Fresh products compartment	–	0 °C	5 °C	0 °C	5 °C
Frozen products compartment	–	−20 °C	−20 °C	−20 °C	−20 °C
population growth		projection Berlin 2030			

model TAPAS (Heinrichs, Krajzewicz, Cyganski, & von Schmidt, 2016; (Hertkorn, 2005)) to determine the passenger transport demand. Within this model, 3% of the private short-term shopping trips for the REAL scenario and 10% for the EXTR scenario were randomly selected and deleted from the trip chain. The last modeling step involved using the software packages jsprit (graphhopper, 2019) and MATSIM to simulate POS-based home delivery tours for the REAL and EXTR scenarios for the households without private grocery shopping trips. Fig. 1 shows the interactions between these models.

These processes yielded values for transport demand with a decreasing number of private shopping trips, passenger kilometers traveled, additional time for standing, and vehicle kilometers driven by delivery trucks. Based on these values, the respective transport performance and CO_2 emissions for each scenario and subscenario (hot and mild) were calculated. In this context, a special focus was on motorized private shopping trips and home delivery tours, including cooling. In the following, the individual models are described in more detail.

3.3. Location prediction and disaggregation of stores

Grocery store locations or points of sales are at the center of the processes we considered in this study since they are the destinations of shopping trips and starting points for home delivery trips. Location patterns may change due to trends such as demographic change and change of consumer behavior. The location model that we used for this study is described in Heldt et al. (2019). Based on data from a retail survey (Senate Department for Urban Development and the Environment, 2015) extended by spatial attributes, it predicts the number of grocery stores of two size categories (below 1,500 m^2 and 1,500 m^2 and more) for each zone, since both categories have different delivery patterns in terms of the type of vehicles and frequency. The number of grocery stores depends strongly on demand in terms of the number of persons in a zone. Other important factors which, however, we assumed to not change over time are the number of transit stops, traffic flow, and the number of center-oriented stores (excluding grocery stores). The

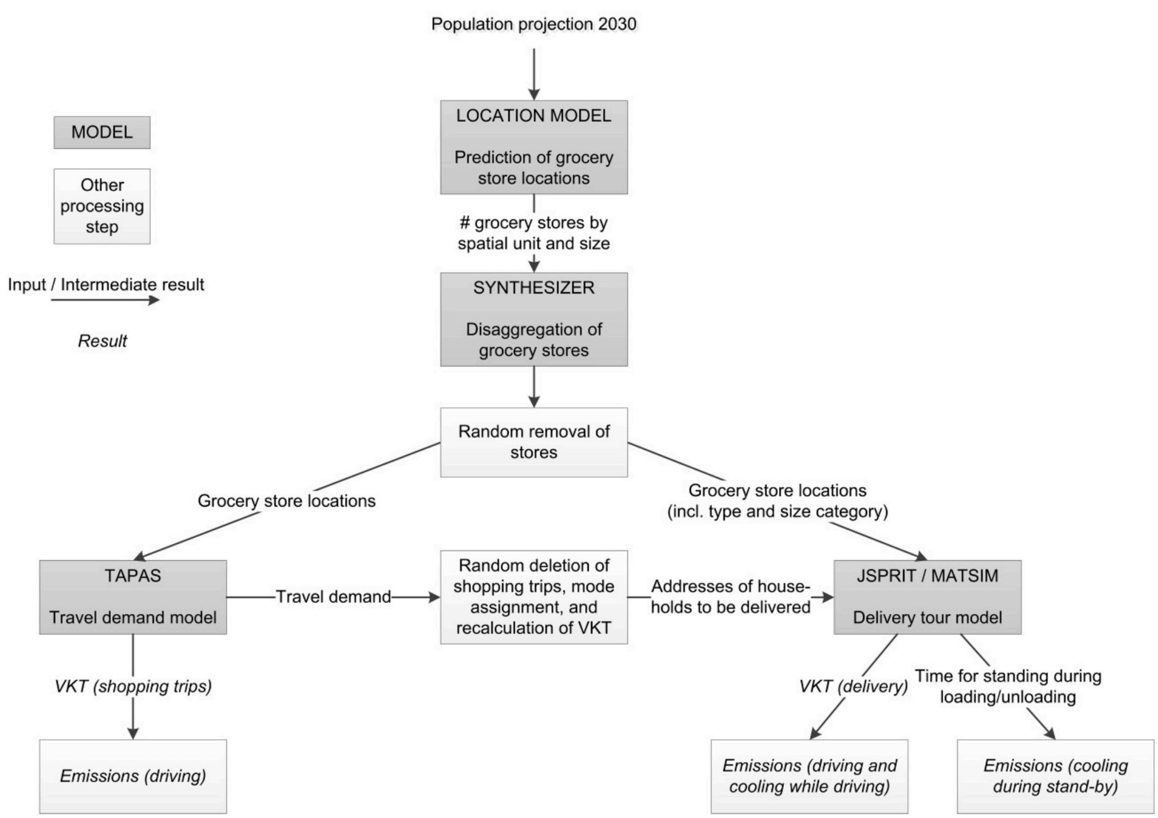

Fig. 1. Model framework and data flows.

location model predicted the number of small and large grocery stores using Poisson regression with calibrated constants in line with values for the year 2015. Assuming a growing population, we applied the resulting model to simulate the location pattern for 2030, taking into account population projections (Senate Department for Urban Development and Housing, 2017). To enable more detailed analyses, the two size categories were further disaggregated into four categories, applying the distribution of stores across size categories in 2015.

Since the tour planning of grocery deliveries requires precise address information, the aggregates from the location model needed to be disaggregated into individual locations. Therefore, the SYNTHESIZER was used. To reproduce structural information, such as data on population or locations (e.g., grocery stores), the program requires disaggregated sample data and aggregated marginal totals. For the NOEC scenario, the same data were used as those used for the location prediction, with the georeferenced data taken as the sample. As marginal totals, the program used the aggregates per zone, predicted from the location model. Compared to the base year 2015, the number of brick-and-mortar grocery markets will rise to 1,224 by 2030 due to the high population growth. However, these data only contain information regarding the size of the stores and not on the type (discount, complete range, organic). Therefore, the aggregates from the retail trade survey on the type of store served as further input data. Using the IPF algorithm (Deming & Stephan, 1940), corresponding target distributions were calculated within the SYNTHESIZER, differentiated according to the size and type of store. However, this method requires the totals of the margins to be equal in their entirety. To achieve this, the marginal totals for the type of store were adjusted proportionally to the predicted total by store size. During generation, the program duplicated the relevant grocery stores from the sample data until the target distribution for each zone was reached. For the NOEC scenario, it should be noted that for some zones there were no stores with a certain combination of attributes (size x type of store), or more stores needed to be generated than there were in the original data set. In this case, appropriate adjustments had to be made to the spatial distribution.

The home delivery scenarios REAL and EXTR used the disaggregated stores generated within the NOEC scenario as sample data. These scenarios take into account a general increase in online sales, which is likely to lead to a decrease in the number of stores. Therefore, the total margins from the business-as-usual scenario were reduced according to the assumptions. Apart from the different input data, the procedure for generating grocery stores was identical for all scenarios.

3.4. Private shopping trips

In order to examine the traffic caused by grocery shopping, we generated travel demand with an activity-based travel demand model named TAPAS (Heinrichs et al., 2016) which is described in the following. This model produces activities for every person in the study area, chooses appropriate locations and modes to perform these activities, and evaluates the final day plan. The modeled activities cover education, work, shopping, leisure, and private errands. The activities are derived from reported day plans from the national household survey MiD 2008 (Lenz et al., 2010). This dataset allows the disaggregation of shopping for short-term, mid-term, and long-term purposes. The trips are processed by activity in the following order of priority: education, work, private matters, shopping, and leisure. The possible locations to perform these activities are selected accordingly. For example, if the activity was shopping for short-term items, only locations for food stores, supermarkets, and discount stores are selected. The destination for a specific activity is chosen by applying two steps. First, a filter is applied, which takes the accessibility of all suitable locations from the starting point into account with respect to the available modes and the remaining time budget. Second, the algorithm selects one specific location from the filtered subset using a gravity-based weighting approach. The weighting factors are used for calibration. The simulated modes of transport include walking, biking, car driving, passenger in a private car, public transport (PT), and car sharing. The mode is selected using a multinomial logit approach, influenced by costs, travel time, activities along the trip, age, and availability of different mobility options. All trips for one person are assembled into a plan for the whole day in the simulation software. This simulated day plan is evaluated based on two criteria: first, the accessibility of locations considering the remaining time budget and, second, the overall time budget compared to the reported time budget. The synthetic population used fits the statistical data of the city of Berlin, Germany, in the year 2010. The main parameters for the population can be found in Table 2.

The model was calibrated to fit the trip-length distribution of the survey data in SrV 2008 (Ahrens, 2009). The lengths of each trip were calculated by a shortest-path router from an OpenStreetMap network. The model was validated to match the reported mode shares. The final calibration results can be seen in Fig. 2.

To analyze the potential reduction in travel demand in the home delivery scenarios, trip chains were analyzed for shopping activities, and shopping trips were randomly selected with probabilities of 3% for the REAL and 10% for the EXTR scenario.

Substituted shopping trips were categorized into two types, and the differences between before and after the substitution were calculated as described in the following. The substituted shopping trip to location B bound by two activities at the same location A (usually at home) were called A-B-A trips. In this case, both trips – the outbound shopping trip and the returning one – were removed from the simulation data and could be counted as a possible reduction in travel demand. When the trip was in between two different locations, a new trip from the preceding location (A) to the next location (C) was generated, leaving out the shopping location (B). These trips were called A-B-C trips. Now, the remaining trip was compared to the two removed ones, and only the deviations were counted as a possible reduction in travel demand. If the mode used on the trip to the shopping location was different from the mode used to leave the location, the mode of the newly created trip was derived from the more highly ranked mode. The ranking ranged from walking to car-sharing. To maintain comparability of these two types, both trips from A to B and B to C were summed up and compared to the direct route from A to C. The occurrence of A-B-A and A-B-C trips by mode is shown in Fig. 3. In total, A-B-A trips account for 55.84% and A-B-C trips for 44.16% of all trips.

3.5. POS-based home delivery tours

The freight transport part of the scenario includes two aspects. The first aspect, which involves supplying grocery stores in order to replenish the stock, was treated in both scenarios (REAL and EXTR) equally because we assumed that the home deliveries that result from online purchases are made from stores of the respective retail chain and not from distribution centers. This assumption is backed by the fact that the distance between these distribution centers and the locations of the potential customers is too far to be covered with a small distribution vehicle that only transports a few shipments, especially as it can be supposed that customers wish their orders to be delivered within a short time. Although the overall volume of goods shipped to the stores does not change for the scenarios in the forecast year, the number of stores varies between the scenarios. Nevertheless, we did not consider possible

Table 2
Population of Berlin 2010 (sources: Statistical Offices of the Federation and the Länder, 2014; Ahrens, 2009).

Berlin 2010	Number
Persons	3,322,985
Households	1,937,355
Cars	1,185,293

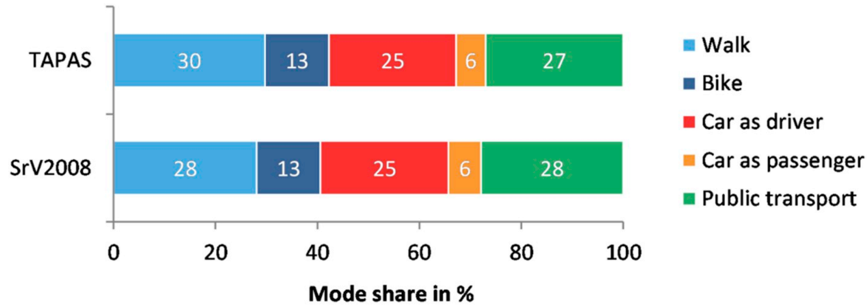

Fig. 2. Modal share of survey data and TAPAS (Sources: Ahrens, 2009 and own data).

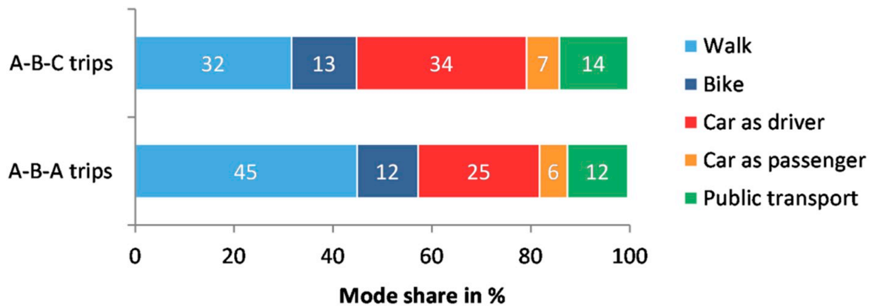

Fig. 3. Trip structure for shopping activities and their mode share (Source: own simulated data).

changes in the transport distance to the stores as our study focuses on the substitution of private shopping trips by home deliveries. As a consequence, the analysis focused only on the second aspect.

Deliveries to private households that order groceries online are carried out with rather short tours that start and end at grocery stores. The private households are the same as the ones in the sample drawn for modeling the effects on passenger transport. The simulation of these trips required a number of assumptions. Each household that decides to buy online has to select a store to shop from. In reality, agents can choose between the online platforms of the various retail chains. The synthesized stores in the predicted year did not include company names and, thus, an assignment according to characteristics of the retail company, such as market share, could not be made. Moreover, it is not clear which retail chains will profit, and to what extent, from the trend towards online shopping. We therefore assumed that each household randomly chooses one of the five stores that are located closest to it. Each store is a potential start or end point of home delivery tours. The number and location of the stores was obtained by the procedure described in Section 3.3. As customers expect a certain assortment to choose from, only stores with a floor space of 700 m^2 or more were assumed to be basis for home delivery vehicles. This is roughly the size of a discount chain store. We further assumed that delivery vehicles have a permissible maximum weight of 3.5 tons and are endowed with a cooling body. The latter has three temperature zones – one that is not refrigerated, one for refrigerated food and one for frozen food (see Section 3.6 and Appendix A). According to DIN8959, the assumed temperatures are 0 °C for refrigerated food, −20 °C for frozen products and 30 °C for the air temperature outside the vehicle. Since these assumptions are not realistic in most cases, we calculated a second set of scenarios with a more realistic temperature of 13 °C air temperature[6] and 5 °C for the refrigeration compartment in order to analyze an extreme case and a realistic one.

In the model, the vehicles travel in tours that start and end at the store to which they are assigned. A tour had a maximum duration of 4 h in order to account for spontaneous orders made by customers within the same day. Each stop was assumed to take 6 min. When there are several stops located close to another, the vehicle does not move, and the time for the single stops is added up.

Based on these assumptions, delivery tours were constructed by solving a Capacitated Vehicle Routing Problem for every store and the assigned households. These problems were solved by applying jsprit version 1.7.2 (graphhopper, 2019) which applies a ruin-and-recreate algorithm based on Schrimpf, Schneider, Stamm-Wilbrandt, and Dueck (2000). The location of the store was determined as depot location for an arbitrary number of vehicles that are needed to fulfill all transport orders at hand. Each household was determined as a service that the vehicles had to perform with a capacity need set to one and the capacity of each vehicle was 50 services. Note that the capacity restriction is not a real constraint to the tour lengths, as each service is assumed to last 6 min and thus the time to serve 50 customers (18,000 s) exceeds the total allowed tour time (14,400 s). The distances between the depot and/or the household locations were calculated using the same road network for Berlin as for passenger transport. This network was represented in the form used by the transport simulation MATSim (version 0.10.0) (Horni, , Nagel, , & Axhausen, 2016), and the shortest path engine of MATSim was also used by jsprit for the repeated calculations of distances, which was necessary to solve the Vehicle Routing Problem. For the sake of simplicity, we fixed the speed on all links to 20 km/h in order to consider some of the other traffic in the city.

3.6. Emissions calculation

Emission factors were used to estimate emissions for the generated trips by both passenger and freight transport for each zone. Emissions heavily depend on the composition of a car fleet and its engine types, such as gasoline, diesel, electric drive, and fuel cell. Developing a model to predict future car fleets is a task in its own right, which cannot be addressed in this paper. Thus, for passenger transport, we applied

[6] In Berlin, the annual average temperature was 10.5 °C in 2018 (Senate Department for the Environment, Transport and Climate Protection, 2018). For our analyses, we assume a higher temperature since groceries are usually delivered during daytime. 13 °C corresponds to the average daily maximum temperature.

standard CO_2 emission factors from Statistisches Bundesamt (2008), which is 144 g of CO_2 per kilometer for an average car in Germany. We focused on the emissions of CO_2, because these emissions are directly correlated to energy consumption. Other emissions such as PM_x and NO_x depend heavily on the driving dynamics of a vehicle, which are not modeled in the simulation at present.

Further emissions arise from freight transport. Home deliveries require fuel for driving and for the cooling unit. Especially the power consumed by the latter depends largely on the context, and information on the fuel consumption of the cooling unit is difficult to obtain from both vehicle body-builders and manufacturers of the unit (James & James, 2010). Therefore, we derived these emissions from several assumptions. In the following, a summary of this calculation is provided. For a detailed explanation, please refer to Appendix. A.

A prototypical vehicle was assumed that is built upon a chassis of a Mercedes Benz Sprinter with an 84 kW diesel engine which consumes 9.4 L per 100 km in local city transport. This vehicle has three equally sized compartments: one for groceries that do not have to be kept cool, one for fresh food such as vegetables, and one for frozen food (see Section 3.5). To keep the temperature constant, particularly during loading and unloading, energy is required which produces emissions. This energy consumption can be calculated according to DIN8959 (Möhlenkamp et al., 2017). It is mainly influenced by three values: the thermal cooling power for the cargo bay, which depends largely on the temperature difference between compartments and the exterior; the coefficient of performance (COP) of the cooling unit, which describes the translation from thermal to mechanical power consumption and had to be assumed due to a lack of data; the way the compressor of the latter is propelled by the engine of the vehicle.[7] A detailed description of the assumed values, the required energy, and resulting emissions is also given in Appendix A.

The factors applied in the emissions calculation are as follows for the hot weather scenarios: Driving emits 259 g of CO_2 per kilometer; food chilling during transport generates 160 g of CO_2 per kilometer, and cooling during stops for loading and unloading produces 55 g of CO_2 per minute. When assuming more realistic temperatures (mild scenarios), chilling during driving is associated with emissions of 70 g of CO_2 per kilometer and cooling while the vehicle is standing generates 23.5 g of CO_2 per minute.

4. Results

The following Table 3 summarizes our main results which will be discussed in the following sections for traffic volume and trip savings, for emissions from transport, and for total emissions including cooling for two assumptions: first, energy consumption according to temperatures defined by DIN8959 which assumes 30 °C ambient temperature (hot), and second, the same for a more realistic temperature of 13 °C (mild).

4.1. Traffic volume and tour patterns

Grocery trips were classified as short-term shopping. Therefore, we show only results for these activities, which cover 66% of all shopping activities per day in Berlin. The traffic volumes related to the regular short-term shopping trips are shown in Table 4. The total distance represents the distance traveled by all people of the synthetic population by mode. These shopping trips are mainly performed on foot (37.8% of all trips), while the traveled distance is mainly performed by car (41% of the total distance). The reason for this is the average trip length. Trips on foot are 1.8 km at average. All other modes show significantly longer distances, up to 4.9 km for public transport and 5.1 km for car trips. Because a change in shopping trips also affects the trip leaving the store, the distance including the subsequent trip location is given in Table 6. The average trip length for people doing short-term shopping on foot in Berlin reported by the MiD2008 is 1.2 km. Therefore, the TAPAS results are higher than expected due to two effects: First, the model does not distinguish between short-term and other shopping during the calibration of the trip lengths, which leads to an overestimation of accessibility during the location choice. Second, many shopping locations are in the same traffic cell as the previous location. Trips within one zone suffer from many local peculiarities, such as shortcuts through parks or multiple entrances, which cause an inaccurate computation of the travel distance for very short trips. Comparing the average lengths of shopping trips and the length that also includes the next leg shows that the returning trips by bike and foot are almost the same length as the shopping trip itself. These tours are usually home bound. The strong preference for car compared to the average mode share is caused by the mode choice, which gives an additional benefit to car usage to reflect the need for transportation capacity for shopping trips.

Table 3
Main results for REAL and EXTR scenarios and hot and mild temperatures.

	REAL		EXTR	
VKT saved		−59,200		−197,000
VKT saved (relative change)		−3.2%		−10.8%
additional VKT from deliveries		17,100		30,200
total VKT saved		−41,100		−166,800
emissions saved from shopping trips		−8.31 t		−28.17 t
emissions saved from shopping trips (relative change)		−3.2%		−10.8%
additional emissions from deliveries (only from driving)		3.76 t		7.82 t
emissions balance (only driving)		−4.55 t		−20.35 t
	Hot	Mild	Hot	Mild
additional emissions from deliveries (cooling)	13.32 t	5.69 t	41.55 t	17.75 t
emissions balance (including cooling)	8.77 t	1.14 t	21.20 t	−2.60 t

The magnitude of short-term shopping trips substituted by home deliveries for the REAL scenario is shown in Table 5. The results of the EXTR scenario are shown in Table 6. For both scenarios, the proportion of walking trips decreases, and the share of public transport trips increases due to the replacement hierarchy, if the shopping location can be accessed by different modes. The share of the other modes remains almost the same. A comparison of average travel times reveals that the time saved is lower than the average trip time for regular shopping trips. This is due to the effect that shopping trips between two different activity locations are substituted by the direct net route of these non-shopping activities. The traffic volume of car trips is reduced by 59,200 km for the REAL scenario and by 197,000 km for the EXTR scenario. Compared to 298,300 short-term shopping trips covering 3.40 million km by car, this corresponds to a reduction in the number of trips by 3.2% in the REAL scenario and 10.8% in EXTR. However, total trip length decreases only by 1.8% in the REAL scenario and by 6.1% in the EXTR scenario. The reduction of traffic volume is much lower than the reduction of trips. One cause for this can be found in the length of the whole tour: Cars are usually used on longer tours that include an intermediate shopping activity. Therefore, not the whole trip but only the detour to the shopping location can be taken into account as vehicle kilometers saved. Finally, this analysis reveals that truck-based delivery events substitute a lot of trips originally performed on foot, by bike, and with public transport, which is likely to have a negative effect on emissions. Thus the reduction potential of home delivery largely depends on the mode share of cars and walking for shopping purposes (cp. Rotem-Mindali & Weltevreden, 2013).

Differences between REAL and EXTR are pronounced in freight transport. POS-based home delivery tours vary between the scenarios

[7] Note that, in every cooling system, there is leakage of the refrigerant that causes the COP to decrease and, in turn, emissions to increase (Tassou et al., 2009). In this study, leakage of refrigerant was not included.

Table 4
Regular short-term shopping trips.

mode	share	Ø distance (km)	total distance (1000 km)	Ø distance incl. leaving trip (km)	total distance incl. leaving trip (1000 km)
Walking	37.8%	1.8	754	3.5	1359.1
Biking	12.7%	4.1	579	8.2	1092.2
Car as driver	28.6%	5.1	1644	10.8	3214.9
Car as passenger	7.3%	5.2	418	10.1	765.3
Public transport	13.1%	4.9	717	10.1	1377.9
Car-sharing	0.4%	4.3	19	8.0	34.9
Total	1,042,001	3.7	4131	7.5	7844.3

Table 5
Replaced short-term private shopping trips for the REAL scenario (= savings).

mode	share	total distance (1000 km)	Ø distance (km)
Walking	34.6%	19.7	1.7
Biking	12.7%	22.0	5.1
Car as driver	28.8%	59.2	6.1
Car as passenger	6.0%	12.1	6.0
Public transport	17.2%	33.6	5.8
Car-sharing	0.8%	1.6	6.1
Total	33,626	148.1	4.4

Table 6
Replaced short-term private shopping trips for the EXTR scenario (= savings).

mode	share	total distance (1,000 km)	Ø distance (km)
Walking	34.5%	64.1	1.7
Biking	12.7%	72.2	5.1
Car	28.9%	197.0	6.1
Car as passenger	5.8%	41.4	6.4
Public transport	17.3%	112.6	5.9
Car-sharing	0.7%	4.6	5.7
Total	111,148	491.9	4.4

and also between different regions in the city. The comparison of the tour shapes in both scenarios shows that the tours in the EXTR scenario are generally shorter than in the REAL scenario (Fig. 4).

The greater trip lengths in the EXTR scenario are associated with a higher stop density and a higher number of stops per tour, which is closer to the maximum feasible number in a shift (Fig. 5). It can also be seen that there are fewer tours with only a few shipments in the EXTR scenario. This points towards possibilities for improving the organization of the distribution system in the REAL scenario. At the moment, each store with a size of over 700 square meters can serve as a depot for delivery vehicles. This assumption can be seen as the lower bound to the cost and environmental efficiency of home deliveries.

When comparing different regions inside Berlin, the division between stores located in the inner city (inside the S-Bahn ring) and in the outer city (outside the S-Bahn ring) shows that the density of customers clearly influences the shapes of delivery tours. In Fig. 6, the shapes of tours that start from stores inside compared to those outside of the S-Bahn ring can be seen. In both scenarios, the lengths of the tours are shorter, and the tours are less spread out in the inner parts of the city, while the number of stops per tour is significantly lower in the outer city (see Fig. 7) although the differences are less clear in the EXTR scenario. In some cases, the tour distances are much longer in the outer city (Fig. 6).

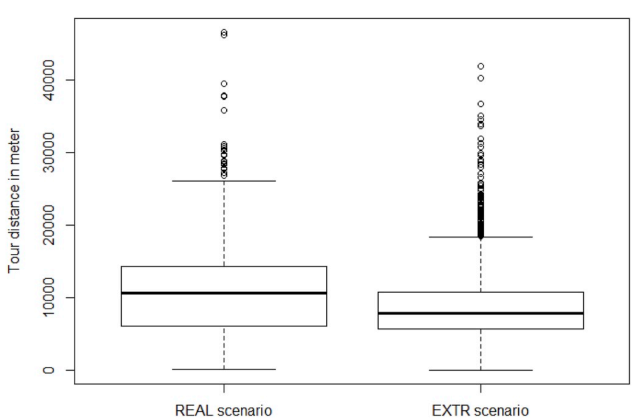

Fig. 4. Distribution of delivery tour distances in REAL and EXTR scenarios.

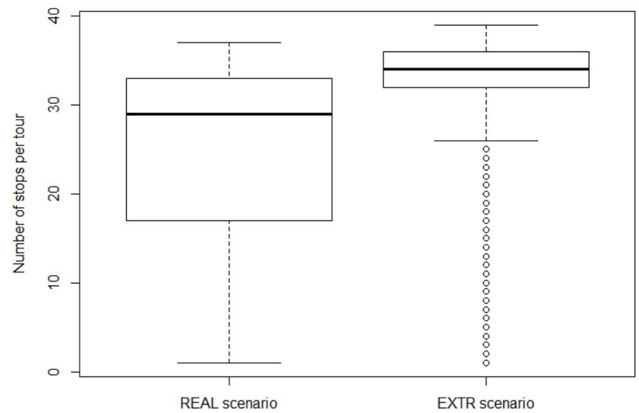

Fig. 5. Distribution of the number of stops per tour in the REAL and EXTR scenarios.

Having established a clear picture of the individual patterns in passenger and in freight transport, we now turn to a holistic and integrated view of both. Home delivery tours replace private shopping trips and change the spatial pattern of vehicle movements. Although they also link the stores and the homes of the grocery shoppers, the goal of the retail companies is different to that of private households. While the latter want to include shopping trips for convenience goods in their overall daily routines, retailers aim to achieve cost savings. Thus, it could be expected from the outset that the distance would be reduced. Comparing the distance saved in passenger trips (59,200 VKT) with the increase caused by additional freight transport tours (17,100 VKT) shows that POS-based home delivery saves about two-thirds of the distance covered in the realistic case. For an even higher substitution rate of 10%, the passenger trip savings are 197,000 VKT in the EXTR scenario, which exceeds the additional distance traveled by delivery vehicles (30,200 VKT) by far, saving 166,800 VKT in total. In other words, one additional delivery kilometer saves about 3.5 vehicle kilometers in private shopping trips in the REAL scenario and 6.5 km in the EXTR scenario. As shown by the analysis of delivery tours, the bulk effect comes into play here. With so many more households being supplied, tours can be carried out more efficiently; tour lengths are shorter, and the relative increase in freight transport is much lower than the decrease in shopping travel. While the number of addresses receiving deliveries increases more than threefold, the VKT in freight transport do not even double. These findings are in line with most of the studies reviewed in Section 2 and confirm the positive effects of POS-based home delivery on transport performance. Fig. 8 depicts the spatial pattern of this phenomenon for the EXTR scenario, where the highest reductions take place in zones at the edge of the city. Interestingly, zones in the inner city show lower

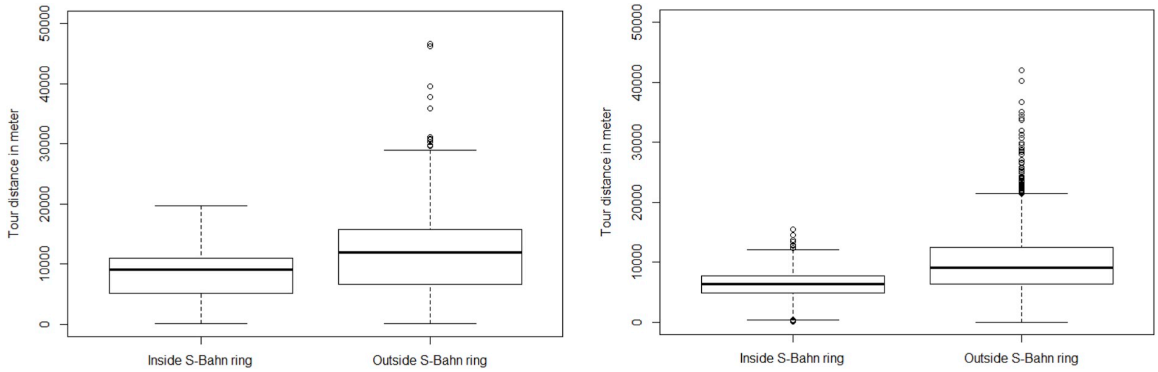

Fig. 6. Distribution of delivery tour distances inside and outside of the S-Bahn Ring for the REAL scenario (left) and the EXTR scenario (right).

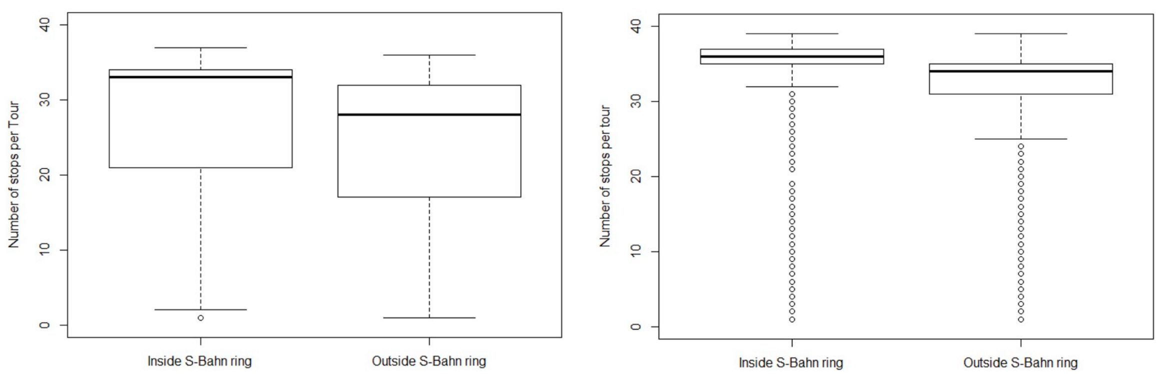

Fig. 7. Distribution of the number of stops per tour inside and outside of the S-Bahn Ring for the REAL scenario (left) and the EXTR scenario (right).

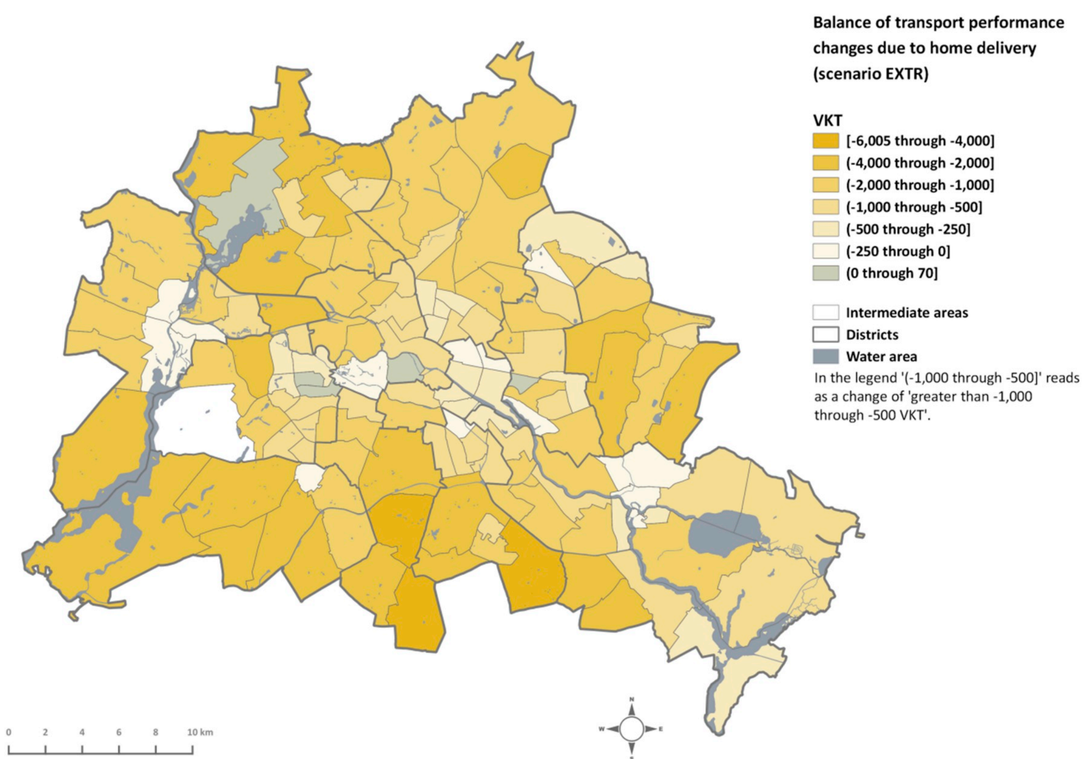

Fig. 8. VKT balance of private shopping trip savings and POS-based home delivery tours (EXTR scenario).

VKT for delivery tours than those at the edge of the city, except for the most central ones. This is due to longer and, in some cases, much longer tour distances in zones outside of the S-Bahn ring. Nevertheless, trip savings from passenger transport are higher in Berlin's outer city. In these zones, car use for shopping is initially higher than in the inner city. Thus, in several inner-city areas, total VKT even increase. People often go shopping on foot in dense city areas, and substituting these trips with delivery services results in more motorized traffic. In areas at the less densely populated edge of the city, on the other hand, more car shopping trips are replaced by home delivery, resulting in higher total savings. These described patterns are more pronounced in the extreme scenario than in the REAL scenario, where VKT savings are much higher in many zones. This confirms the assumptions and findings of most studies dealing with online grocery shopping: Home delivery tours are more efficiently organized than private shopping trips at least if occurring from the POS.

4.2. Emissions from driving

When we examine the calculated CO_2 emissions and only consider emissions that arise from driving alone, we see that our findings confirm previous studies' results: Emissions saved by passenger transport exceed the increase caused by delivery vehicles. Lower increases in freight compared to passenger transport performance translate into emission savings in the REAL and EXTR scenarios due to bulk delivery effects. Savings arising from passenger transport sum up to a total of 8.31 t per day in the REAL scenario and 28.17 t in the extreme case. If emissions caused by driving only are considered, it appears that POS-based home delivery saves emissions. In the REAL scenario, freight transport generates 3.76 t additional CO_2 emissions, which corresponds to total savings of 4.55 t. Obviously, these savings are even higher for the EXTR scenario. Here emissions from freight transport amount to 7.82 t; i.e., taking the reduction through less passenger transport into account, 20.35 t of CO_2 per day can be saved.

In Figs. 9 and 10, we can see that the spatial distribution of changes in emissions is very similar to the changes in VKT; i.e., several areas in the inner city become more polluted, while emissions in neighborhoods at the city's fringe decrease, in some cases substantially. For EXTR, this pattern is much more pronounced, as is the case for changes in VKT. Fewer zones in the inner city show an increase in emissions, and savings are even much higher at the edge of the city, indicating that there is a turning point where a certain number of orders is reached at which home deliveries save much more distance and emissions because deliveries to household clusters are much more efficient.

4.3. Total emissions

4.3.1. Hot temperatures

However, further emissions result from food chilling. These emissions are substantial and therefore need to be included in studies that analyze the effects of home delivery services. However, this differs very much by assumptions about the temperatures inside and outside the delivery vehicle. DIN8959 considers an ambient temperature of 30 °C - this is the first set of scenarios in the analysis and will be described in the following. The results for mild temperatures will be outlined subsequently.

In hot weather, vehicle energy consumption increases by more than three times in the REAL scenario and more than five times in the EXTR scenario if cooling during driving and standing is added to the energy required for driving only. Note that emissions caused by refrigeration result from both chilling while driving and when the vehicle is standing, as described in Chapter 3.5. Emissions add up to 17.08t when 3% of all shopping trips are substituted by home delivery. Only 22% of these emissions are produced by driving, while most of the emissions (64%) are generated by cooling during standing. In other words, cooling produces more than triple the emissions driving generates. Taking passenger transport savings into account, in the REAL scenario, total emissions increase by 8.77t CO_2 per day. In EXTR, POS-based home delivery emits 49.37t CO_2 per day, only 16% of which comes from driving. Hence, cooling causes more than five times more emissions than driving. The reason for this is that delivery tours comprise more stops and, thus, food cooling time during stops is much higher than in the realistic scenario. If the savings from passenger transport are taken into account, this results in a total increase of 21.20t of CO_2 in the EXTR scenario.

Because the amount of emissions is largely related to cooling during loading and unloading, the density of customers, the number of stops, and the total stop times determine the spatial distribution of emissions (cp. Fig. 11). According to our model, in zones with a higher population density, more households order groceries by home delivery. Thus, the number of stops (cf. Section 4.1) and standing times and, therefore, emissions from deliveries in more urban and more central zones are higher than those in the outskirts of the city. This also affects the total balance when including emissions from private shopping trips.

As Figs. 12 and 13 show, there are even some areas where a decrease in emissions can be observed. One cause of this spatial diversity is the higher mode share of pedestrians in the city center, which results in a higher substitution of shorter non-motorized shopping trips by delivery trucks. As mentioned earlier, vans stop more often in the most central zones due to higher population density. Thus, the emissions caused by cooling while standing are substantial. Therefore, POS-based home delivery produces more CO_2 in dense urban areas, aggravating traffic problems there, while savings occur at the edges of the city which have a lower population density and higher car usage. Areas with high VKT in delivery are also affected by high CO_2 emissions from freight transport. However, in some of these zones, total emissions decrease due to the high savings from shopping trips. These patterns are similar in both scenarios but more pronounced in EXTR.

4.3.2. Mild temperatures

For the scenarios that assume more moderate temperatures, energy consumption still increases by more than 2.5 times in the REAL case and more than 3 times in the EXTR scenario. While in the former case about 60% of the total emissions stem from chilling, in the latter case 70% of CO_2 emissions can be attributed to cooling. As could be expected, the magnitude of total freight emissions is much lower when assuming moderate weather. In the REAL scenario home delivery in Berlin is associated with 9.45 t of CO_2 per day which leads to a moderate increase of 1.14 t taking savings from passenger transport into account. In the EXTR case freight vehicles produce 25.57 t of CO_2 each day. This even leads to a moderate decrease in total emissions of −2.60 t CO_2 per day turning results of hot weather scenarios around. Since passenger transport savings are proportional to the percentage of substituted shopping trips this finding may be explained by bulk delivery which becomes relevant if more households are served in the same area (cf. 4.2). In this case, tour lengths and thereby emissions decrease (cf. Fig. 6).

Although the changes in global emissions are moderate, Figs. 14 and 15 show that not all areas in the city are similarly positively affected. As compared to hot weather scenarios emissions increase in REAL and EXTR scenarios in even more inner city areas and a decrease can be observed in more of the remote zones. This points to the same problem found before: although results seem to support POS-based home delivery of groceries in general, this could aggravate existing problems in inner-city urban areas while it might be helpful to substitute private shopping trips by home delivery in more remote and less dense areas.

5. Discussion and conclusion

5.1. Discussion

In this paper, we present a simulation-based methodology consisting mainly of a travel-demand and a delivery-tour generation model that

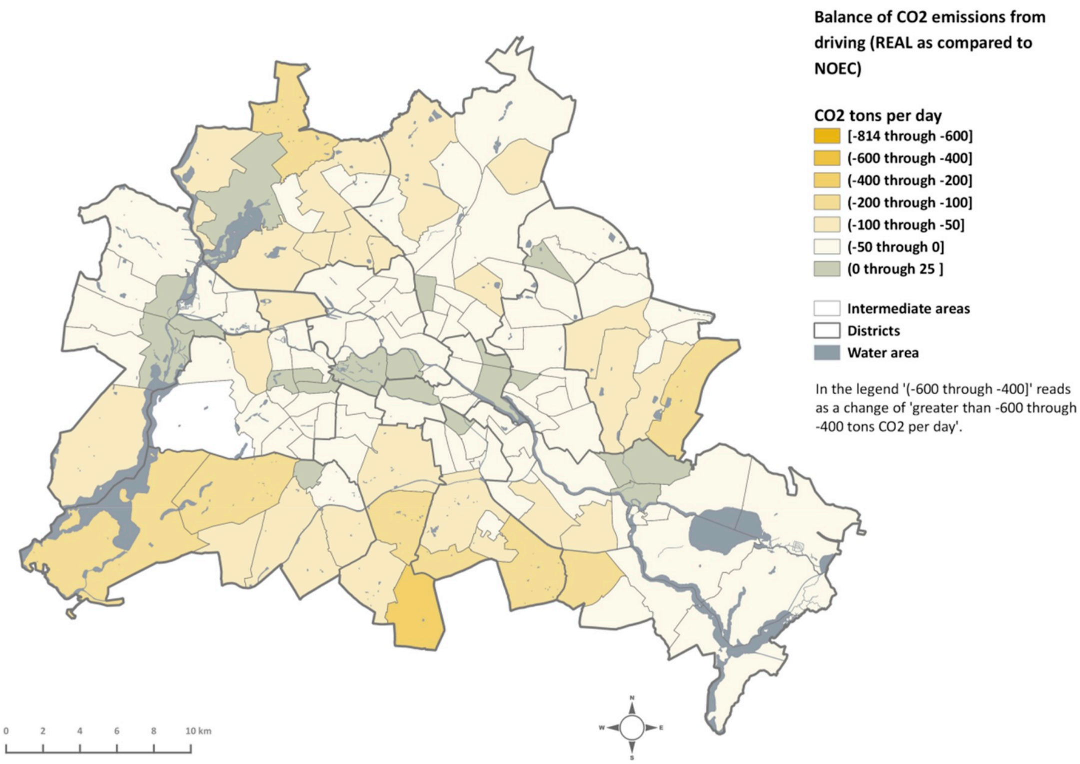

Fig. 9. Emissions balance of private shopping trip savings and POS-based home delivery tours from driving only (REAL scenario).

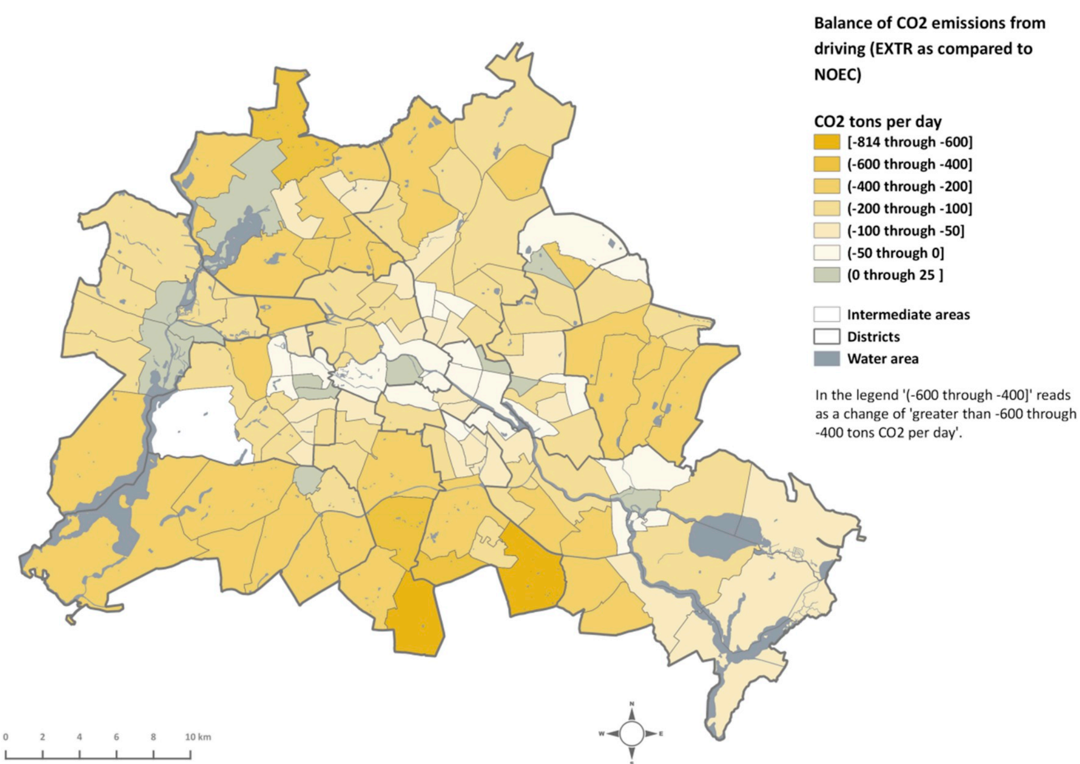

Fig. 10. Emissions balance of private shopping trip savings and POS-based home delivery tours from driving only (EXTR scenario).

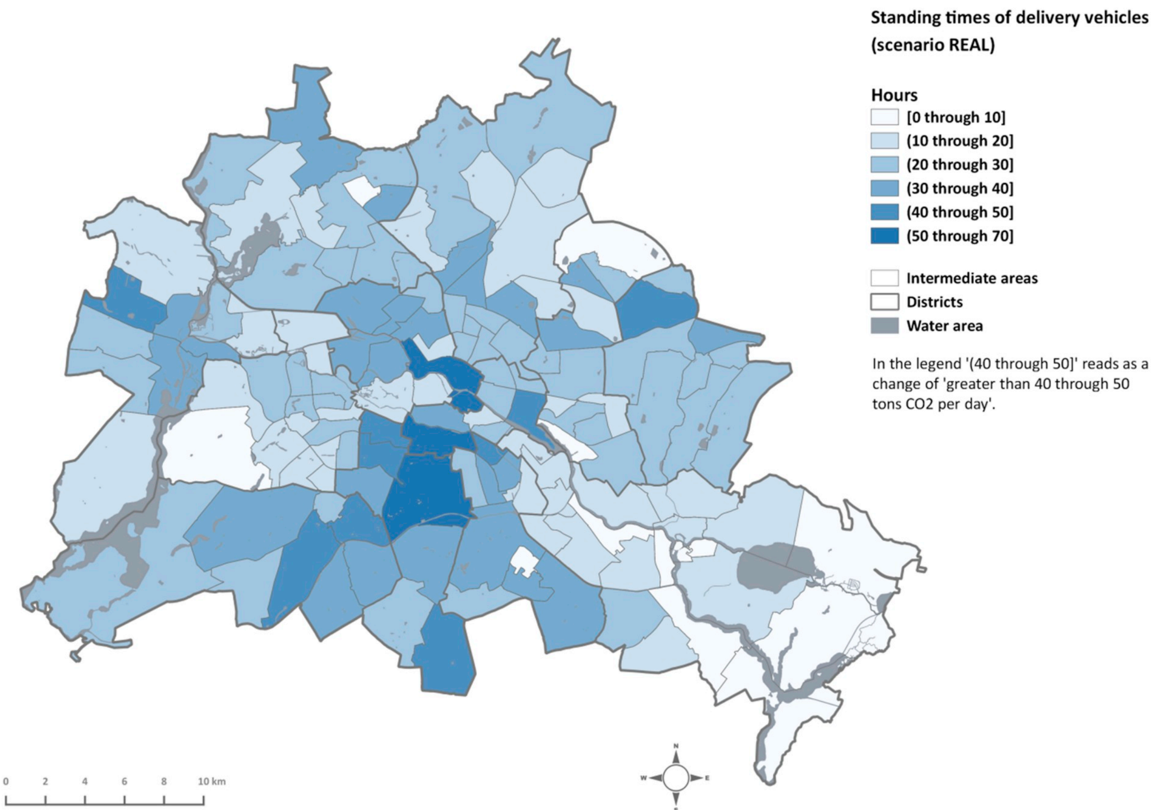

Fig. 11. Standing times for POS-based delivery tours (REAL scenario).

helps to assess these effects under different conditions. In order to test the tool, we introduced two scenarios, assuming different market shares of online grocery shopping and POS-based home delivery and compared the results with a base scenario without e-commerce. Additionally, we analyzed the effects of hot and mild air temperatures as this affects energy consumption and emissions. The results confirm our expectation that VKT in passenger transport decrease. VKT savings also affect shopping trips made with non-motorized modes, as people mostly go shopping for short-term items on foot, at least in Berlin. When taking freight transport into account, we can still see a total decrease in VKT. This is comparable to other studies, like that of Siikavirta et al. (2002), although the magnitude of distance savings (below 3–10%) in our study is much lower than in their study, which reported a reduction of VKT of more than 54% for home delivery scenarios. This is because Siikavirta et al. assume that all traditional shopping trips are replaced by home deliveries. The same applies to the study by Gonzalez-Feliu et al. (2012). For their 50% home delivery scenario, they found a reduction in VKT of 4.4% as compared to shopping at grocery stores only, which is much closer to the results we found. Our study also shows that distance savings are not spatially evenly distributed. Areas in the inner city are more negatively affected while at the city's edges, where delivery tours are longer but savings from private shopping trips are even higher, VKT decrease significantly. This pattern is more pronounced in the extreme scenario, confirming the efficiency of POS-based home delivery as compared to private shopping trips by car, particularly when the number of orders increases.

Similar is true for emissions and this result is also comparable to the findings of Siikavirta et al. (2002), who reported that home deliveries have substantial potential to save CO_2 emissions. The study by Wygonik (2014) found that passenger travel causes higher emissions of NO_X and particulate matter than home deliveries, but generates more CO_2 emissions, and this even for deliveries from regional warehouses. In her description of emission factors, the author also does not explicitly consider a cooling unit. Taking into account food cooling in our study, it becomes apparent that when assuming an ambient temperature of 30 °C e-groceries have a rather negative impact on the environment since emissions increase in total. This had not been considered by previous comparable studies since the emissions factors studied did not seem to consider a cooling unit. Thus, the emissions reported by such studies can be considered too low, and the potential of home delivery to reduce emissions must be treated with more caution. However, entering a realistic temperature of 13 °C into the calculation of emissions, POS-based home delivery of groceries seems to have the potential to truly save emissions if the same amount of private shopping trips is replaced. Nonetheless, this does not apply to all zones similarly. With the exception of Wygonik (2014), the above-mentioned studies did not investigate spatial implications. We found that in hot weather scenarios the increase of emissions mainly occurs in the inner city while several zones at the edge of Berlin even show a slight decrease in emissions. This pattern intensifies much more in the scenarios for milder weather where urban areas are negatively affected by emissions but much can be saved at the city's fringes. Wygonik (2014) similarly found the highest emission reduction potential of home deliveries in more rural areas. These results are concerning as it suggests that the traffic problems in the inner city will be further aggravated and points to a need for spatial regulation of home delivery services.

These findings should support policy makers with decision-making related to home delivery, encouraging them to consider not only emissions from transport itself but also from food cooling and other processes involved in energy transition. More specifically this calls for policies to support the introduction of more environmentally friendly delivery approaches and vehicle technologies, such as e-trucks and e-vans, not only for driving but also for food chilling. For this purpose, communication between policy makers, delivery companies, retailers, and truck manufacturers is required. Delivery companies should be incentivized to introduce low-emission vehicles into their fleets. Furthermore, a

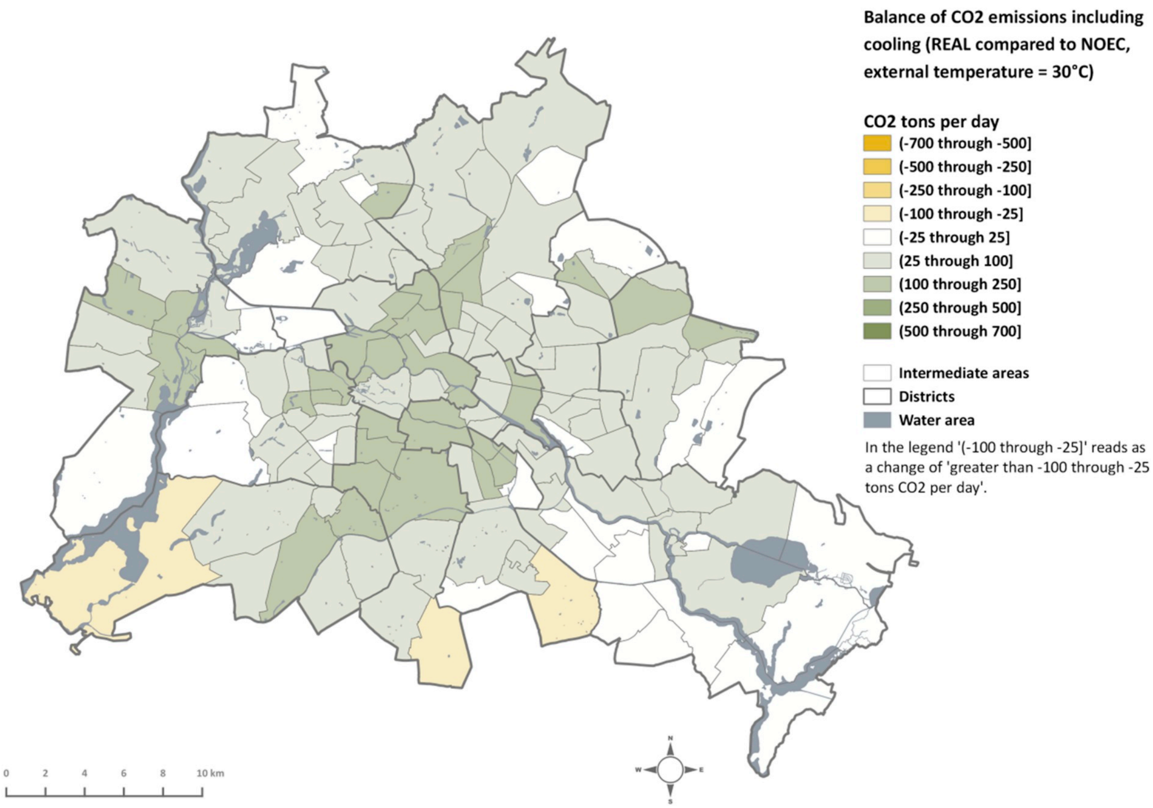

Fig. 12. Emissions balance of shopping trip savings and POS-based home deliveries including emissions caused by driving and food chilling (REAL scenario, hot).

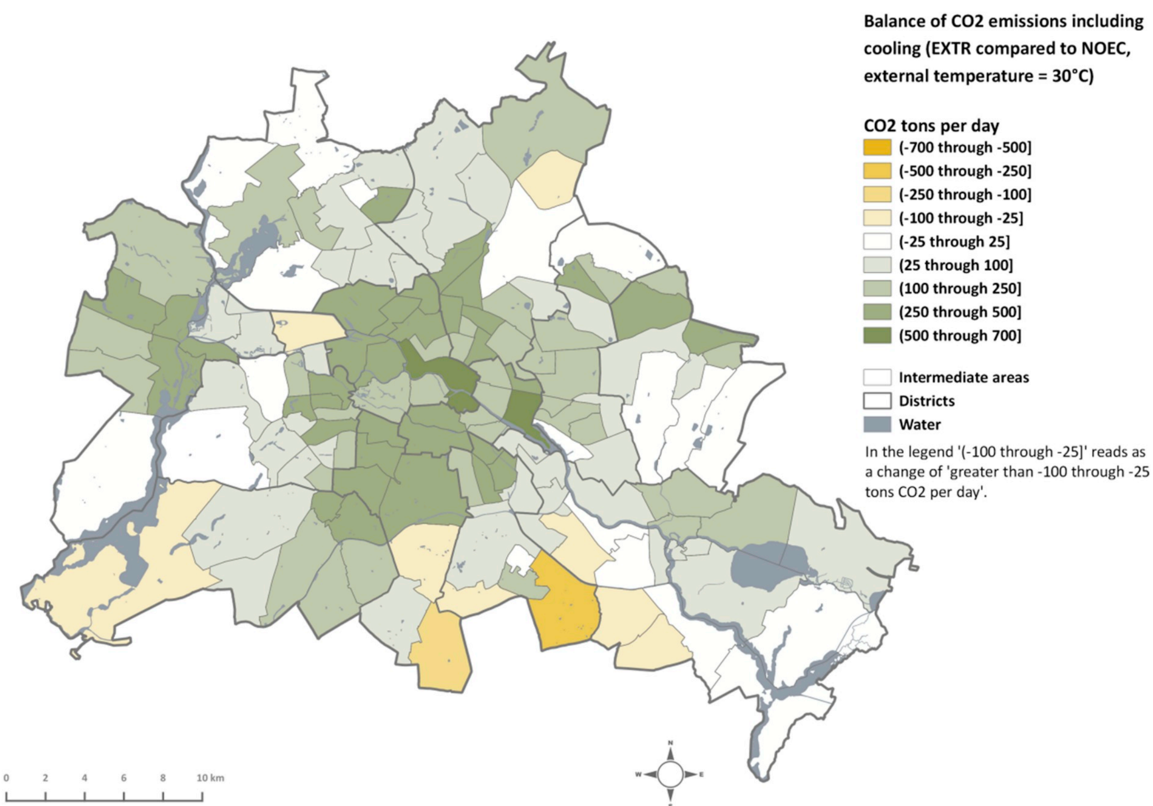

Fig. 13. Emissions balance of shopping trip savings and POS-based home deliveries including emissions caused by driving and food chilling (EXTR scenario, hot).

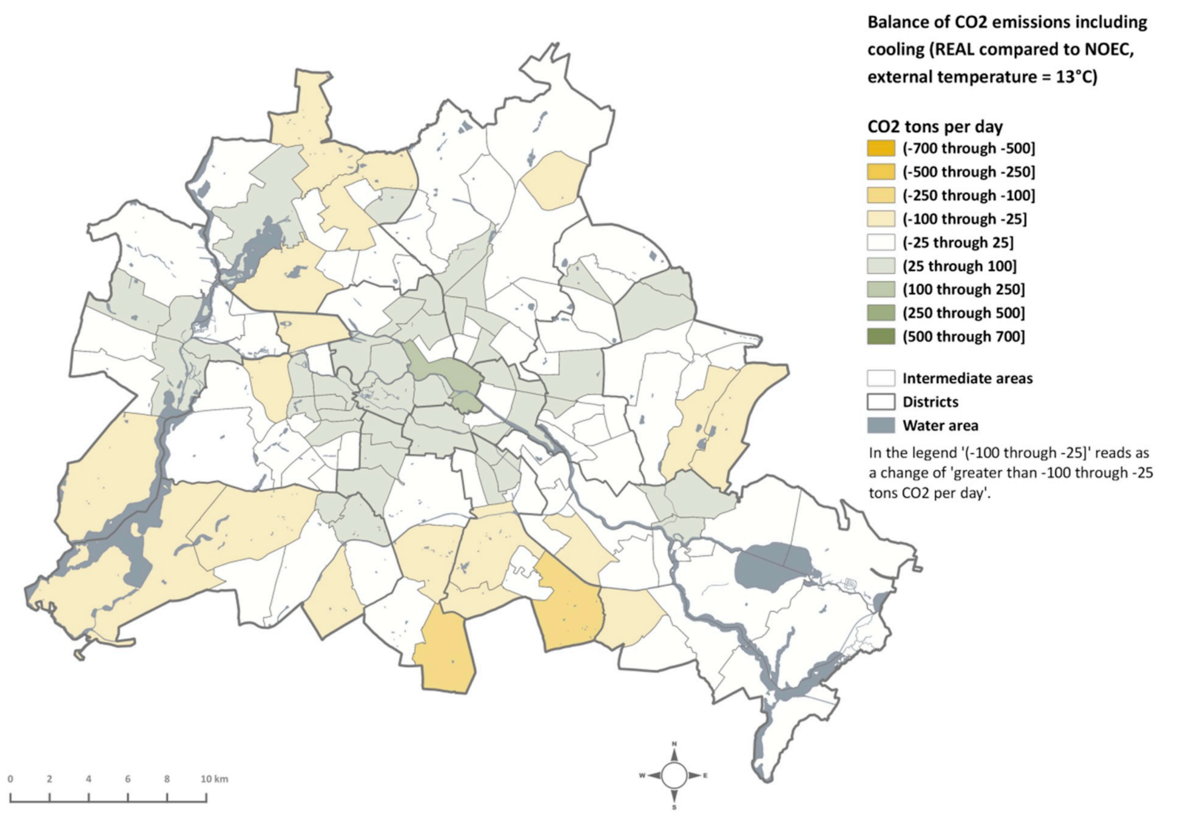

Fig. 14. Emissions balance of shopping trip savings and POS-based home deliveries including emissions caused by driving and food chilling (REAL scenario, mild).

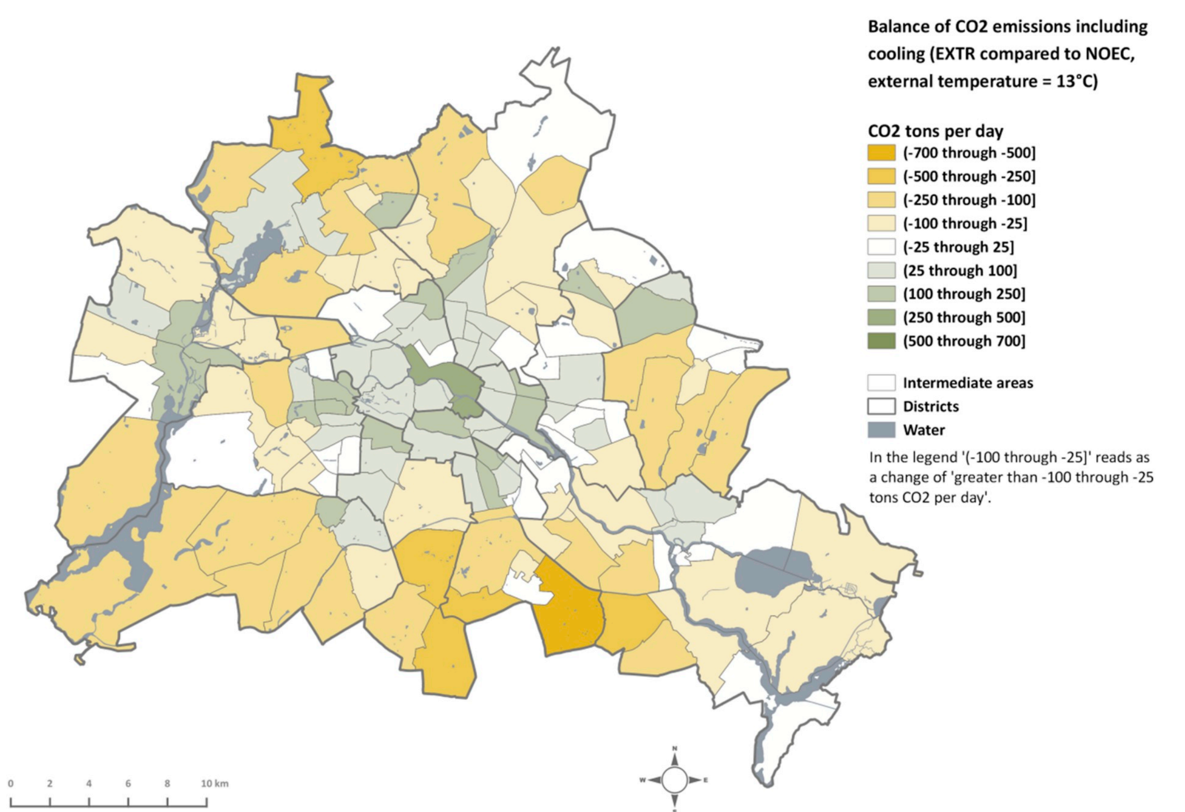

Fig. 15. Emissions balance of shopping trip savings and POS-based home deliveries including emissions caused by driving and food chilling (EXTR scenario, mild).

discussion should be started among stakeholders on how to promote vehicles with eutectic-based refrigeration, where cooling and the transport engine are decoupled. Such vehicles are an intermediate solution, rather than pure e-trucks, and thus more attractive for manufacturers in terms of cost effectiveness. Thereby, fleet lifecycles could be better utilized since the replacement of the engine and cooling unit would be separate. Since the highest share of cooling emissions is generated while the vehicle is standing, it is also important to think about how to make loading and unloading processes more efficient. Distributing groceries from micro hubs by cargo bikes could provide an alternative way to reduce emissions since cooling food during the last mile can be carried out passively using cool packs and sensors to track the temperature. Another approach is a more frequent use of pick-up points in residential neighborhoods, which would reduce distances for the consumer as compared to traditional shopping and the number of tour stops required for delivery services. Furthermore, we need a discussion about when and where transported food has to be chilled and where the required energy comes from. This also involves increasing awareness among consumers about more sustainable food consumption and the actual environmental impact of transport. A further important consideration is that the increasing traffic volume of delivery vehicles is causing problems in the use of road space, since such vehicles often halt in the second lane, at least in Berlin.

5.2. Limitations and future research

Throughout the paper, we made several assumptions that have a direct effect on the results of our simulations. First of all, home delivery in our scenarios is POS-based. Nowadays, many deliveries start at depots. This has implications for the results. Assuming that the density of depots in urban areas is lower than that of grocery stores actual delivery trip distances are likely much longer and when replacing shopping trips total distances and emissions might increase even more. Consequently, future research should include the replacement of depot-based home delivery by private shopping trips in the analysis. Second, we estimated that 10% of stores would close down due to the competition from home deliveries between 2015 and 2030 for the REAL scenario and 15% for the EXTR scenario. It is uncertain how brick-and-mortar stores will actually react. Researchers and experts believe that particularly large stores will be challenged (Suel & Polak, 2017). For Germany specifically, it is unclear how the market share of e-groceries will evolve. High growth rates suggest that the market share will be much larger in the future, but the recent problems of AmazonFresh contradict this (Hielscher, 2018). Experts predicted that the company would change the German grocery market. Instead, AmazonFresh is having problems establishing its services and is growing only at a very low rate. In order to show the possible effects for a range of situations, in our application, we consider a realistic and an extremely high market share for e-groceries in 2030. A further assumption was made about the number of shopping trips to be substituted based on very poor literature and data on the topic. We expect a much lower share of trips concerned as compared to the market share of 10%. This is due to several factors such as other delivery channels (e.g., pick-up points and driving) and due to the fact that in the near future only specific shopping trips and only a limited group of persons in rather urban areas will be concerned (Ernst & Young, 2017). The decrease in the number of stores has also some implications for emissions that we have not considered directly in the study or results. One could expect that average shopping trip distances to grocery stores increase in scenarios with fewer stores and thereby also emissions. Our results show that average distances of regular shopping trips are not significantly longer in REAL and EXTR scenarios. This might be due to the already very high density of outlets in Berlin. Furthermore, with fewer stores, total energy consumption decreases which is not considered in the balance of emissions since we only look at transport and not the whole energy sector. In this context it is important to note that it is unlikely that the number of products consumed decreased with fewer grocery stores, i.e., rather the energy would be needed somewhere else. Nonetheless, if assuming such products were stored in warehouses total energy consumption for cooling is likely lower than in several supermarkets. Such aspects should be considered in future more holistic studies.

To identify the shopping trips to be substituted, random sampling was used. Thus, our results do not indicate an overly strong reduction of car-related trips such as large-basket shopping trips, like in Suel and Polak (2017). There are no sources available that specify the kind of shopping trips that will be replaced by online shopping; the literature mainly reports on the volume of purchased goods and the potential of online shopping to replace such trips. There are two extreme scenarios, and several options in between: On the one hand, the weekly groceries are replaced by an online purchase with a well thought-out shopping list, making a trip to one or several stores superfluous. On the other, shoppers purchase single items that have been forgotten on a recent shopping trip online. In the paper, we assumed that online shopping replaces a typical visit to a grocery store, where some items are bought based on a shopping list and others are bought spontaneously. Accordingly, our results could be improved in accuracy by introducing a model that identifies the persons and trips that are likely to be substituted based on empirical data. Nevertheless, we do not expect the magnitude of vehicle kilometers saved to change very much. An important aspect not considered in most studies is the substitution effect of other activities. It is likely that during the time saved by the shopping trip a person performs additional leisure or other activities that require transport. Here, more research on shopping behavior could help to more realistically assess trip savings, including such effects that might further increase transport. For instance, think about going to the cinema or visiting a friend instead of performing a shopping trip while food is delivered to the home. True reductions in transport, energy consumption and emissions would only occur if one stayed at home or performed trips using other modes than private motorized ones. Further, it should be considered that the delivery of perishable goods such as cooled food requires at least one person to be at home to receive the goods; if not, the delivery would have to be made to refrigerated reception boxes. With the activity-based models used in our approach, such an analysis is possible. However, in order to implement this, more research is required to gather empirical data on the substitution rates between online shopping and other activities. Such studies are also very relevant for finding out the true net effect of cooling and home delivery since other activities might also require energy and generate emissions occurring from other trips or activities themselves.

Another limitation is that we have not addressed the way in which home deliveries are organized by the retail chains in detail. At the moment, there is no optimization, besides the planning of the tours and all existing stores with a floor space of over 700 square meters serve as a depot for delivery vehicles. In a business environment with fierce competition, which is the case for food retail in Germany, more cost-efficient structures can be expected to emerge, providing online shopping gains a significant market share. In particular, the assignment of households to stores in the case of e-commerce could be improved. In the REAL scenario, there is often only one vehicle at each store that makes a single tour per day. Thus, a concentration of stores that serve as a base for home deliveries for each retail chain can be expected. This would, in turn, entail longer vehicle trips and, thus, probably even more severe environmental consequences. Also, although the number of stores (five) to be considered for delivery to a household may seem quite low, it is reasonable for the focus on daily grocery shopping trips. As outlined above such analysis must also consider the delivery from depots.

Finally, the energy needed to run a refrigerator depends on many influences, and our calculation of the required cooling energy according to the German norm cannot account for all of these. One very important assumption is the ambient temperature which we assumed at 30 °C, as this is the standard temperature used in the corresponding norm DIN8959. Scenarios with a more moderate temperature (13 °C) still yielded an increase in emissions but on a much lower scale. In the EXTR scenario with moderate temperature, total emissions even decrease slightly. This implies that cooled grocery home deliveries have a more severe impact on the environment during summer and daytime. However, considering that in reality consumers shop for more specialized needs and, thus, might order from stores farther way, our results might still underestimate the actual traffic volume, and environmental consequences might be even more severe due to additional shopping activities. Future research should use empirically derived numbers for orders, for resulting cooling demand, and for required energy.

5.3. Conclusion

The proposed methodology allows the simulation of transport and its resulting emissions under alternative assumptions such as those mentioned above. It can support policy makers with decision-making related to the increasing volume of grocery home deliveries and to determine the actions necessary to prevent an even heavier burden on urban transport and reduce, or mitigate emissions. The following parameters can be changed by the user: population growth rate, decrease in the number of grocery stores, number of shopping trips to be substituted by home deliveries, number of stores serving as depots for delivery, the retail chain from which the customer orders (this is not necessarily the next store, but rather the one where shopping would be done instead of ordering online), and the duration of delivery tours as well as temperatures and configuration of cooling zones in delivery vehicles. These features make the framework a valuable instrument for assessing the effects of different policies under differing conditions on emissions caused by both passenger and freight transport in general, and the spatial distribution of transport and emissions.

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Appendix A. Calculation of emissions from food cooling

The cargo bay of the assumed vehicle has a length of 3300 mm, a width of 1860 mm, and a height of 1900 mm and is divided into three serial compartments of equal size. Each of these compartments is tempered differently. One of them is not cooled at all and has the ambient temperature; the other two are tempered to 0 °C (class D of the ATP Agreement) and −20 °C (class F of the ATP agreement) (ATP, 2018). With these values, the power needed for cooling the two compartments can be calculated. The calculation follows Möhlenkamp, Lemke, and Köhler (2017) on the basis of the norm DIN8959 This norm specifies the operational and environmental conditions for which temperature controlled vehicles for the transport of food have to be configured. The main numbers relevant for this paper are the ambient temperature (30 °C) the frequency and duration of opening the loading bay (4 times for 3 min each per hour) and the original formula from which Möhlenkamp et al. (2017) derived equation (1) which also considers vehicles with multiple temperature zones:

$$\dot{Q}_{T_{cool}} = 1.3 \cdot C_2 \cdot \left[k \cdot S \cdot (T_{ambient} - T_{cool}) + (C_1 \cdot V \cdot \Delta h) \Big/ 3.6 + \sum \dot{Q}_{interior\ wall} \right] \tag{1}$$

According to Möhlenkamp et al. (2017), equation (1) determines the thermal power that is needed to hold the temperature on the level T_{cool}.with

$$\dot{Q}_{interior\ wall} = k_{interior\ wall} \cdot S_{interior\ wall} \cdot \left(T_{other\ compartment} - T_{cool} \right) \tag{2}$$

specifying the loss of cold within the inner walls towards a warmer compartment. Here, only the negative effect, i.e., the temperature loss between two compartments is considered. The positive effect on the 0 °C compartment from the adjacent −20 °C compartment is neglected.

Variable	Explanation	Value
C_2	Parameter for the temperature increase due to opening of the loading bay (dimensionless)	2
k	Heat transmission coefficient of the external walls of the loading bay	$0.4 W/m^2K$
S	Surface of the compartment	$15.34\ m^2$
$T_{ambient}$	Ambient temperature according to ATP agreement	$30°C$
T_{cool}	Cooling temperature for the two cooled compartments	$0°C,\ -20°C$
C_1	Parameter for the temperature increase due to opening of the loading bay (dimensionless)	2.4
V	Volume of the compartment	$3.88 m^3$
Δh	Enthalpy difference between $T_{ambient}$ and T_{cool} at a relative air humidity of 0.6 $h_{t°C}$ is the enthalpy at the corresponding temperature t	$h_{30°C} = 71.2 KJ/kg \cdot 1.154 kg/m^3$ $h_{13°C} = 27.2 KJ/kg \cdot 1.230 kg/m^3$ $h_{9,5°C} = 20.7 KJ/kg \cdot 1.246 kg/m^3$ $h_{5°C} = 13.1 KJ/kg \cdot 1.267 kg/m^3$ $h_{0°C} = 5.6 KJ/kg \cdot 1.2912 kg/m^3$ $h_{-20°C} = -19.1 KJ/kg \cdot 1.3948 kg/m^3$
$k_{interior\ wall}$	Heat transmission coefficient of the interior walls of the loading bay	$1.5 W/m^2K$
$S_{interior\ wall}$	Surface of the interior wall	$3.53 m^2$

Thus, the thermal energy that is needed for both compartments is:

$\dot{Q}_{0°C} = 1395.55\ \ W$ and $\dot{Q}_{-20°C} = 1804.80\ \ W$

These values specify the power that is needed to maintain the temperatures in the two cooled compartments. This thermal power is different from the mechanical power which the compressor needs to provide. The latter is influenced by the refrigerant, the efficiency of the compressor, and the way in which the compressor is powered. The ratio of power consumption for the mechanical work of the compressor and the thermal power needed for cooling is called the coefficient of performance (*COP*) with. $COP = \dot{Q}_{T_{cool}} / W_{mech}$

There are hardly any public data available on the *COP* from the manufacturers of such vehicles. Thus, the approximations of Stelligwerf et al., 2018, are adopted. For the temperature difference between the ambient temperature and 0 °C, a *COP* of 1 is assumed, and for the difference to −20 °C the *COP* is 0.67. In a multicompartment vehicle, there is normally only one compressor that alternately supplies all compartments. For the example at hand, it is easier to assume that two compressors work in parallel to obtain the amount of power that is needed for cooling. Given the different *COP*s, the need for mechanical power is $W_{mech_{0^\circ C}} = 1395.55$ W and. $W_{mech_{-20^\circ C}} = 2693.73$ W

The compressor is assumed to be propelled by a direct belt drive. This means that it is driven by a belt from the crankshaft of the diesel engine. As Möhlenkamp et al. (2017) state, the energy demand of a diesel engine is around 200 g per kWh of mechanical work at the crankshaft. If the losses by the belt drive are neglected, then the combined demand for diesel per hour is[8] 1.17 l.

Thus, summing up the results and taking a speed of 20 km/h into account, the fuel demand is.

Parameter	Value
Fuel needed for driving per km	0.094 l
Fuel needed for cooling per km	0.050 l
Fuel needed for cooling per min if the vehicle stops for unloading	0.02 l

With an emission coefficient for diesel of 2.753 kg/l (Möhlenkamp et al., 2017), this translates into.

Parameter	Value
CO_2 emissions from driving per km	259 grams
CO_2 emissions from cooling per km	137 grams
CO_2 emissions from cooling per min if the vehicle stops for unloading	46 grams

Appendix B. Available online food options in Berlin[12]

Name	From depot or supermarket	Retail Chain	Delivery	Refri-gerated	Frozen
getnow[10]	From Metro wholesale stores	Cooperation of a startup and Metro	DHL Express on the same day	yes	unclear
Bringmeister[11]	not clear	EDEKA	Own vehicles, on the same day, 1 h time windows	yes	yes
real Drive	supermarkets	real	DHL, from next day	yes	yes
EDEKA 24	only dry food and thus not interesting for the study	EDEKA	parcel, delivery after one to three working days	no	no
Rewe	both	Rewe	Own vehicles, on the same day, 1 h time windows	yes	yes
Amazon fresh	depot		Own vehicles, on the same day,	yes	yes
mytime	depot		Parcel or express delivery by parcel company	yes	yes
AllyouneedFresh	depot		parcel, delivery after one or two working days	yes	no
Netto Markendiscount	only dry food and thus not interesting for the study	Netto Marken-discount	parcel, delivery after one to three working days	no	No
Food.de	Not clear, probably from wholesellers		Own vehicles, on the same day	yes	yes

[10] https://www.supermarktblog.com/2019/02/27/wie-funktioniert-getnow-und-wer-steckt-dahinter/.
[11] https://www.lebensmittel-lieferservice-check.de/online/bringmeister-de-online-supermarkt/.
[12] Found for the ZIP code of one of the authors (12,524, at the edge of Berlin) at http://finden.simplora.de/.

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[8] With a density of 0.82 kg/l at ambient temperature calculated with https://www.aqua-calc.com/calculate/volume-to-weight-temperature-dependent.

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