Transport Efficiency of Off-peak Urban Goods Deliveries: a Stockholm Pilot Study

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Abstract

It is increasingly recognized that even cities with severe congestion during peak hours have available road capacity during nights, evenings and early mornings. Policies that shift urban goods deliveries from peak hours to off-peak hours have the potential to increase the efficiency of freight distribution, as well as to reduce negative external impacts. Between 2014 and 2016, the City of Stockholm ran a pilot project allowing inner city goods deliveries with heavy trucks at night. This paper evaluates the transport efficiency impacts of the Stockholm off-peak pilot. An evaluation framework is defined where transport efficiency is studied in a number of dimensions, including driving efficiency, delivery reliability, energy efficiency and service efficiency. For each dimension, performance indicators are introduced and evaluated. Vehicle GPS probe data, fleet management data, and logistic information are used to assess the impacts. The results suggest that shifting deliveries from daytime peak hours to night-time achieved better transport efficiency in driving efficiency, delivery reliability and energy efficiency. Meanwhile, there were no clear efficiency gains from moving deliveries from mid-day hours. For cities with varying congestion during daytime like Stockholm, the results suggest that night-time deliveries mainly increase the scheduling flexibility of carriers and recipients through the introduction of additional off-peak hours. The conclusions provide input to planners, decision-makers and local authorities to design and implement effective policy initiatives.

Keywords: Urban freight, off-peak delivery, transport efficiency, pilot study

1. Introduction

Increasing urban populations, economic growth as well as structural economic changes (e.g. the growth of the Internet-based economy) have increased the demand from businesses and residents for goods deliveries. In this way, freight activity represents a physical manifestation of the economy. Efficient and reliable urban delivery systems, in turn, are essential for urban economic development (Behrends et al., 2008; Visser et al., 1999). Traffic congestion is a major problem in urban areas throughout the world, and can entail substantial costs for travellers and business operations (Weisbrod et al., 2003). Congestion results in delays and unreliable delivery services for the freight industry; it is estimated that the extra costs to the freight industry due to congestion are as high as 1.5% of GDP in EU countries (European Commission, 2007).

Meanwhile, freight transport itself induces significant negative externalities on accessibility, environment and liveability. Commonly observed external impacts include congestion, air pollution, and greenhouse gas emissions, as well as accidents, visual intrusion, barrier effects, disturbance and noise (Anderson et al., 2005; Giuliano, 2012; Wittlöv, 2012). Freight transport in general is one of the major contributors to air pollution and greenhouse gas emissions, which are among the most severe environmental effects (Figliozzi, 2011). In particular, 20-30% of vehicle kilometres and 16-50% of transport-related emissions of air pollutants (depending on the specific pollutant) in European cities are caused by freight transport (Dablanc, 2007). Urban freight transport in particular pollutes more than long-distance freight transport due to the stop-and-go conditions on congested urban streets, generally older vehicles, shorter delivery runs and the large number of delivery stops.

Traditionally, policymakers have generally left freight transport matters to the private sector, where the demand for and supply of freight transport services are generated (Lindholm and Behrends, 2012; Wittlöv, 2012). Even in countries with strong political institutions, the policy component as applied to urban logistics is relatively weak (Dablanc, 2011). Policy and regulatory measures implemented by urban planners have aimed at imposing restrictions rather than stimulating freight transport operations. Recently, however, policymakers have changed their approach on urban freight transport due to increasing concerns about population growth, economic development and competitiveness, and the environment (Wittlöv, 2012; Hesse and Rodrigue, 2004; Benjelloun et al., 2010). Many major European cities are now including urban freight transport as part of their overall transport strategies (Browne et al., 2014; Hall and Hesse, 2012). Examples of policy instruments considered to increase the benefits of trading commodities while reducing the negative externalities associated with freight transport include certification and labelling, traffic and parking regulation, intelligent transportation systems, and delivery truck fuel efficiency and emission standards (Ambrosini and Routhier, 2004; Crainic et al., 2004; Goldman and Gorham, 2006).

Furthermore, it is increasingly recognized that there is available capacity in the road transport system during off-peak hours (typically nights, evenings and early mornings), even in cities with severe congestion during peak hours (Sánchez-Díaz et al., 2016). By considering policies that shift urban goods delivery from peak hours to off-peak hours, there is potential to increase the efficiency of the freight distribution, as well as to reduce negative external impacts and (to some extent) congestion for other road users during peak hours.

Between 2014 and 2016, the City of Stockholm ran an off-peak goods delivery pilot project, with the objective to examine the feasibility and potential of night-time delivery considering factors such as delivery times, emissions, noise, workforce utilization, requirements on storage facilities and delivery vehicles, as well as work environment (Stockholms Stad, 2014a). Currently, heavy vehicles above 3.5 tons are forbidden in the inner city from 22:00 to 06:00. Within the pilot project, the City of Stockholm issued special permits for two specific heavy delivery trucks, designed and equipped to reduce noise and pollution, to deliver goods in the inner city during the restricted time period.

The aim of this paper is to evaluate the transport efficiency impacts of shifting goods deliveries from daytime to night-time hours, using the Stockholm off-peak delivery pilot project as a case study. A general methodological framework for the evaluation is proposed, in which a set of indicators capturing different important dimensions of transport efficiency for carriers and recipients are defined. For each indicator, a set of sufficient data types for the evaluation is identified. Taking advantage of emerging sensing technologies such as vehicle GPS data and Fleet Management System data, the methodology is applied to the Stockholm off-peak pilot. For one of the trucks, the multiple dimensions of transport efficiency are combined with cost parameters to assess the economic efficiency of the off-peak deliveries. Put in relation to previous studies in New York City, London, etc., the evaluation provides insights into the importance of the congestion characteristics of the area where the policy is implemented for the impacts of permitting night-time deliveries.

The paper is organized as follows. Section 2 reviews existing studies of off-peak deliveries. Section 3 describes the Stockholm off-peak goods delivery pilot project. In Section 4 the general transport efficiency evaluation methodology is presented, followed by a description and results from the evaluation in Section 5. Finally, conclusions are drawn in Section 6.

2. Literature review

Shifting goods deliveries to less congested hours has a very long history, and was implemented already in ancient Rome when Julius Caesar proclaimed a ban on commercial deliveries during the daytime as a solution to reduce congestion in the streets (Dessau, 1902). In recent years, a number of studies have been carried out in large urban areas, targeting goods recipients and carriers. Successful examples include the New York City Off-hour Delivery Project (Holguín-Veras et al., 2005) and the freight transport strategy in London during the 2012 Olympic games (Browne et al., 2014). Similar studies have also been conducted in the Netherlands (Dassen et al., 2008), Spain, Ireland (Forkert and Eichhorn, 2008), and Belgium (Verlinde et al., 2010).

The off-hour delivery project in New York City is one of the broadest studies carried out on this topic. Starting in 2002, the New York State Department of Transport investigated the potential methods for encouraging off-peak deliveries in Manhattan and Brooklyn. The project emphasized the design of the delivery program and various performance measures were evaluated. Regarding the necessary conditions for off-peak distribution systems, it was found that the goods recipients play the dominant role in decisions about delivery time. The project used GPS-equipped cell phones in the participating trucks to record location, velocity, date and time. It was found that average travel speeds were significantly higher during off-hours compared to daytime. Furthermore, service times decreased during off-peak hours, since less time was lost to searching for parking and to locating and interacting with the customers. It was estimated that the potential economic benefits of off-peak delivery in the New York metropolitan area from increased productivity of the freight industry, travel time savings to road users, and environmental benefits to society are in the range of 147 to 193 million dollars per year (Holguín-Veras et al., 2005). A recent study shows that the reduction in the emissions per kilometre in New York City due to a shift to off-peak hours may be as high as 60% (Holguín-Veras et al., 2016).

In the studies carried out in Barcelona and Dublin (Forkert and Eichhorn, 2008), low noise trucks and loading equipment were employed for a few large volume deliveries at night instead of several smaller delivery trucks during daytime. Although the projects provided evidence of noise reduction during both driving and off-loading, no quantitative analysis was presented on the transport efficiency effects in the distribution process.

A framework for quantifying the traffic effects of restrictions with respect to delivery recipient types and times of the day in urban areas was developed in Yannis et al. (2006). Scenarios such as restrictions during morning and afternoon peak hours for grocery stores, supermarkets and department stores were tested in a simulation model of the urban network in Athens, Greece. The simulation outputs showed that the delivery restrictions led to increases in average vehicle speeds in the studied urban network, especially during morning peak hours.

The above-mentioned studies of off-peak deliveries indicate better performance at night than during daytime, and efficient deliveries and reduced environmental impacts are the most evident benefits. However, every urban area has its local characteristics in terms of urban network, population density and demand for goods, and the effects of implementing off-peak deliveries are therefore expected to vary between cities. In particular, unlike heavily congested major cities such as New York City, congestion in Stockholm is generally high during morning and afternoon peak hours but moderate during mid-day hours. The incentives for stakeholders to adopt off-peak deliveries, and the long-term feasibility of such schemes, depend strongly on the associated transport efficiency impacts, including driving times, fuel consumption, delivery time reliability, etc. Sufficient analysis and evaluation of transport efficiency with respect to local characteristics and dynamics are the critical aspects when designing and promoting urban freight policy (Van Duin and Quak, 2007; Cui et al., 2015). Thus, the evaluation of the Stockholm off-peak pilot provides further evidence of the transport efficiency of night-time deliveries for urban areas with varying congestion characteristics.

3. Stockholm off-peak pilot project

3.1. Study area description

Stockholm is a fast-growing city with a current population of 1.5 million people, and the demand for goods distribution increases constantly. In 2010 almost 40 million tons of goods were transported by trucks in Stockholm County, and there were approximately 10,000 heavy vehicles (over 3.5 tons) on the roads every day (Stockholms Stad, 2014a). In 2006, light and heavy trucks accounted for 17% of all traffic entering the city, and 19% of the traffic exiting the city during the congestion charging hours (Transek, 2006).

Figure 1 illustrates the average driving speed in Stockholm inner city during weekdays at different times of the day. The speed is estimated in 15-minute intervals using GPS probe data from about 1500 taxis; for a description of the estimation methods see Rahmani and Koutsopoulos (2013) and Rahmani et al. (2015). The mean speed across days (solid line in Figure 1) shows two obvious congestion peaks, which are marked with blue vertical lines in the figure. One is around 8:45 in the morning when the speed drops to ca. 31 km/h, and the other is at 16:30 in the afternoon when the speed is ca. 30 km/h. The average speed during off-peak hours as defined in the pilot study (22:00-06:00) is around 30%-50% higher compared to the peak hours. The speed variability across days, in terms of the mean speed plus/minus the standard deviation, is shown as dotted lines. The overall variation is low, around 1 km/h, which suggests a relatively reliable service quality of the network. However, the two most congested peaks during daytime also have the highest variability, which indicates that arrival times at delivery points may be less reliable at those times.

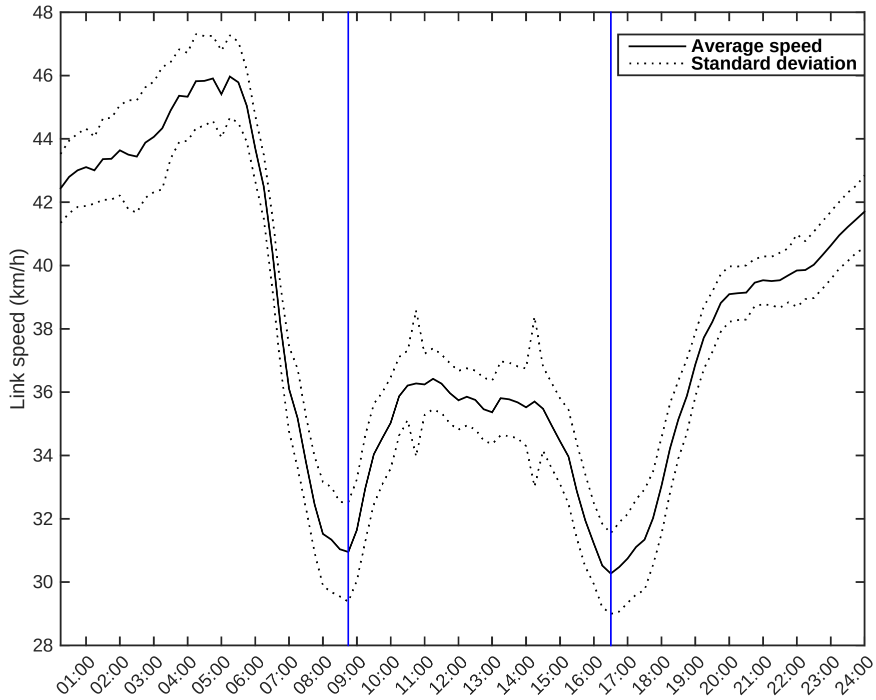


Figure 1 Network-wide average speed (km/h) in Stockholm inner city, as a function of time of day. Solid line: mean network speed across days. Dotted line: mean +/- standard deviation of network speed across days.

3.2. Off-peak pilot description

As part of a programme for improving urban mobility, the City of Stockholm ran an off-peak goods delivery pilot project between 2014 and 2016 (Stockholms Stad, 2014b). The project was the first off-peak trial in the world using environmentally friendly vehicles, and the goal was to examine the feasibility and potential of off-peak delivery considering factors such as delivery times, emissions, noise, workforce utilization, requirements on storage facilities and vehicles, as well as work environment (Stockholms Stad, 2014a).

Currently, heavy vehicles above 3.5 tons are forbidden in the inner city from 22:00 to 6:00 due to concerns over noise caused by traffic and delivery activities. Within the pilot project, no restrictions were imposed on delivery during normal daytime hours, but the City of Stockholm issued special permits for two specific heavy delivery trucks to deliver goods during the restricted time period. The shippers and recipients of the goods were actively involved in the project and saw logistical benefits from adjusting the deliveries to off-peak hours. The two trucks were specially designed to reduce noise and pollution. The first vehicle, denoted truck A in the following, is a hybrid diesel-electric truck. A zone management system was customized in the control unit so that the truck operated with only the electric motor in the inner city area (defined by the Stockholm congestion charging system (Eliasson et al., 2009)) and with the diesel engine elsewhere. The second vehicle, denoted truck B, is gas-fuelled. Moreover, various noise-reducing cargo-handling technologies, such as silent forklifts and roll cages, and increased awareness on the part of the drivers, were implemented in order to reduce noise and vibration levels during delivery.

The two trucks in the pilot study made delivery tours to distinct sets of receivers. Truck A made dedicated large volume deliveries to three grocery stores in Stockholm inner city. The stores were selected by the store chain company based on the feasibility of receiving goods during off-peak hours. The goods delivered to store 1 were received by the store personnel, while the deliveries at stores 2 and 3 were unassisted. Specially designed equipment for receiving goods was installed at these stores and the driver could easily unload the truck.

Most of truck A's delivery route is on the highway; the delivery route in the inner city is shown to the left in Figure 2. The three stores are located at Sveavägen (store 1), Sankt Eriksgatan (store 2), and Södra Station (store 3), and are displayed in the figure as a red circle, a light blue asterisk and a pink cross, respectively. Every weekday (Monday-Friday) evening during the pilot, truck A travelled from the logistics company's terminal located in the north of Stockholm to the warehouse to load the goods to the first store. After completing the delivery to store 1, the truck drove back to the warehouse, loaded the goods for the second store and travelled to the store to make the second delivery. The same procedure was then repeated for the third store. Finally, the truck returned to the terminal.

Truck B made consolidated deliveries of small volumes to multiple customers (hotels, restaurants, etc.) in the city with each tour, both during daytime and off-peak hours. Due to the business characteristics of the customers, the delivery points of truck B varied from day to day. The delivery route on a typical day (16 May, 2016) is displayed in Figure 2, right. The warehouse is located in the south of Stockholm and shown as a green diamond in the figure, while the customers are dispersed in the entire Stockholm region (shown as red dots).

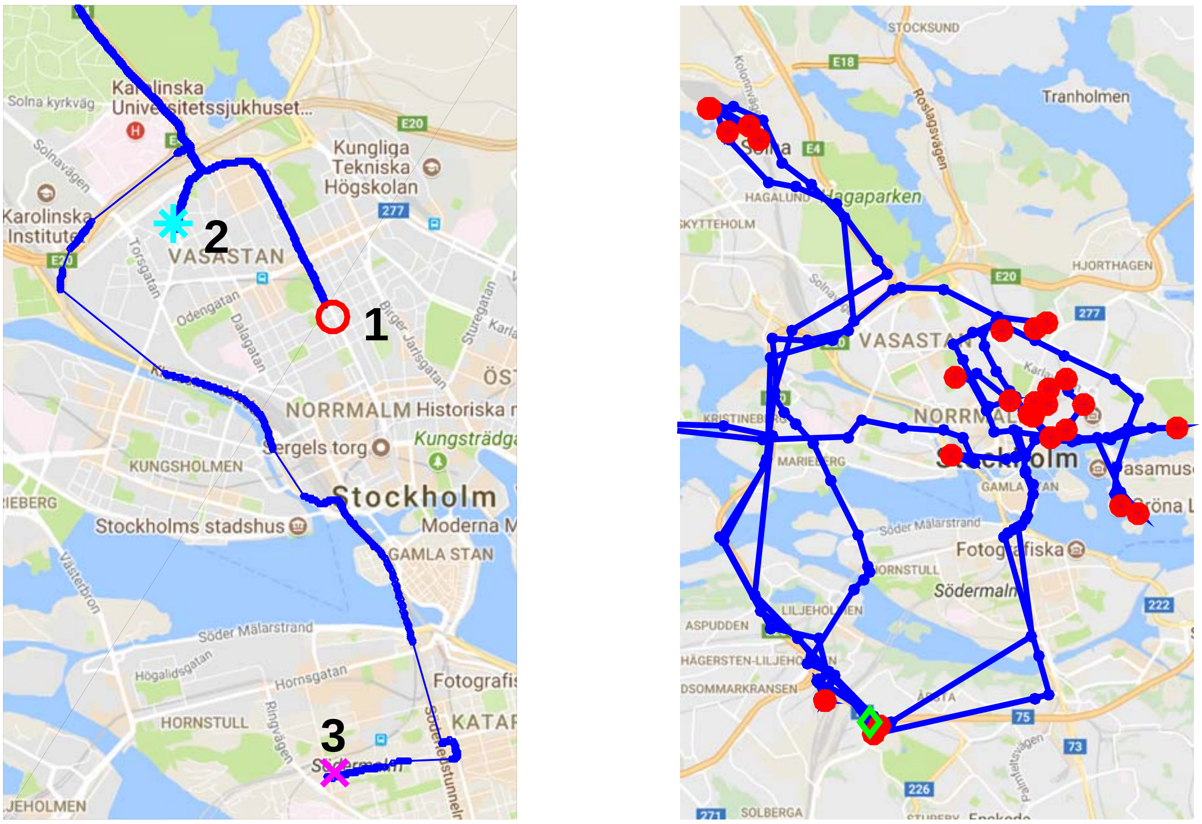


Figure 2. Delivery routes of the two off-peak trucks. Left: Truck A making dedicated deliveries (same route every day). Right: Truck B making consolidated deliveries (a typical day on 16 May, 2016).

4. Evaluation methodology

4.1. Dimensions of transport efficiency

In general, freight transport efficiency refers to the ability to deliver goods without wasting materials, time or energy. Four dimensions of transport efficiency are considered here: driving efficiency, delivery reliability, energy efficiency and service efficiency. Each dimension is discussed in more detail below.

Driving efficiency

Driving efficiency refers to the efficiency with which goods are moved from warehouses to delivery points. Average speed and travel time are the most straightforward indicators for measuring driving efficiency. In a congested urban network, delivery vehicles are forced to travel at low speeds and in stop-and-go conditions, which significantly increases the travel time and reduces the number of customers that can be served during each shift. As pointed out by Holguín-Veras et al. (2011), it is unlikely for carriers to pass on the costs associated with congestion and tolls on to the customers, and this aspect is therefore important from the carriers' perspective since it directly reflects the carriers' productivity and profitability.

Delivery reliability

Delivery reliability concerns the variability of travel times and arrival times to the delivery points. Travel time reliability is increasingly being considered an important aspect of congestion and transport network performance (Chen et al., 2003). High reliability indicates good network performance, and implies that carriers need to allocate less buffer time in order to arrive at the customers on time. Further, the recipients need to keep safety stocks in case the expected deliveries do not arrive on time, which occupies storage capacity physically and capital financially. Delayed delivery can indicate extra costs for both carriers and recipients for reasons such as extra delivery, overtime compensation for workers, and eventually arises stock-out costs for the recipients (Krüger and Vierth, 2015). The aspect is therefore important from both carriers and recipients' point of view. Travel time variability is difficult to evaluate, however, when the delivery routes and expected delivery times are not strictly constrained (Figliozzi, 2010).

Energy efficiency

Energy efficiency is measured by the fuel consumption per distance driven. This indicator not only captures the effects of congestion and stop-and-go traffic, but also disturbances such as traffic lights and pedestrians. For the same reasons as for the driving efficiency dimension, energy efficiency is critical from the carriers' perspective, but it is also an important societal and environmental aspect as it is closely tied to emissions of greenhouse gases and other pollutants.

Service efficiency

The driving and energy efficiency indicators describe the time spent on the road network, but do not include the time spent at the customers. Service efficiency is therefore examined using the indicators of service time per delivery stop, service speed, and number of service stops versus driving time. Service time is the time spent by the delivery vehicle at the customer's location (Holguín-Veras et al., 2005), and it includes the time for loading and unloading the goods, walking between the truck and customer location, contacting the recipient and other related activities. Service speed is defined as the goods volume delivered divided by the service time. For the goods recipients, long service time and low service speed indicate a longer time for the personnel to receive goods, which disrupts their regular business. This aspect is thus critical for both carriers and recipients. The indicator of number of service stops versus driving time is also introduced in our study to examine the characteristics of the delivery service. A higher number of service stops per unit of driving time means that the carriers can serve more customers on a shift. However, the distance between customers and the volume of each delivery should also be incorporated in the analysis in order to give a complete picture. This indicator is important from the carriers' perspective.

4.2. Economic evaluation of transport efficiency

The different dimensions of transport efficiency may be merged into a unified measure based on the economic importance of each dimension. The economic evaluation of transport efficiency is essential for examining the effectiveness off-peak deliveries compared to daytime. Relevant cost parameters for measuring the above-mentioned efficiency dimensions are needed in the evaluation, including the value of time, value of travel time variability, fuel price, and value of service time for freight transport.

4.3. Data sources for transport efficiency evaluation

New sensing technologies have made it possible to continuously measure and monitor the proposed indicators of transport efficiency. Three types of data sources were used in the evaluation and are discussed below.

Fleet Management System data

Commercial vehicles are commonly equipped with a Fleet Management System (FMS) which collects various kinds of data about the vehicle status. At minimum, FMS data typically contain vehicle locations and associated time stamps which are logged at certain intervals or events. From these basic data, the movement of the truck and indicators such as driving time, average driving speed, arrival time at customers, and service time may be calculated. Further, FMS data often contain additional information including fuel consumption, which is needed in order to evaluate energy efficiency. FMS data are thus valuable for evaluating all dimensions of transport efficiency. However, the sampling frequency may be low (sometimes several minutes between reports), which can limit the usefulness of the data.

FMS data were collected for both delivery trucks in the Stockholm pilot, although in different formats and with different frequencies. The FMS data for truck A are event-based, i.e. the system records a new entry when there is a new event such that the driver’s activity changes between driving/working/resting, or makes a stop. When the truck was moving, data were logged every ten minutes. The FMS data contain the time of the event, driver’s ID, driver’s activity, odometer, fuel level, accumulated duration, accumulated driving distance, accumulated fuel consumption, location address, latitude and longitude.

For truck B, the FMS data include timestamp, odometer reading, fuel level, instantaneous speed, GPS coordinates, ignition status, and driver change. The data were logged with a frequency of one record per minute.

GPS data

In situations where FMS data are not available or of insufficient quality, dedicated GPS devices may provide accurate and high-frequency data on the movement of the delivery trucks, including timestamps and latitude, longitude and altitude coordinates (Ben-Akiva et al., 2016). GPS data are thus valuable for evaluating all four dimensions of transport efficiency.

In the Stockholm pilot study, we installed a GPS receiver in truck A to complement the FMS systems and record locations with a frequency of one hertz (one record per second). The GPS receiver was connected to the engine of the vehicle so that the device is switched on when the vehicle is in operation. A fuel level measurement system was also installed and recorded the fuel consumption at the same frequency as the GPS receiver.

Logistics data

FMS data do not in general contain information about the amount of transported or delivered goods. Such logistics data are needed to evaluate service efficiency indicators such as goods delivered per service time, driving time or driving distance, and may be provided by the transport carrier or recipient. In the Stockholm pilot, the logistics data were provided by the goods recipients and include the volume of goods in TPE (standard transport unit) delivered by the trucks to each delivery point each day.

The three different data sources provide all necessary information for computing the above-mentioned indicators of transport efficiency. The framework for evaluating the transport efficiency of off-peak deliveries is shown in Figure 3.

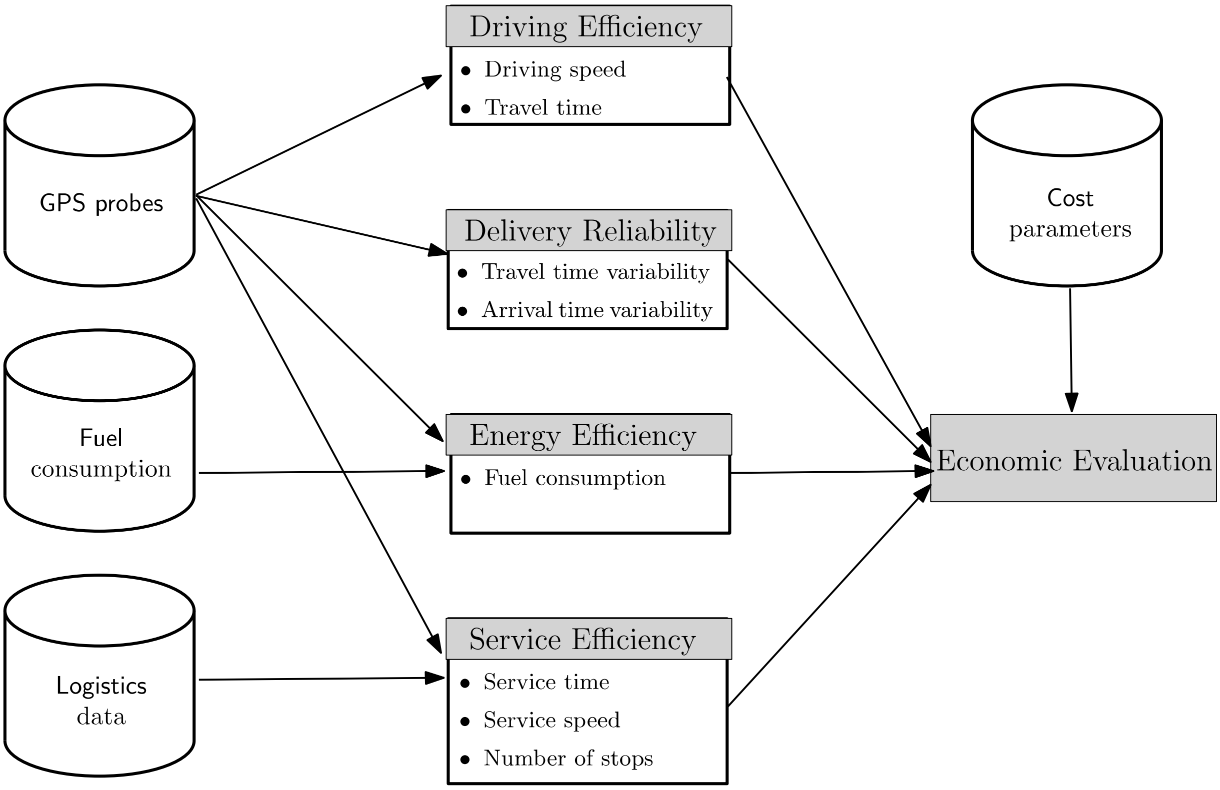


Figure 3. Transport efficiency evaluation framework based on multiple data sources.

4.4. Evaluation design

In order to control for other factors influencing transport efficiency, the evaluation of off-peak delivery would ideally be based on observations of the same delivery routes during both daytime and off-peak hours. However, the practical conditions around the pilot project imposed constraints on the experimental design. First, there were no deliveries to the stores served by truck A during daytime. Second, although truck B was active during both daytime and off-peak hours, the delivery routes varied between daytime and off-peak hours as well as from day to day.

In order to generate the comparison data for daytime deliveries, truck A was instructed to carry out artificial daytime delivery trips during a data collection period between May 9th and May 22nd, 2016. During this period, truck A traversed exactly the same delivery route to the three stores as during the off-peak hours, although no goods were unloaded at the delivery points. In total during the measurement period, five delivery trips were made to each store during daytime, and 10, 10 and 9 trips were made to stores 1, 2 and 3, respectively, at night. Data from these trips are used in the analysis to evaluate the transport efficiency indicators.

The fuel consumption of heavy-duty vehicles depends greatly on the load. In the artificial daytime delivery trips, truck A carried some goods. However, there is no exact report regarding the actual volume carried, thus the average fuel consumption for daytime trips were estimated based on the speed profile assuming that same goods volumes in daytime trips as in night-time hours. Further, the delivery efficiency dimension is not examined since no goods were unloaded in the daytime trips.

For truck B, the delivery routes cover the entire Stockholm region which gives an overall picture of freight transport efficiency during different hours of the day. By comparing the efficiency under off-peak hours and daytime hours, the evaluation incorporates the scheduling and planning of the shipper which takes into account the congestion levels in different parts of the city at different hours of the day. To capture the variation of congestion during the day, the daytime period is further divided into four intervals: 6:00-10:00, 10:00-15:00, 15:00-18:00, and 18:00-22:00. FMS data from a 10-month period (in total 244 days) between September 24th, 2015 and July 24th, 2016 are used in the transport efficiency evaluation. Since the delivery routes and points are different from day to day, the delivery reliability dimension is not studied for truck B.

The evaluation design is summarized in Table 1.

Table 1. Summary of evaluation design.

Delivery vehicle	**Off-peak service**	**Daytime reference**	**Efficiency dimension evaluated**
Truck A (static routes)	Dedicated delivery to single off-peak customers	Artificial delivery on off-peak routes (five days between 9 May and 22 May, 2016)	Driving efficiency Delivery reliability Energy efficiency
Truck B (dynamic routes)	Consolidated delivery to multiple off-peak customers, varying	Consolidated delivery to multiple daytime customers, varying	Driving efficiency Energy efficiency Service efficiency

	day-to-day	day-to-day (244 days between 24 September 2015 and 24 July 2016)	

5. Results

5.1. Driving efficiency

The distributions of driving speed of both trucks are depicted as box-and-whisker plots in Figure 4, with the top and bottom of each box at the 25th and 75th percentiles of the dataset, respectively. The whiskers are drawn 1.5 times the interquartile range away from the top and bottom of the box.

For truck A, the driving efficiency during off-peak hours was monitored in several periods during the pilot study and shows consistency over time. Figure 4, left diagram, shows an overall improvement in driving efficiency during off-peak hours compared to daytime. The driving speed to store 1 is markedly higher, 62.1 km/h versus 46.0 km/h (approximately 31% higher). This is a clear indication that the delivery route is congested during daytime. A t-test reveals that the difference is statistically significant at the 5% level. For the delivery trips to store 2, there is no significant difference in average speed, 64.7 km/h during off-peak versus 64.4 km/h during daytime. For store 3, the driving speed is higher during off-peak hours (59.0 km/h) compared to during daytime (50.7 km/h), although the difference is not statistically significant.

The travel times of truck A are given in Table 2, and are inversely related to the speeds since the delivery routes are fixed. The travel time to store 1 is almost 1.5 times longer during daytime than during off-peak hours (44.2 minutes compared to 31.2 minutes), and the difference is statistically significant at the 5% level. The differences in travel times to store 2 and 3 are not statistically significant.

For truck B, the average speeds during off-peak, daytime overall, and the four individual daytime intervals are shown in Figure 4, right diagram. The results show that in general, off-peak deliveries yield better driving efficiency compared to daytime deliveries. The average speeds during off-peak and daytime deliveries are 22.2 and 18.8 km/h, respectively, and the difference is statistically significant at the 5% level. There is evidence of severe congestion during the afternoon peak period 15:00-18:00 with the average speed of 14.0 km/h. Meanwhile, the average speed during the morning peak hour between 6:00-10:00 is relatively high (21.2 km/h), which is not consistent with typical traffic conditions in Stockholm at that time. The GPS data show that the delivery truck spends most of the morning peak hours in the suburban areas of Stockholm. Interviews with the manager of the delivery company confirm that the delivery schedule of truck B is designed based on the customers' locations to avoid congestion. During the morning peak hours the truck delivers to customers with large delivery volumes located in the suburban areas in Stockholm. The average speeds of the other two daytime intervals 10:00-15:00 and 18:00-22.00 are at the same level (21.7 km/h and 23.2 km/h, respectively) as during off-peak hours. This confirms the results obtained from truck A that there is generally little congestion in the middle of the day. Statistical tests show that there are no significant differences between off-peak hours and the three daytime intervals 6:00-10:00, 10:00-15:00 and 18:00-22.00.

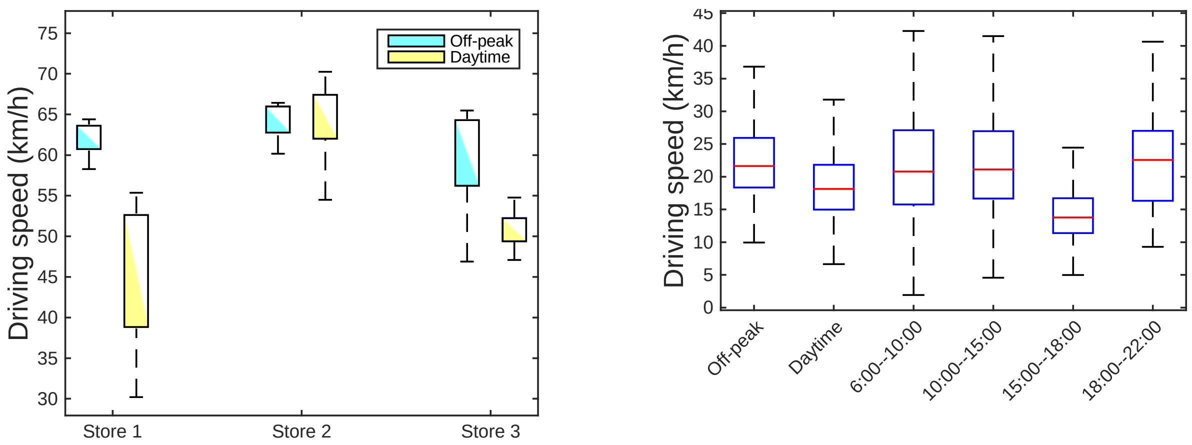


Figure 4. Driving speed. Left: truck A. Right: truck B.

5.2. Delivery reliability

The standard deviation of travel time for truck A to each store is given in Table 2. For deliveries to store 1, the standard deviation is much higher during daytime than off-peak, 12 minutes compared to 2.28 minutes. An F-test shows that the difference is statistically significant at the 5% level. For deliveries to stores 2 and 3, the standard deviations of travel time are approximately the same during daytime and off-peak, and F-tests show that there are no significant differences.

The distributions of the arrival times of truck A to the three stores are shown as box-and-whisker plots in Figure 5 for off-peak hours (left) and daytime (right). Figure 5 indicates that the arrival time variability at store 1 is lower during off-peak than daytime, but an F-test shows that the difference is not statistically significant given the limited number of observations. Further, F-tests of the arrival time variability at stores 2 and 3 show no significant differences between off-peak and daytime trips.

For the off-peak deliveries, arrival time variance is slightly lower for store 1 than for stores 2 and 3. This is because the goods to store 1 are received by the store personnel, and the driver needs to arrive at the store and unload the goods before the store closes at 11PM. The unloading processes at stores 2 and 3 are automated through special storage equipment, which give the driver more flexibility in arrival time. However, statistical tests of the off-peak arrival time variances show no significant differences between the three stores.

Further, it is observed that the daytime delivery trips to store 1 were made between 8:00 to 10:00, which is in the morning peak. This is the reason for the lower driving efficiency as well as higher travel time variability to store 1 compared to off-peak hours. For store 2, the delivery trips were made around 12:00, and the variability of both travel time and arrival time are small. The delivery trips to store 3 were completed around 15:00 at the onset of the afternoon peak (see Figure 1), which could explain the relatively low driving efficiency. Interviews with the manager of the logistics company confirm that traffic conditions on the delivery routes are congested mostly between 7:00-9:00 in the morning, and not congested during the middle of the day. In other words, the truck travels at nearly free flow speed to store 2 during daytime.

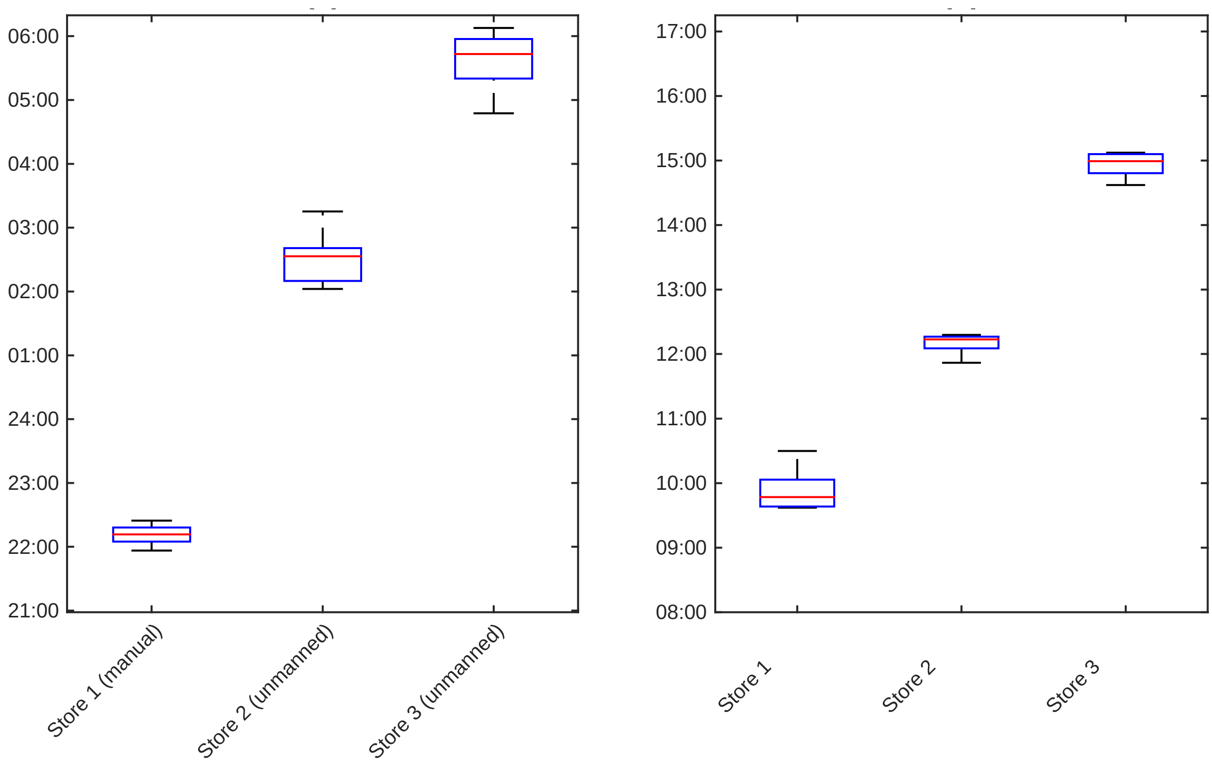


Figure 5. Arrival time of truck A at each store. Left: off-peak hours. Right: daytime.

5.3. Energy efficiency

Figure 6, left diagram, shows the fuel consumption of truck A to each of the three stores. The average fuel consumption to each store during off-peak hours is 28.92, 28.22 and 28.90 litres/100 km, respectively. The fuel usage of the delivery trucks is highly affected by the weight of the carried goods. Unfortunately, there is no information regarding the weight of carried goods for the daytime trips, which means that a straight comparison of fuel consumption between off-peak and daytime trips is not meaningful. Under the assumption that the same volume of goods is delivered as at night, the average emission of the daytime trips is estimated from the average speed profile using the EMFAC Web Database (California Environmental Protection Agency, 2016). Further, the average fuel consumption of daytime deliveries is calculated from the CO_2 emission due to their linear relation (U.S. Environmental Protection Agency, 2016). The estimated fuel consumption of the daytime trips is 37.07, 28.22 and 31.85 litres/100 km (shown in italic in Table 2), respectively, which is 18%, 0% and 10% higher compared to the corresponding night deliveries.

The average fuel consumption of truck B for off-peak, daytime, and the four individual daytime intervals is shown in the right diagram in Figure 6. The fuel consumption during off-peak and daytime is 25.16 litres/100 km and 27.23 litres/100 km, respectively, and the difference is statistically significant. Thus, daytime deliveries consume 8.2% more fuel compared to night trips. In fact, the fuel consumption is significantly higher during every daytime interval compared to the off-peak hours. The fuel consumption is the highest in the afternoon peak 15:00-18:00 (30.96 litres/100 km compared to 27.23 litres/100 km during daytime on average) because of the congestion. As expected, the fuel efficiency of truck B during the different time intervals shows more or less the opposite pattern compared to the driving speed in Figure 4 right diagram, i.e., lower speed results in higher fuel consumption and vice versa.

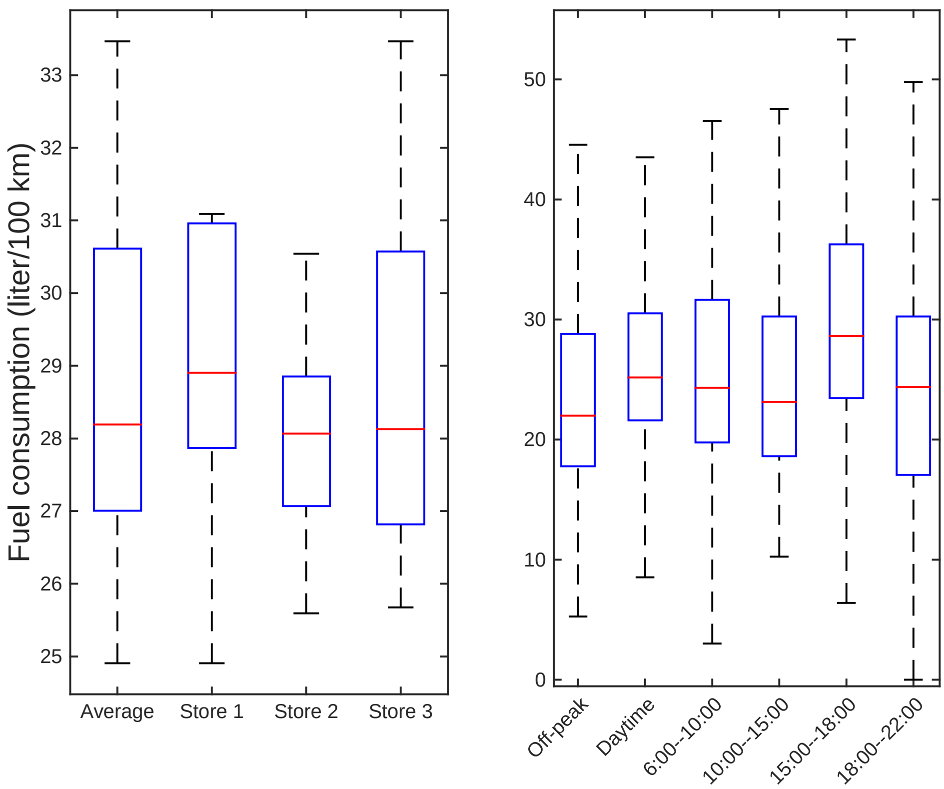


Figure 6. Fuel consumption. Left: truck A. Right: truck B.

5.4. Service efficiency

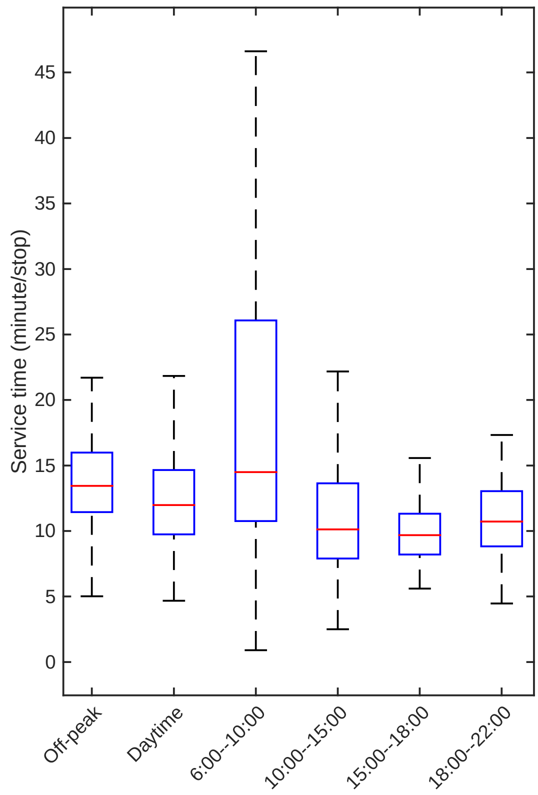
On the daytime trips performed by truck A, no actual deliveries were made to the three stores.

Thus, there is no data for evaluating service efficiency during daytime. For the off-peak deliveries, the average service speed at store 1 (27.6 TPE/h) is higher than at stores 2 (20.9 TPE/h) and 3 (21.4 TPE/h). This could be explained by differences in the unloading process, which is assisted by the store personnel at store 1, but is carried out by the driver alone at the other, unmanned stores.

For truck B, the service times for off-peak, daytime overall, and the four individual daytime intervals are shown as box-and-whisker plots in Figure 7, left. The results show a tendency towards shorter average service time per stop in daytime than during off-peak hours (13.9 minutes compared to 14.4 minutes). This is in agreement with experiences from most previous off-peak delivery studies in which the drivers need to handle the unloading process on their own. However, the difference is small and not statistically significant. Service times are the highest during the morning peak hours, 6:00-10:00. The service times in this period for a typical day (16 May, 2016) are indicated in Figure 8 left. The customers are located in the suburbs of Stockholm and the service time at each stop is relatively long. This is in agreement with information provided by the manager, stating that the truck makes large volume deliveries during this time period.

Finally, the number of service stops per driving hour is shown in Figure 7, right. The number of stops is slightly higher during off-peak hours than during daytime overall, 3.73 versus 3.58 stops per driving hour. This may imply that the truck can serve more customers during off-peak hours than during regular hours even though the service time per stop is longer. However, the difference is not statistically significant at the 5% level. Since the delivery routes and goods volumes are not the same during off-peak and daytime hours, definitive conclusions regarding service efficiency cannot be drawn.

It is worth pointing out that the number of service stops per driving hour in the afternoon peak between 15:00-18:00 is much higher compared to the other time periods during the day, 7.11 stops per hour. This may be explained by the delivery routes during daytime being adjusted so that the truck delivers to locations with a high density of customers in order to avoid getting stuck in the afternoon congestion. Figure 8, right diagram, shows the service locations and service times in the afternoon peak. It can be observed that the customers are located in the city centre and that the service time at each location is short.



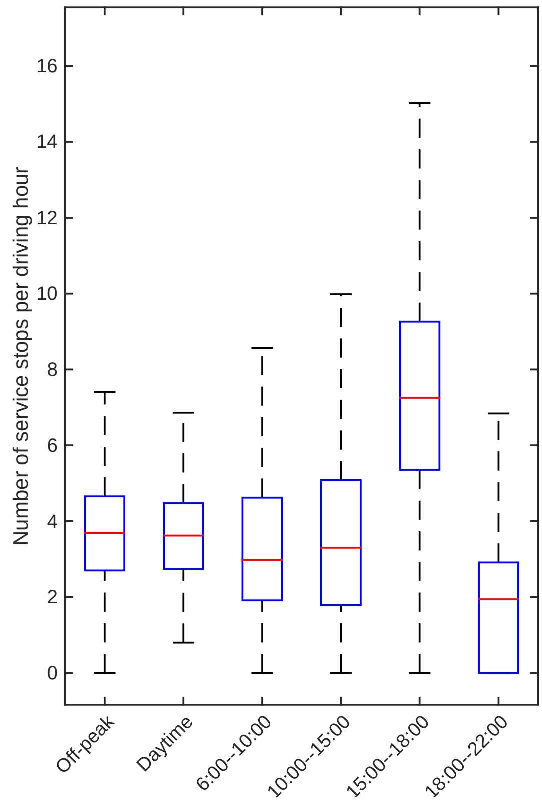
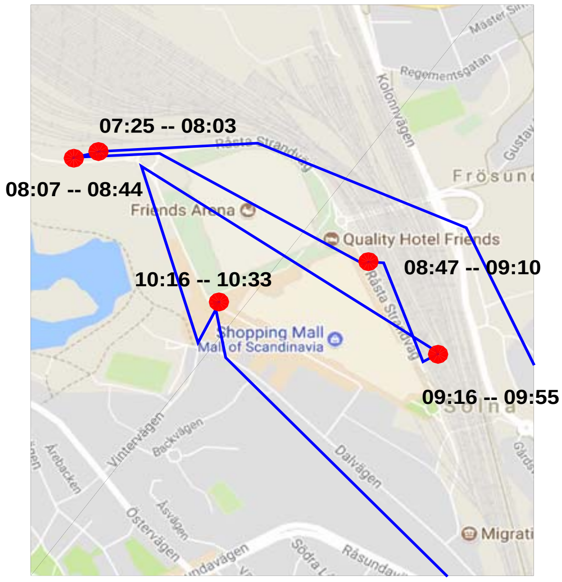


Figure 7. Service efficiency indicators of truck B. Left: service time (minutes/stop). Right: number of service stops per driving time.



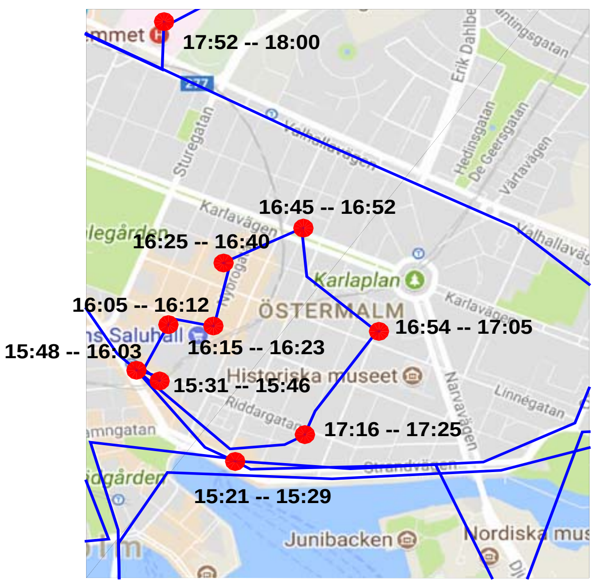


Figure 8. Delivery stops (in red dots) and stop time of truck B on a particular day (16 May, 2016). Left: morning peak hours. Right: afternoon peak hours.

Table 2 summarizes the evaluation of the four dimensions of transport efficiency for both truck A (dedicated deliveries) and truck B (consolidated deliveries) in the Stockholm pilot.

Table 2. Transport efficiency indicators. (Statistically significant differences between off-peak and daytime are in bold. Fuel consumptions of truck A's daytime deliveries are estimated and shown in italic.)

Truck A (dedicated delivery)						
	Off-peak delivery (10PM-6AM)			Daytime delivery (6AM-10PM)		
	Store 1	Store 2	Store 3	Store 1	Store 2	Store 3
Driving efficiency						
Average speed (km/h)	**62.08**	64.71	58.95	**46.00**	64.37	50.74
Travel time (minutes)	**31.23**	29.02	41.21	**44.17**	29.55	44.67
Delivery reliability						
Standard deviation of travel time (minutes)	**2.28**	1.80	5.29	**12.00**	3.05	2.37
Standard deviation of arrival time (min)	35.12	33.87	41.19	21.53	10.40	21.21
Energy efficiency						
Fuel consumption (liter/100 km)	28.92	28.22	28.90	*34.07*	*28.22*	*31.85*
Service efficiency						
Service time (minutes)	46.44	46.17	51.66			
Service speed (TPE/h)	27.63	20.90	21.39			
Truck B (consolidated delivery)						
	Off-peak delivery 22:00 - 6:00	Daytime overall 6:00 - 22:00	Daytime delivery 6:00 - 10:00	Daytime delivery 10:00 - 15:00	Daytime delivery 15:00 - 18:00	Daytime delivery 18:00 - 22:00
Driving efficiency						
Average speed (km/h)	**22.16**	**18.81**	21.17	21.73	**13.96**	23.22
Energy efficiency						

Fuel consumption (litre/100 km)	**25.16**	**27.23**	**28.64**	**27.00**	**30.96**	**24.57**
Service efficiency						
Service time (minutes)	14.35	14.43	18.45	14.36	11.30	11.97
Number of service stops per driving hour	3.73	3.58	3.54	3.73	7.11	2.07

5.5. Economic evaluation of improved transport efficiency

An economic assessment of the transport efficiency impacts is conducted using the results obtained from truck A's delivery trips and the results are given in Table 3. The evaluation is composed of the cost savings due to improved driving efficiency, fuel efficiency and delivery reliability. No real goods were delivered on the daytime trips, thus the delivery efficiency dimension is left out in the economic evaluation. Of the three dimensions, driving efficiency and fuel efficiency are critical to the carriers' perspective and the economic benefits of improved performance are relatively easy to compute. The economic effects on delivery reliability include many factors, such as resources for keeping stocks (recipients' point of view), and allocating more buffer time in order to arrive at delivery points on time (carriers' perspective).

For road freight transport in Sweden, the official average values of time are 7 SEK/vehicle hour for goods costs, 122.09 SEK/vehicle hour for vehicle costs, and 235 SEK/vehicle hour for driver costs (Trafikverket, 2016a). For the cost savings from lower fuel consumption, the unit price 12.79 SEK/litre for diesel in 2016[1] is used. Finally, using a case study with grocery deliveries in Sweden, Andersson et al. (2017) estimated that the value of transport time variability is between 13.3–21.2 SEK per standard deviation of transport time (minutes) each delivery. Here the average value of the study (17.25 SEK per minute per delivery) is used.

In the Stockholm off-peak pilot, the average travel time from the warehouse to store 1 is reduced by 12.94 minutes, which leads to a cost reduction of 78.52 SEK per trip. The fuel consumption from the warehouse to store 1 is reduced from 34.07 liters/100 km in the morning peak to 28.92 liters/100 km at night. The distance between the warehouse and store 1 is 32.25 km, which leads a

[1] Data obtained from Svenska Petroleum & Biodrivmedel Institutet, www.spbi.se

cost reduction of 21.24 SEK per delivery trip. Finally, the reduced standard deviation of 9.72 minutes in travel time standard deviation to store 1 yields a cost reduction of 167.67 SEK per delivery trip. Thus, for each delivery trip from the warehouse to store 1, the economic benefits gained from improved transport efficiency by shifting deliveries from the morning peak to night-time are estimated to 267 SEK.

The economic evaluation for the deliveries to store 2 and 3 are given in Table 3. For the deliveries to store 2, the cost savings are insignificant since the truck travels without any congestion during daytime. To store 3, the improved driving and energy efficiency give modest savings. Due to the automated unloading systems at stores 2 and 3, the driver has the flexibility to complete the deliveries anytime before the stores open in the morning and the arrival time variability is not a critical issue to these two stores. Further, automated unloading process eliminates the need of personnel at the recipients' location and the value of travel time variability is expected to be lower compared to the deliveries to store 1.

Table 3. Economic benefit of truck A's deliveries during night hours compared to daytime (in SEK per delivery).

Cost benefit	Store 1	Store 2	Store 3
Driving efficiency	78.52	3.21	21.00
Energy efficiency	21.24	0	14.22
Delivery reliability	167.67		

6. Discussion and conclusion

The paper evaluated the transport efficiency impacts of permitting night-time urban goods deliveries in an off-peak pilot study in Stockholm, Sweden. Four dimensions of transport efficiency were considered: driving efficiency, delivery reliability, energy efficiency and service efficiency. The efficiency aspects were evaluated using multiple sources of data collected from two delivery trucks in the pilot study, and the results have been verified with statistical tests. The two trucks employed different delivery schemes: truck A made dedicated deliveries to a low number of large customers each night, and was used to study the efficiency aspects on fixed delivery routes at varying times of day. Transport efficiency has been examined over multiple time periods and showed similar performance. Truck B made consolidated deliveries to a large number of varying small customers, and was used for evaluating the overall efficiency impacts in the urban network, incorporating the scheduling and planning of the carrier considering the congestion levels in different parts of the city at different hours of the day. A 10-month data set from truck B was employed in the evaluation.

The evaluation shows that night-time deliveries in general achieved better performance regarding driving efficiency, delivery reliability and energy efficiency. The driving speed on the same delivery route at night is approximately 31% higher than in the morning peak using the data from the truck making dedicated deliveries, and the economic benefit from improved transport efficiency on this delivery route is estimated to 267 SEK per delivery. Based on data from the consolidated deliveries, the study shows that the driving speed in the entire urban network during night is ca. 59% higher than in the afternoon peak. Meanwhile, no significant congestion was observed on the delivery routes in the middle of the day. No definitive conclusion can be drawn regarding service efficiency due to the different amounts of delivered goods during night and daytime.

The findings that off-peak deliveries have positive transport efficiency impacts are in line with previous studies in other urban areas. The impacts on driving efficiency and fuel efficiency are moderate compared to what has been reported in, e.g., New York. An important reason for this is likely that congestion levels in Stockholm are comparatively modest, in particular outside the morning and afternoon peak hours. The evaluation also highlights that the routes and schedule of the truck making consolidated deliveries are already adjusted in order to meet customers' demand and at the same time avoid congestion. The transport efficiency impacts are thus more significant when comparing congested vs. non-congested hours rather than night hours vs. day hours. As a consequence, the permission to deliver goods during night does not necessarily imply an increase in transport efficiency for the carrier and the recipient, but depends on the existing schedule of daytime deliveries. In any case, the removal of the night-time restriction increases the flexibility of the scheduling to consider more non-congested hours.

The study evaluated the performance of both delivery trucks that were allowed to make night-time deliveries in the inner city, and thus represents a full analysis of the Stockholm pilot. Given the limited scale of the pilot study, the conclusions from the analysis are somewhat dependent on the particular features of the two delivery services included in the study. In any case, the case study provides robust evidence for significant increases in travel speed and fuel savings (and, hence, reductions of CO_2 emissions) during off-peak hours compared to peak hours. Implementation of off-peak is associated with additional costs for labour and equipment, etc., which are not considered here. These costs are important for a full evaluation of off-peak deliveries since economic efficiency is a key component of transport system, but are considered out of scope for this paper where the focus is on transport policy.

A full evaluation of the impacts of off-peak strategies, such as the Stockholm pilot, should consider other aspects such as stakeholder satisfaction (carriers, recipients, authorities, the general public, etc.), noise measurement, economic efficiency, and environmental impacts. A comprehensive assessment framework may also act as decision support for policymakers. For the Stockholm pilot study, research on most of these aspects is currently ongoing.

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