Measuring CO_2 emissions induced by online and brick-and-mortar retailing

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Abstract

We develop a method for empirically measuring the difference in carbon footprint between traditional and online retailing (“e-tailing”) from entry point to a geographical area to consumer residence. The method only requires data on the locations of brick-and-mortar stores, online delivery points, and residences of the region’s population, and on the goods transportation networks in the studied region. Such data are readily available in most countries, so the method is not country or region specific. The method has been evaluated using data from the Dalecarlia region in Sweden, and is shown to be robust to all assumptions made. In our empirical example, the results indicate that the average distance from consumer residence to a brick-and-mortar retailer is 48.54 km in the studied region, while the average distance to an online delivery point is 6.7 km. The results also indicate that e-tailing increases the average distance traveled from the regional entry point to the delivery point from 47.15 km for a brick-and-mortar store to 122.75 km for the online delivery points. However, as professional carriers transport the products in bulk to stores or online delivery points, which is more efficient than consumers’ transporting the products to their residences, the results indicate that consumers switching from traditional to e-tailing on average reduce their CO_2 footprints by 84% when buying standard consumer electronics products.

Keywords: E-tailing, Spatial distribution of firms and consumers; *p*-median model; Emission measurement; Emission reduction

JEL codes: D22, L13, L81, R12

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1. Introduction

Environmental considerations are at the center of the agenda for politicians in many countries and much research is devoted to meet the challenges of climate change, sustainability, and related environmental issues. The environmental impact of retailing on CO_2 emissions should not be underestimated. In Great Britain, the average consumer over 16 years old made 219 shopping trips and travelled a total of 926 miles for shopping in 2006 (DfT 2006). Considering that most of these trips were reportedly made by car, and that vehicle miles travelled is the main variable determining CO_2 emissions, ways to reduce car use for shopping are sought (Cullinane 2009).

In a Swedish setting, Carling et al. (2013a) studied the environmental optimality of retail locations, finding that current retail store locations were suboptimal. The suboptimal location of retailers generated on average 22% more CO_2 emissions than did a case in which they were optimally located. Furthermore, in a related study, Carling et al. (2013b) used GPS data to track 250 Swedish consumers for two months. In that study, the authors compared downtown, edge-of-town, and out-of-town shopping in terms of the CO_2 emissions caused by shopping trips. They concluded that downtown and edge-of-town shopping were comparable in CO_2 emissions, but that out-of-town shopping produced approximately 60% more emissions.

As traditional brick-and-mortar shopping entails substantial environmental impact, it would be pertinent to compare the CO_2 emissions induced by brick-and-mortar shopping with those of online shopping. Few recent empirical studies (e.g., Edwards et al. 2010; Wiese et al. 2012) analyze the impact of online shopping on the environment. Wiese et al. (2012) studied the CO_2 effects of online versus brick-and-mortar shopping for clothing in Germany; their main finding is that, although online shopping usually induces lower CO_2 emissions, the opposite is true when the distances involved are moderate. In a study of the carbon footprint of the "last-mile" deliveries of conventionally versus online-purchased goods, Edwards et al. (2010) found that neither home delivery of online purchases nor conventional shopping trips had an absolute CO_2 advantage, though home delivery of online-bought goods likely entailed lower CO_2 emissions unless the conventional shopping trips were made by bus.

Previous literature on online shopping and the environment has thus ignored all but the last-mile environmental impact of online retailing ("e-tailing"). In this paper, we address the issue of emissions along the entire supply chain from entry point to the studied region to consumer residence.

Our study aims primarily to develop an empirical method for measuring the CO_2 footprint of brick-and-mortar versus e-tailing from entry point to a region or country to consumer residence.[1] This method will then be used to calculate and compare the environmental impact of buying a standard electronics product online with buying the same product in a brick-and-mortar store in the Dalecarlia region in Sweden. In addition, the actual locations of brick-and-mortar stores and online delivery points in the region will be compared with the locations that would minimize CO_2 emissions.

We will focus on consumer electronics, as these consumer products constitute the largest e-tailing category in Sweden (HUI Research 2014), presumably leading the way to online shopping for other consumer products in the future. Consumer electronics are exclusively imported into Sweden, and pre-shipping via an entry port is required before a product reaches a consumer's residence, regardless of whether the product is bought online or in a store. Consequently, the product's route on the Swedish transportation network to the consumer's residence can be identified. In brick-and-mortar shopping, the route extends from the entry port via the store to the consumer's residence, while in online shopping, it extends from the entry port via the Swedish Post distribution points to the residence. Part of the route is covered by professional carriers, such as Swedish Post, and other parts of the route are covered by the consumer. We focus on the CO_2 emissions of the complete route from regional entry point to consumer residence.

The study concerns the Dalecarlia region in central Sweden containing approximately 277,000 consumers, whose residences are geo-coded. The region contains seven brick-and-mortar consumer electronic stores and 71 delivery points for online purchases. Consumers reach the stores or delivery points via a road network totaling 39,500 km. Mountains in the west and north of the region restrict the number of gateways into the region to three from the south and east, limiting the routing choices of professional carriers. The region is representative of Sweden as a whole in terms of the use of e-tailing and shares many geographical, economic, and demographic characteristics with, for example, Vermont in the USA.

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[1] Note also that this implies that the development of theory or a conceptual framework is outside the scope of this paper. The interested reader is referred to Cullinane (2009) for the outline of a conceptual framework regarding how e-tailing affects the environment.

This paper is organized as follows. Section 2 thoroughly describes online shopping in Sweden in 2012 and 2013. Section 3 gives details of the data and the heuristic algorithm used in finding optimal locations. Section 4 presents the empirical analysis, which starts by calculating the environmental damage induced by buying a standard consumer electronics product online versus in a local brick-and-mortar store. The results are also aggregated to the whole of Sweden for e-tailing in general as well as for consumer electronics products. Section 5 presents a sensitivity analysis incorporating all assumptions imposed, to arrive at the results presented in section 4. Finally, section 6 concludes the paper.

2. Online and brick-and-mortar retailing of consumer electronics in Sweden

In this section, we start by describing e-tailing in Sweden for consumer electronics and in general. We then describe the delivery system from e-tailers to their consumers. Finally, we discuss the brick-and-mortar retailing of consumer electronics in Sweden and the Dalecarlia region.

First, e-tailing is dependent on Internet access, possessed by approximately 90% of Swedish households. In addition, most workplaces have Internet access, making e-tailing available to the vast majority of the Swedish population. In the last quarter of 2012, 73% of a random sample of Swedish consumers reported having bought consumer products online in the previous three months, and 63% of the sample reported that they would buy products online in the coming three months (HUI Research, 2014).[2] Moreover, 90% of respondents reported having shopped online at some time, the main cited reasons for online shopping being that it is simple, cheap, and increases the consumer’s product selection. Most online consumers use their desktop or laptop computer for online shopping, but one in five reported having used a smart phone or tablet for online shopping in 2012 (HUI Research 2014).

As stated above, we are studying the online and brick-and-mortar markets for consumer electronics. We chose electronics as the studied market because it is the largest e-tailing category in Sweden with sales of SEK 8.8 billion in 2013 (HUI Research 2014). Clothing is

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[2] The information about Swedish online shopping comes from e-barometern 2012 and 2013. e-barometern is a yearly report on Swedish online shopping behavior produced by HUI Research (a Swedish research and consultancy firm working mainly in the retail trade industry), Posten AB (the Swedish Post), and Svensk Distanshandel (a federation of commercial enterprises in the online retail industry). The questions asked differ somewhat between years, so some statistics are from e-barometern 2012 reporting statistics for 2011 (HUI Research 2013) and others are from e-barometern 2013 reporting statistics for 2012 (HUI Research 2014).

the next largest category with SEK 7.2 billion in sales followed by books (SEK 3.3 billion), furniture (SEK 1.2 billion), and sporting goods (SEK 1.0 billion). The fastest growing categories are sporting goods, furniture, and electronics, with annual growth rates of 28%, 19%, and 15%, respectively, in 2013. A sample of consumers was asked in a survey what products, if any, they bought online in 2013: 44% reported having bought books online, 40% clothing, 25% computers and computer accessories, and 21% other home electronics products (HUI Research 2014). There are some gender differences in e-tailing, books being the main category for women and computers and computer accessories for men (HUI Research 2013).

Though the sales growth rate is impressive for sporting goods, this category is starting at a low level. As consumer electronics will continue to be one of the most important e-tailing categories for the foreseeable future, it was chosen for the present analysis.[3]

Swedish Post delivers most e-tail packages in rural areas in northern Sweden, where over ten packages per year per household are delivered in many northern municipalities. The three municipalities with the most packages delivered are Storuman, Jokkmokk, and Gällevare, all located in northern Sweden and all averaging 11.4–12.0 packages delivered per year per household. In contrast, in most municipalities in southern Sweden, particularly the three main cities, fewer than seven packages are delivered per year per household. In the municipalities of Malmö, Gothenburg, and Stockholm, 5.9–6.1 packages are delivered per household and year. The Dalecarlia region lies between the extremes of Sweden with seven to nine packages delivered per household and year by Swedish Post, with two exceptions: in the municipalities of Malung and Sälen, in the remote north of the region, over ten packages are delivered per household and year, while in Borlänge, in the center of the region and with a well-developed retail trade, fewer than 7 packages are delivered per household and year (HUI Research 2013). As such, the Dalecarlia region as a whole can be considered representative of most of Sweden, except, perhaps, for the major cities and the remote far north.

In Sweden, the consumer is offered a choice of delivery points for picking up online purchases. Swedish Post, handling most e-tail packages, offers consumers a list of delivery

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[3] This paper examines the environmental impact of transportation related to the retailing of consumer electronics, not the import or manufacturing of such products. It should, however, be noted that approximately 80% of the environmental impact of consumer electronics comes from manufacturing rather than transporting them (Weber et al. 2007). Note also that the method developed here could be used to measure emissions in any setting where the entry points into the studied region, emissions per kilometer for the transport method used, location of the final destination, and available transport network are known. The method may therefore also have important uses outside the retail sector.

points, the nearest the consumer's residence being the suggested primary alternative. The opening hours of these outlets are usually 9.00–20.00. As pointed out by Cairns (2005), delivering products to intermediate points with a longer pickup time window for the consumer permits more efficient delivery, possibly reducing peak-period congestion. The vast majority (85–90%) of surveyed consumers chose to pick up products at the proposed nearest outlet, and the consumer's preferred pickup time at the outlet was Monday to Friday after 18.00 (HUI Research 2014).

Fifty percent of online shoppers reported having returned an online purchase, and 77% reported the experience of doing this as good or very good (HUI Research 2014). The return process usually entailed the consumer returning the package to the outlet where it was picked up. It should also be noted that Swedish e-tailers are not overly exposed to foreign competition, though increased competition from abroad is expected in the future. However, 40% of surveyed consumers reported never having bought anything from a foreign e-tailer, and an additional 40% reported having bought products from foreign retailers only once per or less often per year (HUI Research 2014).

Brick-and-mortar consumer electronics retailing in Sweden has a total annual turnover of approximately SEK 35 billion, but the sector's profitability is not that impressive. In summer 2011, the Swedish brick-and-mortar electronics retail chain Onoff filed for bankruptcy, and its stores were taken over by its competitor Expert. However, less than a year later, Expert also filed for bankruptcy, meaning that two large, nationwide retail chains in consumer electronics have exited the market. In addition, several other chains are reporting weak profits. Meanwhile, Elgiganten, which has both brick-and-mortar stores and e-tailing for consumer electronics, is currently the best performing chain in Sweden. It is therefore conceivable that brick-and-mortar electronics retailers may leave certain local geographic markets in Sweden due to competition from e-tailers, increasing the potential environmental benefits of e-tailing.

In 2012, there were seven brick-and mortar consumer electronics stores in Dalecarlia (see Fig. 1a), all parts of consumer electronics retail chains. Two of the chains (Elgiganten and Euronics) had three stores each, while one chain (SIBA) had only one store. Most of the stores are located in Dalecarlia's major towns. The largest town, Borlänge, is the only town with two stores. One chain, Euronics, has a somewhat different localization pattern than do the other two chains, with two of its three stores located in smaller settlements (i.e., Malung and Svärdsjö) in the region.

3. Data and method

To determine the effect of retailing on CO_2 emissions, several research approaches can be considered. A first would be to check the correlation between time series of CO_2 emissions and of retailing activity, such as sales. This approach would obviously be very sensitive to other changes occurring during the studied time interval, which would be difficult to control for in the analysis. In some lucky instances, sales might vary exogenously due, for example, to strikes, weather conditions hindering shipments, and production stops at major plants. In the present case, however, we are unaware of any such lucky instances and have therefore ruled out this approach, a decision strengthened by the fact that CO_2 emissions in Sweden are measured at a low frequency. A second approach would be to exploit the tagging of products to trace their shipment routes. In the unlikely event that retailers disclosed such data, however, the tracing would be crude, the transport mode from outlet to consumer would remain unknown, and the CO_2 emissions would still need to be linked to the route. A third approach would be to obtain expert opinions from retailers and consumers, but then it would have to be proven that their assessments of the CO_2 emissions were correct.

Instead, we identify the route and transport mode the product follows on its way from regional entry port, via the retailer, to consumer residence, and calculate the emissions induced by this transport. To do so, we draw on data from the Dalecarlia region in central Sweden, and impose several identifying assumptions (labeled using Roman numerals) that are scrutinized by means of sensitivity analysis in section 5.

There are several reasons for choosing the Dalecarlia region when evaluating the measurement method developed. To perform a thorough investigation of how the various assumptions and data requirements affect the model output, we need access to data as detailed as possible regarding the location of people’s residences, the region’s road network, and all other necessary measurements.

First, in Dalecarlia, the population’s residences are geo-coded in 250 × 250-m squares, meaning that the actual residential location may err by 175 m at most.[4] Fig. 2a shows the geographical distribution of the population: considering that consumer electronics is a broad category of products appealing to almost everyone, it is reasonable to regard anyone in the population irrespective of disposable income, gender, and age as a potential buyer of such

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[4] In a 250 × 250-m square, the longest distance from the center point to the edge is $\sqrt{125^2 + 125^2} = 175$.

products. The population totals 277,000 people whose residency is represented by 15,729 squares whose center coordinates are known (census data from Statistics Sweden as of 2002). The population density is high in the southeast part of the region, along the two main rivers, and around a lake in the center of the region. The western and the northern parts of the region are sparsely populated.

Second, previous work has carefully examined the road network in the region, so potential pitfalls encountered in working with these large databases are known (Carling, Han, and Håkansson 2012; Han, Håkansson, and Rebreyend 2013; Carling, Han, Håkansson, and Rebreyend 2014). Fig. 1b depicts the road network of Dalecarlia (actually the national roads only, as showing the many local streets and private roads in the dataset would clutter the map). The network was constructed using the national road database (NVDB), a digital database representing the Swedish road network and maintained by the National Transport Administration (Trafikverket). The database contains national roads, local streets, and private roads (both government subsidized and unsubsidized); the version used here was extracted in 2010, representing the network of that time. Furthermore, attributes of the road segments, such as their position, length, and nominal speed limits, are also given (for details, see Han, Håkansson, and Rebreyend 2013). A very realistic travel distance for a potential consumer can be derived by calculating the distance along the road system from the home to any point where either a brick-and-mortar store or a Swedish Post delivery point is located.

Fig. 1 about here.

Third, an in-depth study of consumer shopping trip behavior was conducted in Borlänge, a centrally located city in the region (Carling, Håkansson, and Jia, 2013b; Jia, Carling, and Håkansson 2013). Some 250 volunteer car owners were tracked for two months using GPS. Typical travel behavior for trips to a store selling durable goods was to drive the shortest route from the home to store, implying the lowest possible CO_2 emissions. Consequently, we approximated shopping-related trips using the shortest route in the following analysis.

Fourth, there are only three gateways[5] into the region, meaning that it is relatively straightforward to obtain information about how consumer electronics products arrive there

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[5] Mountains in the west and north of the region limit the number of gateways into the region to three from the south and east, limiting the routing choices of professional carriers (cf. Figure 1b). Although there are two airports in the region, neither of them is used or is suitable for freight shipments. The brick-and-mortar retailers have confirmed that all their shipments are by truck. However, Swedish Post might occasionally use train for

and are then distributed to consumer residences, irrespective of whether the purchase is made online or at a brick-and-mortar store.[6] Fig. 1a also shows the current location of the seven existing brick-and-mortar consumer electronic stores and the 71 delivery points for products purchased online.

Altogether, the region's road network is represented by 1,964,801 segments joined in about 1.5 million nodes. This means that a consumer can follow a myriad of potential routes to get to the store or delivery point. Based on previous work, we stipulate that the consumer takes the shortest route (Jia et al. 2013). However, identifying the shortest route given this vast number of alternatives is challenging in itself. We follow the convention of using the algorithm proposed by Dijkstra (1959) to find the shortest distance between all node pairs in the road system, an effort that is very time-consuming but done only once. The algorithm, in its naïve form, specifies a starting node, identifies all its adjacent nodes. Thereafter, it seeks second-order nodes adjacent to the starting node and identifies the distance to them via the adjacent nodes. Then the third order nodes adjacent to the starting node are identified and the distance to the staring node via the nodes adjacent to the staring node and the second order nodes adjacent to the starting node are identified. This process continues until all node pairs of interest have been assigned a distance. In other words, the algorithm starts with nearby nodes and calculates stepwise the distance between nodes farther and farther apart. Finally, a (non-symmetric) matrix of road distance between all node pairs is obtained in which the rows of the matrix refer to the nodes of the residences and the columns to the nodes of the stores or delivery points. Zhan and Noon (1998) confirmed that the algorithm, used successfully, identifies the shortest route in a network.

Though road distance is not the same as CO_2 emissions, we nevertheless assume a perfect correlation between the two. We do this despite being aware that other factors, such as speed, time, acceleration, deceleration, road and weather conditions, and driver and vehicle types, are being ignored. Stead (1999), based on data from the 1989–1991 National Travel Survey, suggested using road distance as a proxy for vehicle emissions because of the ease of collecting and computing it. Previous work in Dalecarlia indicates that, while intersections

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partial shipments of the products. In such cases, our approach overestimates the CO_2 emissions induced by online shopping, as we assume truck transport.

[6] The important point for us is to identify the point where the distribution network starts to differ between online and brick-and-mortar stores. This would also be the case if there were local production in the studied region, so this would not in principle affect the method developed, except that in such cases we would have to identify where in the Dalecarlia region the distribution network from producer to online or brick-and-mortar retailers started to differ.

and arterial roads imply higher emissions, emissions crucially depend on road distance (Carling, Håkansson, and Jia, 2013b; Jia, Carling, and Håkansson 2013). It is an approximation to replace CO_2 emissions with road distance, though it is a fairly good one, as we can demonstrate in the sensitivity analysis presented in section 5.

To calculate the CO_2 emissions we assume the following. First, the consumer drives a gasoline-powered Toyota Avensis 1.8 with CO_2 emissions[7] of 0.15 kg per km[8], making the trip solely to pick up a consumer electronics product (e.g., a computer or a small stereo) and return to his or her residence. The product is sold in a $0.3 \times 0.6 \times 0.6$ m^3 box weighing up till 10 kg. The product is transported by a professional carrier using a Scania truck and a trailer with a standard loading volume of 100 m^3 respecting the Swedish restriction of 24 tons of load per vehicle. The Scania truck runs on diesel, emits 1.08 kg per km of CO_2 (according to the producer; see www.scania.com), and is loaded to 60% of its capacity with identical products, such that the consumer's product constitutes one of 600 in the load and is responsible for approximately 0.002 kg per km of CO_2. Emissions when on- and offloading the product and when moving it indoors are neglected, and emissions from transporting the product to the region's boundary from the manufacturer are assumed to be the same irrespective of its being purchased online or in a store and are thus set to zero in the calculations. Moreover, we stipulate that each person in Dalecarlia is equally likely to purchase the product, i.e., that there is no geographical variation in the likelihood of purchase.

The online-purchased products are assumed to first arrive at the region's six Swedish Post distribution centers via the shortest route upon entering the region through gateway B from Stockholm where parcels are sorted (see Fig. 1b). They are then transported to the 71 delivery points, again via the shortest routes. For a product purchased in a store, we assume that the product arrives at the store from the boundary of the region via the shortest route. Furthermore, we assume that the product enters through one of the three gateways such that the gateway implies the shortest distance to the store (see Fig. 1b). This assumption is conservative, as it might underestimate the product's actual transporting distance to the store if the retailer's logistics solution does not use the shortest route. Though the companies were

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[7] This emission rate is according to the EU norm for testing car emissions and refers to driving on a mixture of urban and non-urban roads. In 2012, newly registered cars in Sweden emitted 0.14 kg per km of CO_2, whereas the existing car fleet in Sweden emitted somewhat more CO_2.

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not particularly willing to disclose their logistics solutions, it should be noted that they have economic incentives to minimize transportation costs and should therefore usually choose the shortest route.

The current locations of stores and delivery points, shown in Fig. 1a, are presumably suboptimal and potentially subject to reconsideration. We therefore use the *p*-median model to find the best possible store locations from an environmental perspective. Hakimi (1964) developed the *p*-median model to find the optimal location of switching centers in a network, which is a discrete location problem on a map with spatially distributed demand points (Hakimi 1965; Daskin 1995). In the *p*-median model, the demand points are assumed to be assigned to the nearest facilities. The distance is weighted by the mass of the demand points, in this case, the number of residents at a point. The goal is to locate *p* centers or facilities such that the average individual distance is minimized. Consequently, it is impossible to find more environmentally friendly retail outlet locations than the solution to the *p*-median model under our assumptions that consumers take the shortest routes and choose the nearest stores or online delivery points and that road distance and CO_2 emissions are perfectly correlated.

The *p*-median problem is non-deterministic polynomial-time (NP) hard and, unless the combinatorial problem is modest, it is impossible to find an exact solution. Instead, an approximate solution is sought using a heuristic algorithm. In this paper, we use simulated annealing (SA) because it generally provides good solutions to *p*-median problems, is flexible enough to be controlled, and has worked well on other *p*-median problems in similar contexts (Chiyoshi and Galvao 2000).

Han et al. (2013) give details of SA implementation. The algorithm starts with a configuration of *p* facilities picked at random. One facility is picked at random and is examined to determine whether the average distance is reduced by moving the facility to any of its neighboring nodes. If so, this configuration is accepted as an improvement and the previous step of randomly selecting a facility and searching its neighborhood is repeated. If not, the original configuration is kept with a preset probability and a poorer configuration is selected with one minus this probability. This gradual movement away from the original configuration continues until the average distance is near the minimum. We use the Carling and Meng (2014) approach to obtain confidence intervals for the minimum distance, to ensure that we are only meters away from the best possible solution.

For clarity, we end this section by gathering together all identifying assumptions discussed above and on which the results build. Three assumptions are related to the measurement method as such: (*i*) the road distance and CO_2 emissions are perfectly correlated; (*ii*) the number of brick-and-mortar stores is fixed during the studied period; and (*iii*) the consumer population is stable during the studied period. These three assumptions, along with knowledge of the locations of brick-and-mortar stores, online delivery points, and residences of the population of the region, and of the transportation networks used to transport goods in the studied region, are all the methodological assumptions and data required to use the model.

However, the model also requires assumptions about human behavior, which can of course be altered in infinite ways. In this paper, we will test robustness to seven additional assumptions regarding consumer behavior and three additional assumptions regarding producer behavior.

There are several additional assumptions about consumer behavior. (*iv*) Online-purchased products are picked up at the delivery point nearest the consumer's residence, as confirmed by the surveys (HUI Research 2013 and 2014) cited in section 2. (*v*) Consumers in Dalecarlia take the shortest route from their residence to the brick-and-mortar store or online delivery point, as suggested by a previous study (Jia et al. 2013). (*vi*) Consumers always pick up the product by car and drive a car emitting 0.15 kg per km. According to the National Transport Administration, new cars in Sweden emitted on average 0.138 kg per km in 2012. Although precise figures are lacking, the older fleet of cars would typically have higher emissions, making 0.138 kg per km an underestimation of the overall average emissions. (*vii*) The region's consumers are equally likely to purchase a given product. (*viii*) The consumers either purchase the product on visiting a brick-and-mortar store or purchase it online. (*ix*) The consumers are indifferent to whether they shop in a store or online. (*x*) The consumers shopping at a brick-and-mortar store choose the nearest one.

There are three assumptions about producer behavior. (*xi*) The truck is loaded to 60% of its capacity. (*xii*) Online-purchased products arrive at the delivery point by first going via the shortest route to one of the six distribution centers and then via the shortest route from the distribution center to the delivery point. This is essentially how Swedish Post described their logistics solution to us, although they were unwilling to go into detail. (*xiii*) A product destined for a brick-and-mortar outlet arrives at the store via the shortest route from the nearest of the three gateways into the region. The sensitivity to all these assumptions will be scrutinized in section 5.

4. Empirical analysis of CO_2 emissions induced by consumers shopping

To set the scene, consider a stereotypical consumer electronics product, such as a desktop computer or small stereo. Such a physical product needs to be transported to the consumer's residence, typically by car, inducing marginal freight trips for delivery to the consumer and causing additional environmental damage. On the other hand, it is a marginal product for delivery by the professional carrier, as its volume and weight are marginal to standard trucks. Of course, some consumer electronics products (e.g., ebooks and DVDs) are tiny and easily transported by consumers walking, biking, or riding a bus from the store. However, in Sweden these products would also typically be delivered by ordinary mail to the consumer's residential mailbox.[9] Hence, we believe that the environmental impact of the transport of these tiny products can be abstracted from.

Table 1 shows the consumer's travel distance on the road network from home to the nearest store and back. The average distance to the 7 current brick-and-mortar stores in Dalecarlia is 48.5 km, with considerable variation between consumers. For 5% of consumers, the nearest store is within walking distance (under 2.6 km), while for another 5%, the nearest store is over 162 km from home. Obviously, the postal delivery points are much more conveniently located, approximately 25% of consumers having to travel under 2.1 km to the nearest delivery point, with an average of 6.7 km for consumers overall. Assuming that CO_2 emissions approximately coincide with distance travelled, the average consumer induces only 14% more CO_2 emissions when buying the product online rather than at a store.

Table 1 also shows the hypothetical situation when stores and delivery points are optimally located according to the *p*-median model. A first observation is that the postal delivery points are currently nearly optimally located, as the mean distance differs by under 0.7 km between the current and hypothetical locations. Note also that, comparing the current with the optimal online delivery points, the travel distance to the current locations is less than the optimal one for consumers living in urban areas in the region, while the opposite is true for consumers in rural areas.

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[9] Of course, at some point online retailing could expand to the point at which Swedish Post would be required to add additional delivery trips. Although online retailing is expanding, the analysis of such effects is outside the scope of the present paper. It should also be noted that some low-end TV sets and other electronics products are sold at some of the largest retail food outlets (e.g., ICA Maxi and Coop Forum) in Dalarna, but the sales of such products are limited and thus excluded from our analysis.

The brick-and-mortar stores could, from the environmental and consumer perspectives, be better located. Optimally locating the 7 stores would reduce the average consumer's trip from 48.5 to 28.8 km a 41% reduction. Optimally locating the brick-and-mortar stores would generally most benefit the quartile of consumers today living farthest from a store, but optimal locations would reduce travel distance for all percentiles.

Table 1 about here.

The consumer's trip to pick up the product represents a substantial part of the transport effort; the other part is transporting the product to the pickup point, whether store or postal delivery point. Table 2 shows the distance the product travels from entry into the region to the store or delivery point. The values in the table are calculated assuming travel via the shortest route and derived assigning equal weight to all outlets. The average distance from regional boundary to store is 47 km, whereas the average distance is 123 km to the delivery point. Three unsurprising things can be noted from Table 2. First, products purchased online must travel farther to the pickup point than do ones sold in stores. Second, professional carriers usually carry products farther than do consumers (cf. Table 1). Third, optimally locating stores from the consumer perspective would mean longer-distance transport to the stores for the professional carriers (averaging 62 km).

Table 2 about here.

However, a consumer carrying a product in a car induces much higher CO_2 emissions per travelled kilometer than does a professional carrier bringing many product units on the same trip. Hence, the values in Tables 1 and 2 cannot simply be added. Following Wiese et al. (2012), we started by calculating total CO_2 emissions from traditional brick-and-mortar stores and then turned to CO_2 emissions from e-tailers. Wiese et al. (2012) analyzed one German clothing retailer, comparing two selected brick-and-mortar stores with an e-tailing system. The retail chain provided information about distances from the central warehouse to the two stores, type of transportation used, the quantity delivered to the stores, and the delivery frequency, making it possible to calculate the supply chain's environmental impact. The demand side environmental impact was investigated using a consumer survey administered to customers of the chain's brick-and-mortar stores. The questionnaire provided information about customer postal code, type of customer transport, and number of products bought at the store.

We instead use information about the location of all individual residences, brick-and-mortar electronics stores, and Swedish Post delivery points in Dalecarlia.[10] In addition, we know the layout (i.e., the different types of roads and the speed limits) of the road network connecting the brick-and-mortar stores and the outlet depots to the individual household residences. We believe that the total environmental impact of online and brick-and-mortar retailing can be calculated with more precision than previously.

Table 3 about here.

Table 3 shows the average total CO_2 emissions per purchase of a standard consumer electronics product (e.g., a desktop computer or small stereo). Purchasing the product in a brick-and-mortar store induces on average 7.4 kg of CO_2 emissions. This is substantially more than in the case of e-tailing, where the average is 1.2 kg of CO_2, implying 84% lower emissions. Many consumers (about 50% according to Table 1) live near a delivery point and may prefer to pick up the product on foot, rather than by the car as assumed above (*iv*). The fourth and fifth columns in Table 3 show the resulting emissions if every consumer within 2 km of an outlet walks to pick up the product. This behavior is probably not that common if a desktop computer or small stereo is assumed to be the product. However, other small electronics may conveniently be carried while walking, in which case the difference in induced emissions would be greater (1.0/7.4 meaning 86% lower emissions).

As mentioned in the third section, several brick-and-mortar stores were recently closed due to bankruptcy. Such unplanned closures will lead to brick-and-mortar stores being poorly located relative to consumers, so there is room for the brick-and-mortar stores to be better located. Table 4 again shows the average total CO_2 emissions per purchase of the standard consumer electronics product, but assuming stores and delivery points to be located so as to minimize average CO_2 emissions per purchase. In this case, seven optimally located brick-and-mortar stores would still lead to four-times-higher CO_2 emissions per product than would the online alternative. It is clear that e-tailing is environmentally preferable to brick-and-mortar retailing, even if it were possible to locate the brick-and-mortar stores optimally from an environmental perspective.

Table 4 about here.

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[10] The Swedish Post delivery points also distribute goods for other carriers, such as DB Schenker and DHL.

What does this effect of e-tailing in terms of reduced CO_2 emissions amount to at a national level? Consumer electronics retailing totals SEK 44 billion annually, of which approximately SEK 8.8 billion constituted online purchases in 2013 (HUI Research 2014). Consumer electronics constitutes almost 25% of e-tailing, so when Swedish Post delivers eight products purchased online per household per year in Sweden, two of these packages can be expected to contain consumer electronics.[11] Statistics Sweden estimated the number of households in Sweden in 2011 at approximately 2.24 million. Consequently, approximately 4.5 million consumer electronics packages were delivered in Sweden due to e-tailing. If we assume that consumer electronics items purchased in brick-and-mortar stores are comparable to those bought online, then consumers took home approximately 22.5 million packages from consumer electronics stores. Before 2005, when e-tailing was nearly nonexistent in Sweden, these 27 million packages would have induced $27 * 7.4 = 200$ million kg of CO_2. Today, they instead induce $22.5 * 7.4 + 4.5 * 1.2 = 172$ million kg of CO_2 thanks to the availability of e-tailing. In the unlikely event of brick-and-mortar stores being completely replaced by e-tailing, the emissions reduction would be substantial at $27 * 1.2 = 32$ million kg of CO_2. Such an exercise in aggregation should, of course, be considered only indicative, but nevertheless illustrates that further growth in e-tailing might have more than a trivial impact on the environment.

5. Robustness of the measurement method

To estimate the average CO_2 emissions per purchased consumer electronics product, several identifying assumptions were imposed. Here we look at the sensitivity of the results to each of these assumptions. We begin with the method-related assumptions, and then investigate the consumer behavior assumptions and finally the producer behavior assumptions.

Assumption (i): The first assumption concerns the relationship between CO_2 emissions and road distance. Carling et al. (2013b) found that emissions peaked at intersections and on arterial streets in urban areas due to non-constant velocity. The CO_2 emissions of travelling to a delivery point could be underestimated, as such travel would usually occur in urban areas where constant speed is difficult to maintain. In towns and near intersections, the speed limit is usually 50 km per h or lower. To check assumption (i), we elaborate on the CO_2 emissions

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[11] A fraction of the packages are probably delivered directly to the consumer's residence thereby inducing even less CO_2-emissions. It is hard to say how large the fraction is. However, as an indication, the consumers report that at least 70% of them prefer to have a cell phone delivered to the delivery point rather than directly to their residence (HUI Research, 2014).

for travelling on urban roads and streets by assigning higher emissions to road segments with speed limits of 50 km per h and below. On these segments, we increase the CO_2 emissions of cars by 50% and trucks by 100%, as the latter are even more sensitive to varying driving speed.

Considerable transport effort related to shopping occurs on urban roads with speed limits of 50 km per h and below. On average, consumers in Dalecarlia patronizing online delivery points travel on such roads for 66.3% of the distance travelled, while 36.0% of such consumers travel exclusively on them. Trucks and consumers travelling to brick-and-mortar stores as well as trucks travelling to online delivery points travel more on inter-urban roads and are therefore less exposed to urban roads inducing speed fluctuations. Nonetheless, their exposure to urban roads is non-trivial, calling assumption (i) into question.

Table 5 compares products purchased in brick-and-mortar stores and online when CO_2 emissions are stipulated to be higher on urban roads in the region. As seen in the table, this stipulation increases emissions in urban areas, making the online solution somewhat less attractive than the brick-and-mortar one relative to the baseline results. However, the differences are too small to significantly change our results, so we deem our original measurements robust to the assumption that distance equals emissions.

Table 5 about here.

Assumptions (iii) and (vii)[12]*:* Assumption (*iii*) was that the population of the studied region remained stable during the studied period, while assumption (*vii*) was that all residents of the region were equally likely to purchase the product. Age is an important part of the consumer profile that we cannot access, so we may have to allow for heterogeneity between age groups. Age is highly correlated to income, for example, but can also be used to model geographical redistribution likely to represent future demographic changes in the region, i.e., assumption (*iii*). This is because people born into older cohorts largely live in rural areas, whereas people born into younger cohorts are more concentrated in urban areas. Due to this spatially skewed age distribution, there is an ongoing process of birth deficits and population decrease in rural areas and the opposite in many urban areas (e.g., Håkansson 2000). Table 6 shows results comparable to those in Table 3, but weighted by age. Elderly consumers (≥65 years old) have a weight of 0.5, young consumers (≤15 years) a weight of 1.5, and those in between a weight

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[12] Assumption (*ii*) will be tested together with assumptions (*ix*) and (*x*), below.

of 1. Note that these changes can be seen as altering both the population composition and likelihood of purchasing, testing both assumptions (*iii*) and (*vii*) at once. Although young consumers are now considered three times more likely to purchase electronics than are old consumers, the values in Table 6 are almost identical to those in Table 3, so we conclude that the results are insensitive to these assumptions.

Table 6 about here.

Assumption (iv): One assumption regarding consumer behavior (*iv*) is that online-purchased products are picked up at the nearest delivery point. This assumption has been confirmed in most cases in Sweden via the surveys cited in section 2 (HUI Research 2013 and 2014), in which 85–90% of surveyed consumers selected the outlet nearest their residence.

Assumption (v): This assumption, that consumers in the Dalecarlia region take the shortest routes from their residences to the brick-and-mortar stores or online delivery points,[13] was supported by a study cited in section 3 (Jia et al. 2013). Researchers compared actual travelling routes with the shortest routes to a shopping center, finding that only 5 of 500 investigated shopping trips did not take the shortest routes.

Assumption (vi): The calculations presented above assumed that the consumer drives a car emitting 0.15 kg per km of CO_2, roughly equaling the emissions of a Toyota Avensis. According to the National Transport Administration, new cars in Sweden emitted on average 0.138 kg per km in 2012, while the older fleet of cars typically had higher emissions, making 0.138 kg per km an underestimation of the overall average emissions. What is important here is that the total emissions for each purchase are calculated as follows:

$$\begin{aligned}\text{Total emissions} = \quad & (\text{consumer's car emissions per km} \times \text{km driven by consumer}) + \\ & (\text{distributer's truck emissions per km} \times \text{km driven by distributer}) \quad (1)\end{aligned}$$

As can be seen from equation (1), the car's emissions can be changed at will and the total emissions recalculated, since this is only a scale factor for the total emissions of car travel. Note also that the same holds if we want to investigate how a change in truck emissions or choice of travel route (i.e., distance traveled) affects total emissions.

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[13] The method suggested can also be used if more consumers than in the studied Swedish region travel from work to the delivery points, with the added data requirement that we then also need to know where the consumer works and the additional distance traveled to pick up the package. However, as demonstrated by Jia et al. (2013), such behavior is unimportant in our empirical setting.

Assumption (viii)[14]*:* We assume that consumers made the purchase either at the store or online. According to Cullinane (2009), however, if people browse online and shop in brick-and-mortar stores, some shopping journeys can be saved, but if they browse in the stores and shop online, additional travel will likely be incurred. Moreover, the RAC Foundation (2006) reports that almost 80% of surveyed consumers travel to brick-and-mortar stores to compare products. We accordingly repeated the analysis, but stipulated that each online purchase was preceded 80% of the time by a trip to a brick-and-mortar store to physically assess the product and its substitutes. Under this behavioral assumption, we find that online shopping would induce 7.89 kg of CO_2 on average, comparable to the exclusively brick-and-mortar store case. The environmental benefits of online shopping would be completely offset if as many as 80% of consumers behaved in this way; in fact, more detailed analysis indicated that if 71% or more of consumers behaved in this way, the environmental benefits of online shopping would be offset. It should be noted that in Sweden in 2013, only 6% of consumers buying consumer electronics online reported first visiting a brick-and-mortar store and then purchasing the product online, while 32% reported first researching what product to buy online and then purchasing the product from a brick-and-mortar store (HUI Research 2014).

Assumptions (ix), (x), and (ii): Table 7 shows the results of simulations in which certain customer behavior assumptions are imposed. The identifying assumptions (*ix*) and (*x*) concern how attractive a consumer finds a brick-and-mortar store relative to online shopping and the consumer's propensity to travel to shop for consumer electronics. In this, we are applying the idea of a gravity model as proposed in an operational research setting by Drezner and Drezner (2007), which in turn draws on work in the marketing literature (particularly Huff 1964). Drezner and Drezner (2007) specify the probability that a consumer residing at q will patronize a facility located at p as $\frac{A_p e^{-\lambda d_{qp}}}{\sum_{p \in P} A_p e^{-\lambda d_{qp}}}$, where A_p is the attractiveness of the facility, λ is the parameter of the exponential distance decay function,[15] and d_{qp} is the shortest distance between residence and facility. We adapt this probability to the context such that the probability of patronizing brick-and-mortar store p is $Pr(p) = \frac{A_p e^{-\lambda d_{qp}}}{\sum_{p \in P} A_p e^{-\lambda d_{qp}} + A_O e^{-\lambda d_{qO}}}$, where $A_O = 1$ is the normed attractiveness of online shopping and d_{qO} is the shortest distance to the nearest delivery point for online-purchased products. To understand this specification,

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[14] Assumption (*vii*) was investigated together with assumption (*iii*), above.

[15] The exponential function and the inverse distance function dominate the literature, as discussed by Drezner (2006).

consider a consumer who can choose between one brick-and-mortar store and one delivery point for online-purchased products and who lives equidistant from the two outlets. The attractiveness parameter for the brick-and-mortar store then describes how much more likely the consumer is to choose the brick-and-mortar over the online alternative. For example, $A_p = 2$ means that the consumer would patronize the brick-and-mortar store two times out of three.

In the analysis, we consider three values of $\lambda = 1.0, 0.11, 0.035$, the first referring to a situation in which the consumer is very likely to choose the nearest store or delivery point, the second being the estimated parameter value based on Californian visitors to shopping malls (Drezner 2006), and the third being the estimated value based on Swedes' self-reported trips to buy durable goods (Carling et al. 2012). The values of λ can be converted into average distances travelled to a store of 1, 9, or 30 km. Furthermore, we let $A_p = 1.0, 2.0, 5.0$ represent the brick-and-mortar stores, including the case of consumers indifferent to whether they see the product in the store or online ($A_p = 1.0$) and that of a consumer who finds it much more attractive to see and touch the product physically $(A_p = 5.0)$. Table 7 shows how the market share of the brick-and-mortar stores increases due to their attractiveness when the market share is computed as the expected number (implied by the model) of consumers patronizing any brick-and-mortar store divided by the number of consumers. Focusing on the case in which consumers are willing to consider travelling to stores other than the nearest one ($\lambda = 0.035$), we note that the market share of brick-and-mortar stores increases from 55% if consumers find them as attractive as online shopping $(A_p = 1.0)$ to 83% if consumers find them much more attractive than online shopping $(A_p = 5.0)$. Considering that $\lambda = 0.035$ is the most likely estimate in Sweden and that brick-and-mortar stores currently sell approximately 80% of all purchased consumer electronics, one may conjecture from Table 7 that Swedish consumers currently regard brick-and-mortar shopping as about two to five times more attractive than online shopping, on average.

The last column of the table gives the average CO_2 emissions per consumer and purchase. In calculating the emissions, we take into account that the consumer will shop at various brick-and-mortar stores and sometimes shop online. The formula is $\sum_{p=1}^{7} Pr(p) * \left(d_{qp} * C_E + \tilde{d}_p * T_E\right) + \left(1 - \sum_{p=1}^{7} Pr(p)\right) * \left(d_{qO} * C_E + \tilde{d}_O * T_E\right)$, where C_E and T_E are the CO_2 emissions per kilometer driven by consumer cars and delivery trucks, respectively, $\tilde{d}_p$ is the road distance the truck travels to store p, and $\tilde{d}_O$ is the road distance the truck travels to the online delivery point. The formula therefore gives the consumer's expected CO_2 emissions for repeated purchases. An increased likelihood to travel for shopping implies a higher market share for brick-and-mortar stores, which in turn leads to a dramatic increase in CO_2 emissions. Consider, for example, the case when brick-and-mortar and online shopping are equally attractive to consumers, i.e., $A_p = 1.0$. If consumers are unwilling to travel ($\lambda = 1$), they will almost always shop online and pick up their purchases at the nearest delivery points, as that implies the least travelling with resulting low CO_2 emissions of 0.32 kg. If they are likely to travel ($\lambda = 0.035$), then they will sometimes shop online, sometimes at stores near their residences, and sometimes at stores far from their residences. As a result, their travelling will on average be extensive, resulting in high CO_2 emissions of 5.47 kg.

Table 7 about here.

Some of the results presented in Table 7 are illustrated in Fig. 2, which indicates the geographical areas dominated by brick-and-mortar shopping. The left panel presents the case in which $\lambda = 0.11$ and $A_p = 1$, showing that most of the region, except for the centermost areas surrounding the brick-and-mortar stores, is served by e-tailing. In the right panel, consumers supposedly are likely to travel for shopping ($\lambda = 0.035$) and find brick-and-mortar stores more attractive $A_p = 2$than online shopping ($A_p = 2$), so the more densely populated areas of the region are served chiefly by brick-and-mortar shopping.

Fig. 2 about here.

We also elaborate on the closure of brick-and-mortar stores to check the sensitivity of assumption (*ii*) by stepwise removing, one at a time, the store with the smallest market share. For example, Table 8 presents the situation after closing the two stores attracting the smallest shares of consumers. Although store closure leads to a smaller market share for brick-and-mortar shopping, the general pattern found in Table 7 remains.

Table 8 about here.

Assumption (xi): The truck is assumed to be loaded to 60% of its capacity, though the loading could be lower or higher. We therefore check the sensitivity to this assumption by stipulating that the truck is loaded to 30% of its capacity, which might be the case if the truck typically returns empty from the delivery points. We also consider an 80% loading, corresponding to efficient distribution and a good solution to the travelling salesman problem, in which the truck finds an efficient route to pass all scheduled delivery points. Table 9 shows that varying the loadings only modestly affects the CO_2 emissions induced by selling a standard electronics product at a brick-and-mortar store. The assessment of the online-purchased product's emissions is somewhat more sensitive to the stipulated loading, but the difference in emissions between brick-and-mortar- and online-purchased products remains large.

Table 9 about here.

Assumption (xii): Online-purchased products arrive at the delivery point by first going via the shortest route to one of the six distribution centers and then via the shortest route from the distribution center to the delivery point. This is essentially how Swedish Post described their logistics solution to us, although they were unwilling to go into detail.

Assumption (xiii): A product sold at a brick-and-mortar outlet comes to the store via the shortest route from the nearest of the three gateways into the region (*xiii*).

Assumptions (*xii*) and (*xiii*) may be flawed and could in that case lead to underestimated CO_2 emissions. From our analysis, we know the distances traveled via the shortest routes from points of entry into the region to consumer residences, and use these to calculate total emissions in accordance with equation (1). If interested, one could use equation (1) to introduce longer transportation routes[16] for both the consumer and/or retailer distribution networks and recalculate the total emissions. Note, however, that for our purposes of comparing the emissions of e-tailing with those of brick-and-mortar retailing, this is only important if there are systematic differences in this type of sub-optimization between the two types of retailing.

6. Discussion

Retailing creates an environmental impact that should not be underestimated. In Great Britain, the average consumer made 219 shopping trips and travelled a total of 926 miles for retail

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[16] One could also use equation (1) to recalculate emissions if one suspected that consumers often used multi-purpose trips when shopping, in which case we would introduce only shorter routes specifically reflecting the marginal transport effort related to shopping. Multi-purpose shopping trips are not that common in Sweden (Jia et al. 2013) and are only relevant when comparing online and brick-and-mortar shopping if behavior differs systematically between the two types of shopping.

purposes in 2006 (DfT 2006). Meanwhile, in a Swedish setting, Carling et al. (2013a) reported that the current location of retailers in the Dalecarlia region of Sweden was suboptimal, and that suboptimal retailer locations generated on average 22% more CO_2 emissions than did optimal locations.

An empirical literature (e.g., Wiese et al. 2012; Edwards et al. 2010) analyzes the environmental impact of online shopping. However, this literature has focused on the emissions induced by consumers traveling to and from brick-and-mortar stores or online delivery points, and has not compared any but the “last-mile” environmental impacts of online versus brick-and-mortar retailing.

This paper sought to develop a method for empirically measuring the CO_2 footprint of brick-and-mortar retailing versus e-tailing from entry point to a region (e.g., country, county, and municipality) to the consumer’s residence. The method developed was then used to calculate and compare the environmental impacts of buying a standard electronics product online and in a brick-and-mortar store in the Dalecarlia region in Sweden. The method developed only requires knowledge of the road network of the studied region, the location of the residences of the population (measured as precisely as possible), and the locations of the brick-and-mortar outlets and e-tailer delivery points. The method also requires several assumptions that need scrutiny to determine whether the method is robust to changes in the underlying assumptions. This was done thoroughly in this study, and the results indicate that the method developed is very robust to changes in the underlying assumptions.

The results indicate that e-tailing results in a substantial reduction in CO_2 emissions from consumer travel. The average distance from a consumer residence to a brick-and-mortar electronics retailer is 48.54 km in the Dalecarlia region, while the average distance to an online delivery point is only 6.7 km. As such, making the purchase online will lead to only 14% of the consumer travel emissions that would have resulted from purchasing the product in a brick-and-mortar store. It should also be noted that the online delivery points in the Dalecarlia region are well located relative to consumer residences. The actual delivery point locations differ from those that would minimize CO_2 emissions caused by consumer travel by under 0.7 km. The results also indicate that e-tailing causes the distance traveled from regional entry point to delivery point (i.e., brick-and-mortar store or online delivery point) to increase. On average, the product travels 47.15 km to the brick-and-mortar store versus 122.75 km to the online delivery point.

However, one must recall that a product carried in a consumer car induces much higher CO_2 emissions than does the same product delivered by a professional carrier transporting many units simultaneously. As such, we have also calculated the total CO_2 emissions from regional entry point to consumer residence for the two options, i.e., e-tailing or brick-and-mortar stores. The results indicate that purchasing the product in a brick-and-mortar store on average causes 7.4 kg of CO_2 to be emitted along the whole chain from regional entry point to consumer residence, while purchasing the same product online only induces on average 1.2 kg of CO_2 emissions. As such, consumers in the Dalecarlia region who switch from buying the product in a store to buying the same product online on average reduce their CO_2 emissions by approximately 84%.

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Table 1. Consumers' return travel distance on the road network from home to nearest brick-and-mortar store and online delivery point (in km), showing current and *p*-median optimal locations.

	Current location		Optimal location	
Percentile:	Brick-and-mortar stores	Online delivery points	Brick-and-mortar stores	Online delivery points
5	2.64	0.80	1.64	0.92
25	7.12	2.08	5.20	2.12
50	25.86	3.64	16.46	3.70
75	77.96	7.88	40.12	7.56
95	162.10	22.58	88.80	17.68
Mean	48.54	6.70	28.76	5.98
St. dev.	55.72	8.46	36.96	7.14

Table 2. Distance products travel on the road network to brick-and-mortar stores and online delivery points (in km).

	Current location		Optimal location	
Percentile:	Brick-and-mortar stores	Online delivery points	Brick-and-mortar stores	Online delivery points
5	-	22.25	-	29.15
25	14.23	75.75	18.00	78.39
50	39.86	104.89	51.20	107.97
75	52.63	168.53	115.45	192.93
95	-	253.17	-	272.25
Mean	47.15	122.75	62.28	130.81
St. dev.	40.61	70.54	47.24	76.49

Table 3. CO_2 emissions (in kg) induced by transporting a typical product from the regional boundary to consumer's home via current outlets.

Percentile:	Brick-and-mortar stores	Online delivery points	Brick-and-mortar (incl. walking)[a]	Online (incl. walking)[a]
5	0.48	0.29	0.08	0.06
25	1.13	0.51	1.13	0.18
50	3.96	0.78	3.96	0.41
75	11.79	1.42	11.79	1.42
95	24.58	3.65	24.58	3.65
Mean	7.44	1.22	7.40	1.05
St. dev.	8.41	1.30	8.44	1.39

[a] It is assumed that all consumers within 2 km of the outlet walk to pick up the product and while doing so produce no CO_2 emissions.

Table 4. CO_2 emissions (in kg) induced by transporting a typical product from the regional boundary to the consumer's home via outlets that are environmentally optimally located.

Percentile:	Brick-and-mortar stores	Online delivery points	Brick-and-mortar (incl. walking)[a]	Online (incl. walking)[a]
5	0.56	0.28	0.10	0.06
25	1.39	0.52	1.39	0.18
50	3.13	0.77	3.13	0.41
75	6.50	1.29	6.50	1.29
95	13.44	3.04	13.44	3.04
Mean	4.77	1.12	4.73	0.95
St. dev.	5.31	1.13	5.35	1.23

[a] It is assumed that all consumers within 2 km of the outlet walk to pick up the product and while doing so produce no CO_2 emissions.

Table 5. CO_2 emissions (in kg) induced by transporting a typical product from the regional boundary to consumer's home via current outlets; greater CO_2 emissions assumed in urban areas.

	Baseline		Higher urban emissions	
Percentile:	Brick-and-mortar stores	Online delivery points	Brick-and-mortar stores	Online delivery points
5	0.48	0.29	0.75	0.43
25	1.13	0.51	1.87	0.79
50	3.96	0.78	4.99	1.21
75	11.79	1.42	13.26	1.95
95	24.58	3.65	26.92	4.38
Mean	7.44	1.22	8.67	1.64
St. dev.	8.41	1.30	9.05	1.45

Table 6. CO_2 emissions (in kg) induced by transporting a typical product from the regional boundary to consumer's home via current outlets; consumers weighted by age.

Percentile:	Brick-and-mortar stores	Online delivery points	Brick-and-mortar (incl. walking)[a]	Online (incl. walking)[a]
5	0.48	0.29	0.08	0.06
25	1.14	0.50	1.14	0.18
50	3.98	0.77	3.98	0.41
75	11.87	1.40	11.87	1.40
95	24.58	3.61	24.58	3.61
Mean	7.46	1.21	7.42	1.04
St. dev.	8.40	1.29	8.44	1.38

[a] It is assumed that all consumers within 2 km of the outlet walk to pick up the product and while doing so produce no CO_2 emissions.

Table 7. Market share of brick-and-mortar stores and average CO_2 emissions (in kg) induced by transporting a typical product from the regional boundary to consumer's home via current outlets; seven brick-and-mortar stores.

A_p	λ	Market share (%)	CO_2 emissions
1	1	11.53	1.23
	0.11	30.56	1.85
	0.035	55.43	5.95
2	1	16.87	1.24
	0.11	41.70	2.16
	0.035	69.06	7.44
5	1	24.86	1.27
	0.11	55.10	2.66
	0.035	82.68	9.20

Table 8. Market share of brick-and-mortar stores and average CO_2 emissions (in kg) induced by transporting a typical product from the regional boundary to consumer's home via current outlets; 5 brick-and-mortar stores.

A_p	λ	Market share (%)	CO_2 emissions
1	1	8.60	1.23
	0.11	25.42	1.79
	0.035	49.42	5.51
2	1	12.78	1.24
	0.11	34.47	2.07
	0.035	62.45	7.08
5	1	19.32	1.27
	0.11	45.38	2.53
	0.035	76.40	9.17

Table 9. CO_2 emissions (in kg) induced by transporting a typical product from the regional boundary to consumer's home via current outlets; trucks loaded to two capacity levels.

	30% loading		80% loading	
Percentile:	Brick-and-mortar stores	Online delivery points	Brick-and-mortar stores	Online delivery points
5	0.58	0.40	0.46	0.25
25	1.21	0.69	1.12	0.46
50	4.04	1.01	3.94	0.72
75	11.88	1.65	11.77	1.35
95	24.84	3.93	24.51	3.60
Mean	7.54	1.43	7.41	1.16
St. dev.	8.46	1.34	8.40	1.29

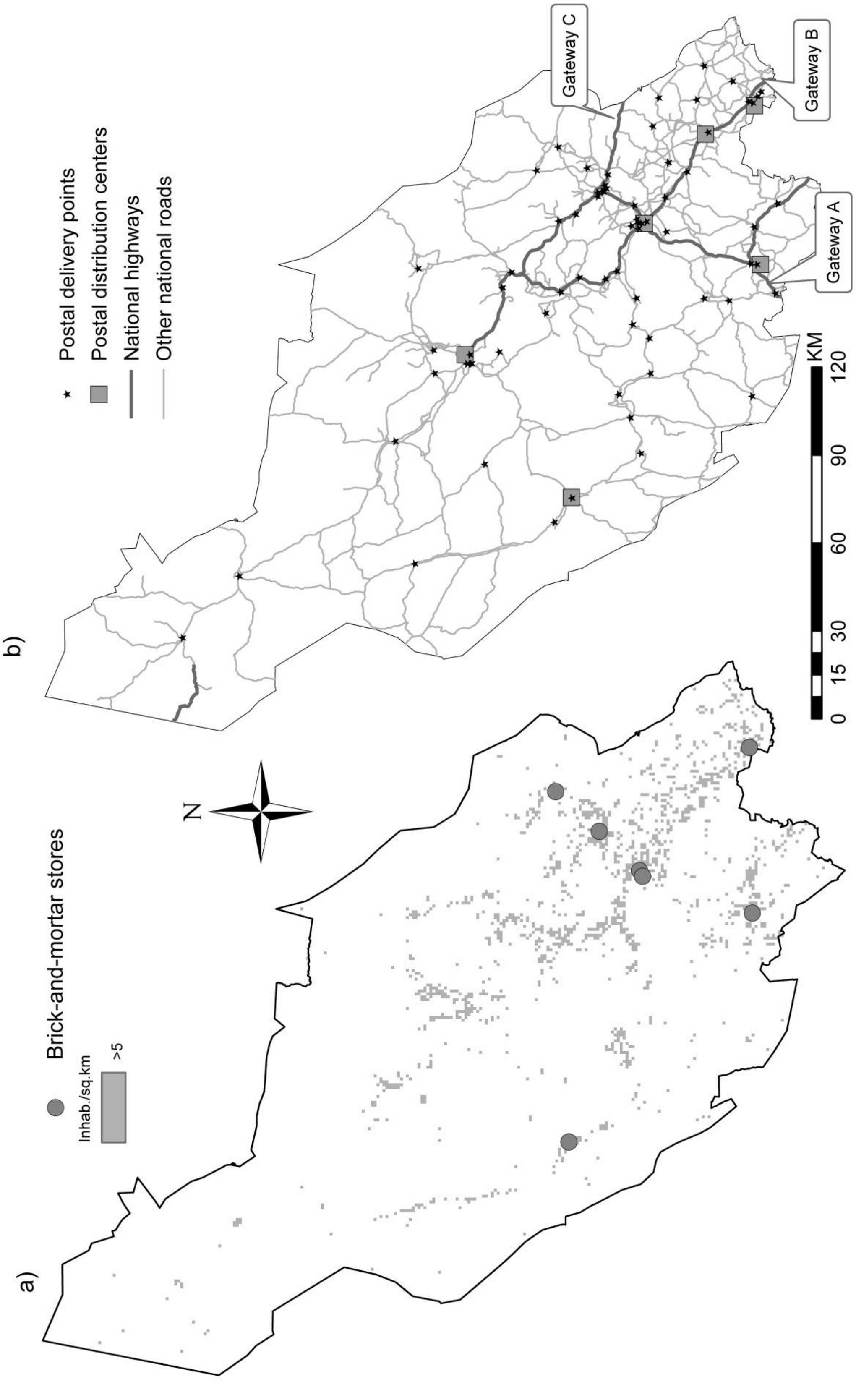

Figure 1. a) Consumer residences and current locations of brick-and-mortar stores; b) national road network and current locations of postal distribution centers and delivery points.

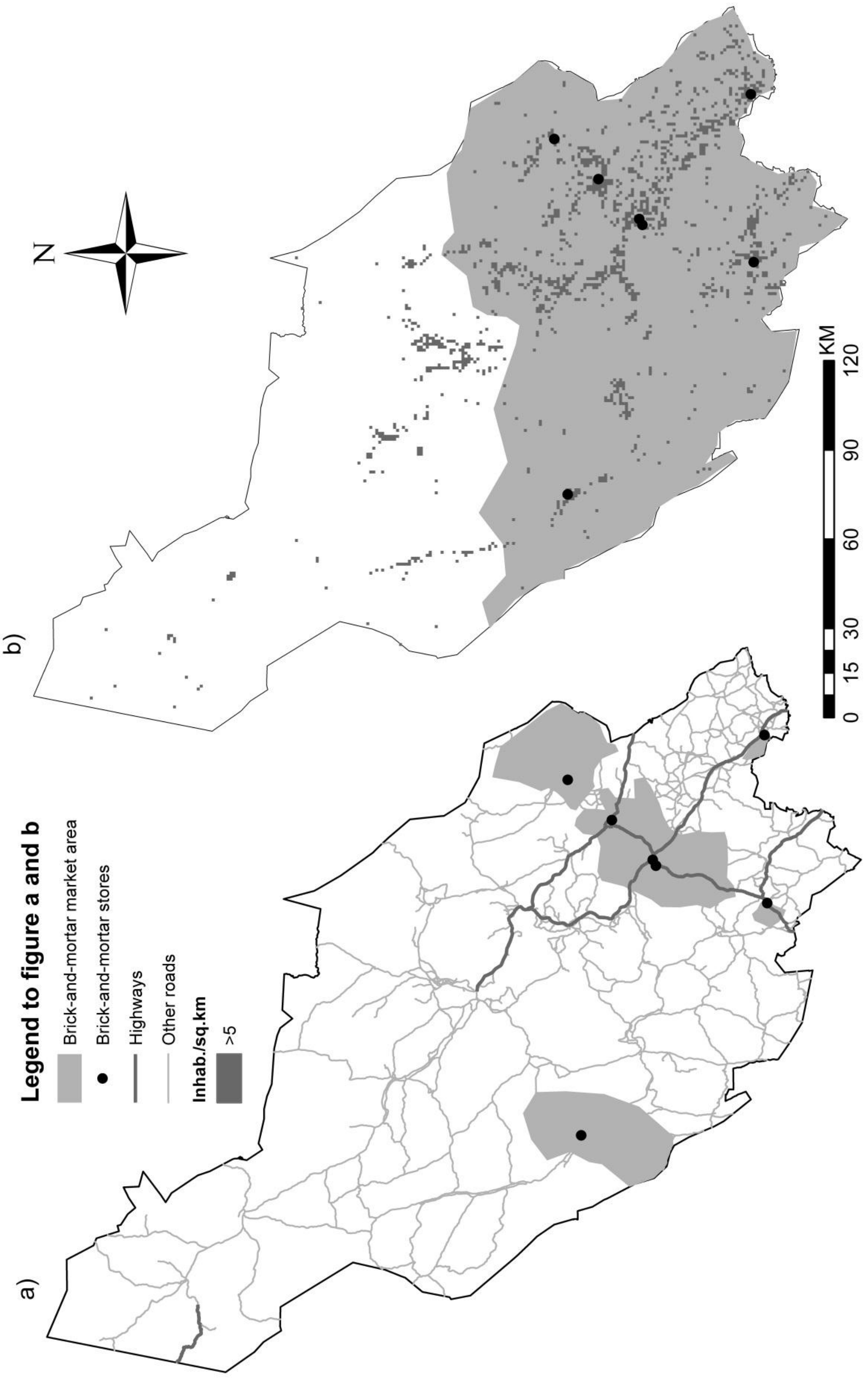

Figure 2. Market areas when (a) $\lambda = 0.11$ and $A_p = 1$and when (b) $\lambda = 0.035$ and $A_p = 2$ for current brick-and-mortar stores.