To what extent are CO\textsubscript{2} emissions from intra-urban shopping trips by cars affected by drivers’ travel behaviour and store location?

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Nr: 2016:03  
Editor: Hasan Fleyeh
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By

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This version 2016-04-07

Abstract:

Transportation is seen as one of the major sources of CO₂ pollutants nowadays. The impact of increased transport in retailing should not be underestimated. Most previous studies have focused on transportation and underlying trips, in general, while very few studies have addressed the specific affects that, for instance, intra-city shopping trips generate. Furthermore, most of the existing methods used to estimate emission are based on macro-data designed to generate national or regional inventory projections. There is a lack of studies using micro-data based methods that are able to distinguish between driver behaviour and the locational effects induced by shopping trips, which is an important precondition for energy efficient urban planning. The aim of this study is to implement a micro-data method to estimate and compare CO₂ emission induced by intra-urban car travelling to a retail destination of durable goods (DG), and non-durable goods (NDG). We estimate the emissions from aspects of travel behaviour and store location. The study is conducted by means of a case study in the city of Borlänge, where GPS tracking data on intra-urban car travel is collected from 250 households. We find that a behavioural change during a trip towards a CO₂ optimal travelling by car has the potential to decrease emission to 36% (DG), and to 25% (NDG) of the emissions induced by car-travelling shopping trips today. There is also a potential of reducing CO₂ emissions induced by intra-urban shopping trips due to poor location by 54%, and if the consumer selected the closest of 8 existing stores, the CO₂ emissions would be reduced by 37% of the current emission induced by NDG shopping trips.

Keywords: CO₂ emission; GPS trajectory; travel behaviour; store location; durable/non-durable goods
1. Introduction

Transportation of humans between destinations is seen as one of the major sources of CO\textsubscript{2} pollutants nowadays. It is estimated that the transport sector contributes 23 percent of the total CO\textsubscript{2} emissions in the world, and transportation that takes place on roads emits up to 75 percent of the transport-related emissions in developed countries (Schipper et al., 2009). In order to reduce the emission on roads with effective policies, it is essential to know accurately how much emission is generated and consequently understand its main driving factors. Most existing models for estimating emission are based on macro-data, designed to generate national or regional inventory projections (Jia et al., 2013), although there are a few models based on micro-data, designed to estimate emission in urban areas (Ando and Nishihori, 2012; Afotey et al., 2013). The micro-data models often consider that emissions are mainly influenced by travel behaviour and vehicle categories, while none of these models takes into account the impact from urban form, or destination location. Hence, in this study we examine emissions from the point of view of both travel behaviour and destination location in an urban area, which is in line with a long concern in the research literature.

A frequent aspect of concern in research is how the urban form itself affects the vehicle miles travelled (VMT) (e.g. Anas et al., 1998; Schwanen et al., 2001; Grazi et al., 2008; Zhao, 2013; Zhao and Pendlebury, 2014). If urban form is of importance, spatial planning to achieve an efficient urban form is believed to be a tool in reducing VMT, and therefore CO\textsubscript{2} emissions (Andersson, et al., 1996; Ewing, et al., 2003). Some studies suggest that there is a relationship between travel length and urban form (Grazi et al., 2008; van Acker and Witlox, 2010; Boarnet, 2011), while others have found that urban form has limited or varied impact on travel behaviour, and that other socio-economic factors might be of greater importance (Peng, 1997; Schwanen, et al., 2001; Scheiner and Holz-Rau, 2007). Besides that, many researchers argue that the location of frequent-visit destinations for many urban households is important for the travel length, and could provide significant information for city planners working with transforming the urban physical structure, by relocation planning towards less CO\textsubscript{2} emission induced by travelling.

Among quantitative studies in the field, most are based on questionnaires, whereby a group of people are asked about their travel behaviour. This is a conventional way of obtaining information on human travel activity, but it is problematic for several reasons when emphasis is put on CO\textsubscript{2} emissions induced by motorized vehicles. Firstly, it often provides only small data samples and is time-consuming. Secondly, to accurately estimate CO\textsubscript{2} emissions induced by, for instance, a car, it is important that the actual footprint generated by the vehicle should be recorded in detail, which is not the case with surveys. Thirdly, urban transportation is not straightforward, as it often involves many route choices, accelerations and decelerations, due to traffic jams, stop signs, and intersections. It is commonly recognized that motor vehicles pollute heavily during acceleration. However, with advancement in Global Positioning System technology (GPS), as well as Internet and Communication technology, we are afforded a massive fine-scale movement data regarding human travelling in cities. This data is typically adopted to examine human activity patterns (Reades, et al., 2009; Jia, et al., 2012a). In this context, the data not only contributes to accurately estimating CO\textsubscript{2} emissions induced by cars, but also enables detection of complex urban transportation involving many route choices, accelerations and decelerations, due to traffic jams, stop signs, intersections etc.
Therefore, GPS data on travelling offers new perspectives in conducting micro-data analysis of emission patterns in transportation.

The impact of CO$_2$ emissions due to transport in retailing should not be underestimated (e.g. Seebauer et al., 2015). For instance, the typical consumer in Great Britain in 2006 made some 220 shopping trips with a total length of 926 miles (DfT, 2006). Since cars were used for most of these trips, and the transport vehicle miles travelled is an important variable in determining CO$_2$ emissions, ways to reduce car use for shopping are sought (Cullinane, 2009). In a recent empirical study of CO$_2$ effects from transportation due to store location, it was concluded that restricting location choice for stores was not enough, and that available policy means therefore have limited effect on the absolute reduction of CO$_2$ emission induced by retail-related transportation (Seebauer et al., 2015). It was thus argued that behavioural changes among consumers were also needed.

In a recent empirical study using GPS tracking data, consumer behaviour travelling to shops was studied (Jia, et al., 2013). For shopping trips by car, it was shown that the median consumer makes around 1.5 trips per week to a shopping mall, and that the consumer mostly stops at one place during a shopping trip. Furthermore, it was shown that most shopping trips by car take the most environmental friendly route to the shopping mall. This implies that the consumer behavioural potential of reducing CO$_2$ emissions, induced by car travelling to a shopping mall, lies in the reduction of the number of trips taken per week, while the potential to reduce CO$_2$ emissions induced by alternative routing, or by decreasing multi-stop shopping, is insignificant. However, it should be noted that this study also involved inter-urban trips. It is likely that trips that only take place within a city have a wider range of alternative routes that can be taken, which implies the possibility that the shortest route is not selected is higher. That analysis was outside the scope for the study conducted by Jia et al. (2013).

In another recent study by Carling et al. (2013a), the impact of store location on CO$_2$ emission was investigated, and it was shown that car travelling to out-of-town shopping induced 60 percent more CO$_2$ emissions, compared to a down-town or edge-of-town location. In some contradiction to Seebauer et al. (2015), these results point in the direction that policy measures, such as relocation planning of city landmarks, could be a means for reducing car transport induced CO$_2$ emissions from shopping.

Although the studies by Jia et al. (2013) and Carling et al. (2013) examined emission patterns from the aspects of travel behaviour and store location, respectively, the results refer mostly to shopping of durable goods (DG). There is no differentiation between different types of products, or the two major types of shopping establishments: those dominated by sales of durable goods (clothes, consumer electronics, etc.), and those dominated by sales of non-durable goods. We also note that there seems to be a weak relationship between shopping trips to establishments dominated by sales of non-durable (NDG) and establishments dominated by sales of durable goods (DG) (also compare with Seebauer et al. (2015) elasticities on substitution demand between groceries and all other products). Despite this, little seems to be known regarding the emission patterns induced by intra-urban travel behaviour and store location, with respect to DG and NDG shopping.

Against this background, the aim of this study is to implement a micro-data method to estimate the CO$_2$ emission induced by intra-urban car travelling to a retail destination of non-durable and durable goods. We estimate the emissions from the aspects of travel behaviour and store location. In doing
so, we also compare the pollution patterns induced by durable and non-durable shopping trips. The study is conducted by means of a case study in the city of Borlänge, where GPS tracking data on intra-urban car travel is collected from 250 households. Using GPS trajectory data, we first identify and study travel behaviour patterns for all types of intra-urban trips, and then we extract the DG and the NDG trips, by using the parking lots at two large shopping establishments; we then study the travel behaviour for these shopping trips separately. We have selected two retail establishments that are equally accessible to the consumers in the city. Travel behaviour is observed in terms of travel time, travel speed, travel turns, travel halts and travel route, which is then also used to calculate the CO₂ emission, with the Ogushi’s model (Ogushi et al., 2002). Finally, we carry out a counter-factual analysis with three experiments, which aims to enable the understanding of the store location effect on CO₂ emissions, induced by intra-urban car travelling.

The remaining article is structured as follows. We introduce the datasets and methods used to calculate CO₂ emissions in Section 2. In Section 3, the empirical results are reported. The article ends with a concluding discussion in Section 4.

2. Data and methods

2.1 Data

The city of Borlänge has approx. 45 000 inhabitants. Borlänge is the labour market and retail centre of the region and there are high levels of inflow of both commuters and shoppers to the city. About 25 percent of the population lives in multi-detached houses, mostly in the centre of the city. However, the majority of the population lives in single-detached houses in suburban neighbourhoods. Most shopping by the population in Borlänge takes place in the city. One important reason for this is that the city is remotely located, vis-a-vis other larger cities. The city is located 220 kilometres to the north-west of the Swedish capital, Stockholm, making the inter-urban transportation cost significant. We believe that the selected case can be seen as a typical solitary regional centre, where the suburban population is fairly dependent on the use of a car in their lives.

The datasets used in this study are shown in Figures 1a and b. GPS trip data is extracted from the continuous GPS trajectory data, which was collected by 258 volunteers in Borlänge (please see Jia et al., 2012b, for the detailed technique for extracting volunteer trips). The volunteers were recruited from four large sports associations with high compliance and participation rate, and the data collecting time period lasted from 29 March to 15 May, 2011. GPS trip data contains a total number of 6241 volunteer trips, and each trip contains a sequence of time-ordered locations, including information of longitude (x), latitude (y), time (t) and velocity (v). Volunteer trips cover a total length of 61 219 km, and have an average length of 10 km, which roughly approximates the diameter of the downtown region. As can be seen in Figure 1b, these trips cover the vast majority of streets in the city.
Figure 1: Local street network, location of case shopping establishments (a) and volunteers’ home location and routes for all trips in Borlänge city.

The street network data is freely obtained from OpenStreetMap project, which contains a total number of 44,650 street segments, with a length of 18,420 km in the province of Dalarna. Note that the street network is topologically connected for ease of navigation. The typically allowed speed limit in the city is 40 kilometres per hour. Streets with the lower speed limits are often located in the city’s residential and down-town areas. The maximal speed limit in the city is 110 kilometres per hour, found on only a small fraction of the roads. The typical speed limit on highways in the city is 70-80 kilometres per hour. As can be seen from Figure 1a, these highways go through the central parts of the city.

To study the driving behaviour of the consumer during shopping trips, we identify stops and starts on the parking lots (see Figure 1a) at two shopping destinations that are the main establishments for DG (Kupolen), and NDG (ICA Maxi) in the city of Borlänge. These two establishments are selected for a couple of reasons. They are the largest shopping establishments, both located at the edge-of-town of the city and both with parking lots that are well-defined spatially, and easy to identify. In addition, we obtained and used the residential locations of the volunteers (see Figure 1b), since a few of the volunteers did not provide their home locations for privacy reasons. The locations of the volunteers’ residences are spatially correlated with the distribution of the underlying urban population. Also shown on the map are the other NDG stores located in the city, which we have used to conduct a counterfactual analysis in the study.

CO$_2$ emission is considered as the main causal factor of global warming and consequent climate change, which has continued to increase, although at a slower rate of growth for most countries (Jos
et al., 2014). Most of this is related to road transport using the combustion engine (Stead, 1999). Important for the CO₂ emissions are, of course, how energy-efficient the combustion process in the vehicle is. Besides that, factors such as trip-length, speed, and acceleration/deceleration are also important factors that affect the CO₂ emissions of a trip. Hence, a trip emits less amounts of CO₂ if it is energy-efficient, taking into account several factors of the car driver’s behaviour. To evaluate the CO₂ emission from car driver behaviour for each shopping trip, we use the energy-efficiency of the whole trip as a proxy. In the research literature, there are several models that can be used to estimate CO₂ emission, such as the very simple models of average speed (Redsell et al., 1988) and the travel length model (Stead 1999; Carling et al., 2013b); the more complex site specific macro-scale models of the MOVES model, EMFAC Model, COPERT model, LIISA model, and the German Traffic Emissions Estimation Model (Jia et al., 2013); the micro-scale instantaneous emission models of the CMEM model (Barth et al., 2004), and the eco-driving model (Ando and Nishihori, 2012). In this study, we adopt Oguchi’s model (2002), since it provides a reasonable balance between simplicity with coarse estimation and complexity requiring more data input.

Oguchi’s model (2002) is an empirically evaluated model, belonging to the micro-scale instantaneous family of models, and it is well-suited for using the GPS tracking data collected by petrol-powered vehicles, as is the case in this study. Specifically, it considers the instantaneous working conditions of an on-road vehicle, such as speed change in terms of acceleration or deceleration, trip duration, and trip length. As noted in Eq. (1), where KC is the emission coefficient with the value of 0.002322 kg(CO₂)/cc(gasoline), T is the trip duration (in seconds), D is the trip length (in meters), vi is the vehicle speed at the ith GPS location, an indicator value of 0 (vi > vi-1) and 1 (vi <= vi-1), and E is the total estimated CO₂ emission in kilograms. Applying this model to the trips, we obtain the estimated emission for each trip. Further, the emission for each trip is standardized by dividing it with its length.

\[ E(Trip) = K_c \ast \left( 0.3T + 0.028D + 0.056 \sum_{i=2}^{n} \delta_i \ast (v_i^2 - v_{i-1}^2) \right) \]  

From the entire number of trips that the GPS tracking devices generated, we initially extracted a total number of 4923 intra-city trips. As shown in Table 1, almost all volunteers (247) make at least one trip by car during the investigated period. These trips act as a benchmark for comparison with shopping trips in the study. We then continue to identify the NDG and DG shopping trips from all intra-city trips. This was done in three steps. The first step is to conduct a spatial filtering operation, which uses a point in polygon analysis to extract trips going to or coming from the parking lots. In order to mitigate the effect of data uncertainty due to GPS signals, the parking lot area is buffered with 10 meters, to allow more potential trips to be included. The second step is to refine the shopping trips, according to the opening hours of the stores, and those trips are removed if their visiting time falls outside the opening hours. The third step is to remove the shopping trips of employees, whose purpose is working not shopping. An employee is identified if he/she has trips to the shopping stores before the opening, but close to the opening hour, for up to five days per week during the study period. By applying these techniques to the intra-city trips, we obtained 291 NDG shopping trips with a total travel length of 1259 km, and 127 DG shopping trips with a total travel length of 436 km.

In order to calculate CO₂ emissions for alternative routes as a complement to observed routes, we follow the procedure developed by Carling et al. (2013). To calculate the CO₂ emission in the street
network induced by car driving, we have used the GPS data of car driving on the streets in Borlänge. Ogushi’s model (2002) is implemented to calculate the emissions between all positional recordings of a trip. All emission values during all the registered trips taken have then been summarized to the street segments on which each positional recording was registered. The total emissions on a street segment were then normalized by the number of cars passing the street segment. To calculate the emission during a trip is simply a matter of summarizing the emissions on the street segments where a trip is conducted.

3. Empirical Analysis

3.1 Descriptive summary of intra-urban travel behaviour

A common feature of many transports is that the trip lengths are highly skewed and follow an exponential distribution (Liang et al., 2011). It is found in this study that both the trip length and duration fit very well to an exponential distribution for trips in general and trips for DG as well as NDG shopping (Figure 2). The fact that the travel behaviour is aligned to common observations elsewhere is important from the point of view of generalising the results.

![Figure 2](image_url)

Figure 2: The distribution of observed intra-urban trip length and duration for a) all trips, and b) DG and NDG trips.

With regard to the speed values during all trips, it is found that a large share, 54.21%, of the GPS recorded locations during a trip, have velocity values of less than 1 km/h (Figure 3a). This means that the car for a large part of an intra-urban trip in general, more or less, is standing still and the engine is idling. The observed distribution for all trips can be approximated by a Gaussian mixture distribution with three peak values, including 0.23 km/h, with mixing proportion of 52%, 27.51 km/h, with mixing proportion of 22%, and 49.24 km/h, with mixing proportion of 26% (Figure 3a). Regarding the distribution of speed values for the DG and NDG trips, it is observed that only a small fraction of the positioning recordings indicate speeds below 1 km/h during a trip. In the case of NDG trips, 3.35% of positional recordings have a speed of less than 1 km/h, and for the DG trips, the share is 2.93% (Figure 3b). This small fraction of low-speed recordings is in contrast to the findings regarding all trips, and suggests that shopping trips tend to be more energy-efficient than other types of trips. It is found that a Gaussian mixture distribution with three peak values, respectively, can be used to model the speed distributions (Figure 3b). Specifically, NDG trips are modelled as 21.62 km/h, with a mixing proportion of 42%, 49.58 km/h, with a mixing proportion of 43%, and 64.03 km/h, with a mixing proportion of 15%, and DG trips are modelled as 19.18 km/h, with a mixing proportion of...
33%, and 47.24 km/h, with a mixing proportion of 67%. The results indicate that DG trips generally have a higher concentration of travel speed than corresponding trips on average.

![Graph showing the distribution of observed intra-urban trip speeds for DG and NDG trips.](image)

Figure 3: The distribution of observed intra-urban trip speeds for a) all trips and b) DG and NDG trips.

It should be noted that the typically allowed speed in the city is 40 km/h, mostly located either on streets in the residential areas, or in the city centre. Higher speeds are allowed on highways linking the different parts of the city. The most common speed limit on highways is 70 and 80 km/h. Since a large proportion of the shopping trips have speeds well above 40 km/h, it indicates that most of the trips take place on the intra-urban highways. This is in sharp contrast with trips in general. The large proportion of speeds significantly below the typically allowed speed limit indicates that trips for a large proportion of their length take place in residential or down-town areas with low speed limits, or/and that the travel behaviour of volunteers is constrained by the urban traffic context on larger and smaller roads where they have taken place.

Table 1: Basic descriptive statistics on intra-urban car travel behaviour in Borlänge.

<table>
<thead>
<tr>
<th>Purpose</th>
<th># of trips</th>
<th># of volunteers</th>
<th>Avg. no. of trips</th>
<th>Avg. no. of stops per trip</th>
<th>Avg. time (min)</th>
<th>Median time (min)</th>
<th>Avg. length (km)</th>
<th>Median length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG shopping</td>
<td>127</td>
<td>74</td>
<td>1.72</td>
<td>0.35</td>
<td>7.0</td>
<td>6.0</td>
<td>3.43</td>
<td>3.18</td>
</tr>
<tr>
<td>NDG shopping</td>
<td>291</td>
<td>115</td>
<td>2.53</td>
<td>0.42</td>
<td>8.4</td>
<td>6.5</td>
<td>4.33</td>
<td>3.43</td>
</tr>
<tr>
<td>All trips</td>
<td>4923</td>
<td>247</td>
<td>19.93</td>
<td>0.38</td>
<td>9.9</td>
<td>6.0</td>
<td>4.25</td>
<td>3.28</td>
</tr>
</tbody>
</table>

Table 1 gives some summary statistics about the intra-urban trips studied. We observe that the shopping trip for purchasing non-durable goods (NDG) is more than twice as common and involves 40 percent more volunteers than shopping trips for purchasing durables (DG), during the study period. The table further shows that most trips include only one stop, implying that multi-purpose shopping, which includes driving between different stores, is rather sporadic.

Further, the average trip in general is 4.25 km, and NDG trips are somewhat longer in length, while DG trips are significantly shorter. Not surprisingly, the median distance diverges from the average distance, illustrating the skewed distribution of travel distances of the trips. The difference is even less when the median is compared. However, it is still significant, since the median length for a NDG trip is 8 percent longer than for a DG trip. The patterns are similar when the trip duration is compared.

### 3.2 CO₂ emissions induced by intra-urban trips by car
Table 2 shows the CO₂ emissions per trip induced by intra-urban travel. It shows that trips in general, on average, pollute more than shopping trips, even though on average they are shorter than NDG trips. It can also be observed that NDG trips pollute on average 24% more and on the median 7% more, than DG trips. These differences are approximately similar to the differences in travel length and duration. Note that that there is a tendency for the difference in CO₂ emissions between NDG and DG trips to be greater among the shortest and longest trips. A DG trip among the 5 % shortest trips induces just 61% emission, and for the 5 % longest trips it induces 71 % of the emission of a comparable NDG trip. In relation to trips in general, it is obvious that the level of emissions is more similar to DG trips for the shortest distances, while levels of emission become more similar to NDG trips for longer distances. These differences in emission levels can be affected especially by speed changes during the trip, as well as high traffic levels that increase travel time. We therefore first turn to an analysis of the importance of average component speed changes, duration and length of the trip.

### Table 2: CO₂ emissions (in kg) induced by an intra-urban trip with a car.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Percentile</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>DG shopping</td>
<td>0.101</td>
<td>0.304</td>
</tr>
<tr>
<td>NDG shopping</td>
<td>0.165</td>
<td>0.326</td>
</tr>
<tr>
<td>All trips</td>
<td>0.103</td>
<td>0.307</td>
</tr>
</tbody>
</table>

In Figure 4, the importance of the emission components during a trip is shown. It shows that in most cases, trip duration is by far the most important factor for inducing CO₂ emissions. DG trips diverge somewhat from trips in general and from NDG trips, since neither trip length nor speed change seems to make any significant contribution to the CO₂ emissions, while for trips in general, and NDG trips especially, the length is of importance in at least 25 percent of cases. Since the duration of a trip partly depends on length, and partly on the traffic situation, we now turn to an analysis of temporal emission patterns.

![Figure 4: The importance of duration, length and speed change contribution to CO₂ emissions, from intra-urban car driving with different purposes.](image-url)
We observe the total temporal emission pattern, for Monday to Friday (weekdays) and Saturday and Sunday (weekends) (Figure 3a). For trips in general, during weekdays, two emission peaks are observed around seven o’clock in the morning and four o’clock in the afternoon, respectively. In both cases, the time corresponds with travel to and from work. During weekends, the emission values last from ten o’clock in the morning to five o’clock in the afternoon, with small fluctuations, which is the time span when shops are open at weekends and when leisure activities normally take place. These findings, therefore, coincide well with the rhythm of local residents’ life, and thus may be useful for sustainable location planning.

The temporal total emission patterns for the DG and NDG trips are also presented in Figure 3a. As shown in the figure, the emissions from NDG trips at weekdays tend to have two emission peaks, observed around three o’clock in the afternoon, and six and seven o’clock in the evening, while DG trips are more likely to be spread out evenly from two o’clock to five o’clock in the afternoon. For emissions at weekends, NDG trips are more likely to have two earlier emission peaks, around twelve o’clock and between four and five o’clock in the afternoon, while DG trips are more likely to be
concentrated on one peak period, around three o’clock in the afternoon. From this, it seems that DG trips demonstrate temporally more evenly distributed emission patterns for both weekday and weekend, and they are less (approx. 10 times) compared to the total emissions. We can further conclude that emissions from shopping trips partly have another daily temporality pattern when compared to trips in general. However, note that the peak for emissions induced by NDG trips takes place at times when the largest emission peak from all trips occurs, implying that the volume of traffic has more cars on the roads when these trips are made. However, that is not the case. Figure 3b shows the temporal emissions patterns per trip. Observations indicate that there is no observed trip. The observation that can be made is that a car seems to pollute at the same rate, no matter what time of day, day of the week or purpose of the trip. Variations over time seem to be random. Therefore, we conclude that the temporal emission patterns that can be observed are related to the number of trips taken, but that does not affect the emissions resulting from a single trip.

To control for emissions related to trip length, we calculate the CO₂ emissions per kilometre of travel. The result is shown in Table 3. Note that the average emission value reported here is in line with values reported previously for a Swedish private car, which guarantees the plausibility of the method to calculate the CO₂ emission. With regard to DG and NDG shopping trips, it can be observed that the differences in emission levels are small (generally around 2 %), in most cases across the trip length distribution. Not surprisingly, the differences in driver behaviour from a CO₂ emission point of view during a DG and a NDG trip per kilometre seem to be insignificant. When the shopping trips are compared to trips in general, the differences are somewhat greater (around 8 %, on average). A possible explanation for this is that a larger part of such trips takes place on arterial roads in the central parts of the city, with streets organised in city blocks, and with no highway or marked through way, implying a less CO₂ efficient driving behaviour. However, the overall conclusion, so far, is that the dominating driver behaviour factors for CO₂ emission levels is the length and duration of the trip, and how frequent the activity is that generates the trip.

Table 3: CO₂ emissions (in kg) per kilometre travelled, induced by an intra-urban trip by car.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Percentile</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>DG shopping</td>
<td>0.176</td>
<td>0.194</td>
</tr>
<tr>
<td>NDG shopping</td>
<td>0.171</td>
<td>0.176</td>
</tr>
<tr>
<td>All trips</td>
<td>0.173</td>
<td>0.200</td>
</tr>
</tbody>
</table>

As a last analysis of the CO₂ emissions induced by driver behaviour, we investigate how well-chosen the actual route is, from a CO₂ emission point of view during the shopping trips. In a previous study, it was reported that the length of an actual trip is highly correlated with that of the shortest route, with R square value as high as 0.96, using a Pearson correlation (Jia et al., 2013). However, the trips in that study included both intra-urban and inter-urban movements by car. In this study, using the Pearson correlation, we find a moderate correlation with an R square value of 0.532, between observed DG trips and the shortest route, between point of origin for the trip and its destination. We find a weak correlation with an R square value of 0.274, between observed NDG trips and the shortest route, between point of origin for the trip and its destination. The moderate and weak statistical relationship between optimal and observed routes in intra-urban trips indicates that the trips include detours and consequently are not environmental efficient.
Table 4: CO₂ emissions (in kg) induced by observed intra-urban trip and shortest intra-urban route on the road network, between place of origin for the trip and the DG and NDG establishment, by car.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Observed mean travel distance</th>
<th>Shortest mean travel distance</th>
<th>Observed median travel distance</th>
<th>Shortest median travel distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG shopping</td>
<td>0.587</td>
<td>0.217</td>
<td>0.555</td>
<td>0.212</td>
</tr>
<tr>
<td>NDG shopping</td>
<td>0.726</td>
<td>0.224</td>
<td>0.594</td>
<td>0.182</td>
</tr>
</tbody>
</table>

Table 4 reports the average and median observed CO₂ emissions during shopping trips and the CO₂ emissions, if the most environmentally efficient route to the establishment was selected. The table shows that a NDG trip, on average, produces 0.7 kg of emission during a trip, which would be reduced to 0.2 kg, if the shortest route was selected. The same pattern can be observed for DG trips. It seems that the potential for reducing CO₂ emissions during intra-urban shopping trips is significant, since the reductions that an environmentally optimal trip would result in 36% (DG), and 25% (NDG) of current pollution levels. When the DG and NDG trips are compared, the difference in CO₂ emission levels between the observed route and the shortest route for the trip shows that what seems to be an environmental disadvantaged location of the NDG store is actually not the case. In this sense, we now have a mean to measure, and an idea of the importance of locational land-mark factor in the city of Borlänge. However, the empirical results, so far, are based only on those members of the population making the DG and NDG shopping trips. In the following section, we will focus on the total population.

3.3 Counterfactual analysis of the location effect

It is common knowledge that buying the same product at stores located in different areas implies different CO₂ emissions (Seebauer et al., 2015). Hence, apart from the analysis on emission patterns from the aspect of travel behaviour above, in this section, we intend to further examine the impact from the location of NDG/DG stores on CO₂ emission patterns. To achieve this aim, we adopt the method of counter-factual analysis (Carling et al., 2013a). In the counter-factual analysis, we first assume that a trip starts from the volunteer’s residence. We further assume that each volunteer takes the shortest and most environmental friendly route to the DG or NDG shopping establishment, as in the case studies above. This assumption is necessary, in order to allow for the large impact on CO₂ emissions that driver behaviour which implies detours have on the effects. Other driver behaviour effects (such as, speed and speed changes) on CO₂ emissions are internalized in the emission values on the street segments in the city. Not all Borlänge residents are included in the analysis, due to the difficulty of identifying car-owning residents. Instead, the household locations of 250 volunteers and their observed trip frequencies are implemented in the counter-factual analysis. Our experiments are organised in three experiments.

In the first counter-factual experiment (see Table 5 for results), it is assumed that each volunteer makes only one shortest route from his/her home to each of the shopping stores. Hence, there are a total number of 250 trips induced by each store, and the information, including average number of turns, average distance and average CO₂ emissions, and is consequently derived. In our second experiment (see Table 6 for results), we relax the assumption that each volunteer conducts one trip. Instead, we weight each NDG/DG shopper with the number of observed shopping trips. Note that the volunteers who actually do not conduct a trip during the study period still are assumed to make
one and are thus assigned weight 1. This implies a more realistic modelling of the volunteers’ shopping behaviour. In total, we then result in 296 trips to the DG store, and 404 trips to the NDG store. The results in Tables 5 and 6 are similar. We can observe that there is just a marginal difference (1.6%) in emissions, on average, from traveling to DG or NDG stores, if the route travelled was the shortest. It can therefore be concluded that the differences in CO₂ emission induced by shopping trips, in this case, is by far related to behaviour differences in the population, with regard to how frequent the shopping activity is, and route choice. Both establishments have equal accessibility to the population and the location effect is, therefore, in this case, of insignificant importance with regard to differences in CO₂ emissions induced by car trips.

Table 5: Counter-factual analysis of CO₂ emissions induced by 250 volunteers making one car trip along the shortest route to a DG and a NDG store in Borlänge. Note: standard deviation is in parentheses.

<table>
<thead>
<tr>
<th>Destination of the shopping trip</th>
<th># of trips</th>
<th>Avg. # of turns</th>
<th>Avg. distance (km)</th>
<th>Avg. CO₂ emissions (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG</td>
<td>250</td>
<td>54</td>
<td>4.12</td>
<td>0.30 (0.13)</td>
</tr>
<tr>
<td>NDG</td>
<td>250</td>
<td>55</td>
<td>4.23</td>
<td>0.29 (0.17)</td>
</tr>
</tbody>
</table>

Table 6: Counter-factual analysis of CO₂ emissions induced by 250 volunteers weighted by at least one trip, or by the observed number of shopping trips along the shortest route to a DG and a NDG store in Borlänge. Note: standard deviation is in parentheses.

<table>
<thead>
<tr>
<th>Destination of the shopping trip</th>
<th># of trips</th>
<th>Avg. # of turns</th>
<th>Avg. distance (km)</th>
<th>Avg. CO₂ emissions (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG</td>
<td>296</td>
<td>55</td>
<td>4.10</td>
<td>0.30 (0.13)</td>
</tr>
<tr>
<td>NDG</td>
<td>404</td>
<td>53</td>
<td>4.09</td>
<td>0.28 (0.17)</td>
</tr>
</tbody>
</table>

Table 7: Counter-factual analysis of CO₂ emissions induced by 250 volunteers making one car trip along the shortest route to an inaccessibly located NDG store and to the closest of one of the 8 existing NDG stores in Borlänge. Note: standard deviation is in parentheses.

<table>
<thead>
<tr>
<th>Destination of the shopping trip</th>
<th># of trips</th>
<th>Avg. # of turns</th>
<th>Avg. distance (km)</th>
<th>Avg. CO₂ emissions (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDG (1 store inaccessible location)</td>
<td>250</td>
<td>58</td>
<td>6.4</td>
<td>0.43 (0.19)</td>
</tr>
<tr>
<td>NDG (8 stores)</td>
<td>250</td>
<td>29</td>
<td>2.8</td>
<td>0.19 (0.13)</td>
</tr>
</tbody>
</table>

In the third and last experiment conducted, we relax the assumption that all volunteers travel to the NDG store that has been the study object so far, and let them, instead, select the closest NDG store from home, among the 8 identified stores in the city. We also select the NDG store among the 8 existing stores in the city and assume all volunteers travel to that store. We also assume that the volunteers only make one shopping trip. With these assumptions, we set out two scenarios, as shown in Table 7. The results shown in the table suggest that the location effect can be significant. The CO₂ emission induced by shopping trips by car would increase by 54% if all volunteers’ shopping trips were made to the most inaccessibly reached NDG store in the city, instead of the NDG store that has been the main study object in this study. The result also suggests a decrease in emissions by 37%, if the volunteer shopping trip was made to the closest of the 8 existing NDG stores in the city. Hence, it answers the question of how much CO₂ emissions could be decreased by, due to store location.
Concluding discussion

In this study, we conduct a comparative study on emission patterns of two types of retail channels for non-durable goods and durable goods, from the aspects of travel behaviour and store location. The study is conducted by means of a case study in the city of Borlänge, where GPS tracking data on intra-urban car travel is collected from 250 households. Using GPS trajectory data, we first identify and study travel behaviour patterns for all types of intra-urban trips, and then we extract, by using the parking lots at two large shopping establishments, the durable goods and the non-durable goods trips. We then study the travel behaviour for these shopping trips separately. The travel behaviour is observed to two store establishments, equally accessible to the consumers, in terms of travel route, travel time, travel speed, travel turns, and travel halts, which then also are used to calculate the CO₂ emission. A counter-factual analysis with three experiments is then conducted to enable the understanding of store location effect.

We find that a behavioural change during a trip towards a CO₂ optimal travelling by car has the potential to decrease emission to 36% (DG) and 25% (NDG) of emissions induced by car travelling shopping trips today. We also find that there is a large potential to reduce CO₂ emissions induced by intra-urban shopping trips by store relocation. In a small city, like Borlänge, the excess CO₂ emissions due to poor location is 54%, and if the consumer selected the closest of 8 existing stores, the CO₂ emissions would be reduced by 37% of the current emission induced by NDG shopping trips. As a side result, we note that the emissions induced by shopping trips are 10% less than the total emission from trips in general.

What is presented here is one case study, and more studies are needed. However, we believe that the selected case city is fairly representative of many cities of its size, and has thus some external validity. We believe that the findings in this study emphasise the importance of both location planning and the need to change travel behaviour, in order to reduce CO₂ emission induced by intra-urban travelling. The methodology used in this study offers a means at micro level to identify inaccessible as well as accessible location of destinations, in relation to population distribution, which is a basic prerequisite for an environmental optimal relocation planning, at city level. It can also contribute to identifying the environmental impact induced by different car driving behaviour during a trip.

References


Barth, M., Younglove, T., Scora, G., 2004. The development of a heavy-duty diesel vehicle model. Transportation Research Record, 1880, 10-20


