Abstract

It is increasingly recognized that even cities with severe traffic congestion during peak hours have available road capacity during nights, evenings and early mornings. Policies that shift urban goods deliveries from daytime to off-peak hours have the potential to increase the efficiency of the freight distribution, as well as to reduce negative external impacts. Between 2014 and 2016, the City of Stockholm ran a pilot project to assess the benefits and drawbacks of allowing inner city goods deliveries during off-peak hours, from late evening to early morning. This paper evaluates the transport efficiency impacts of the Stockholm off-peak pilot project. 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 the deliveries to the off-peak hours achieved better transport efficiency in driving efficiency, delivery reliability and energy efficiency.

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

1. Introduction

Urban population and economic growth have increased the demand for goods by businesses and residents. 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 impose 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 the GDP in EU countries (European Commission, 2007).

At the same time, goods deliveries negatively affect 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 of air pollution and greenhouse gas emissions, which are among the most severe environmental effects (Figlioizzi, 2011). In particular, 20%-30% of vehicle kilometres and 16%-50% of transport-related emissions of air pollutants (depending on the specific pollutant) are caused by freight transport in European cities (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 trips and the large number of delivery stops.

In the development of urban delivery systems, some cities tend to focus on building new or improving existing infrastructure, such as increasing road network capacity or building logistics parks, while others focus on operational changes with institutionally oriented initiatives to improve system performance without substantial new capital investments (Dablanc et al., 2013). However, urban freight distribution is an inter-dependent system with complex distribution networks, as well as a diverse set of stakeholders including shippers, recipients, logistics service providers, residents and local authorities (Macharis and Verlinde, 2012; Taniguchi and Thompson, 2011). Traditionally, policymakers have generally left freight transport matters to the private sector, where the demand for and the supply of freight transport services are generated (Lindholm and Behrends, 2012; Wittlöv, 2012). Even in countries with strong political entities, the policy component as applied to urban logistics is 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 are changing their approach on urban freight transport due to population growth in urban areas, urban economic development and competitiveness, and increasing environmental concerns (Wittlöv, 2012; Hesse and Rodrigue, 2004; Benjelloun et al., 2010). Many major European cities are now paying attention to urban freight transport as part of their overall transport strategies (Browne et al., 2014; Hall and Hesse, 2012). Examples of policy instruments considered to improve urban freight movements 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 road networks 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 daytime to off-peak hours, there is a potential to increase the efficiency of the freight distribution, as well as to reduce negative external impacts and (to some extent) congestion for other traffic during peak hours.

Between 2014 and 2016, the City of Stockholm ran an off-peak goods delivery pilot project, with the goal to examine the feasibility and potential of off-peak delivery considering factors such as delivery times, environmental and noise aspects, 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 6:00. Within the pilot project, the city of Stockholm issued special permits to two heavy delivery trucks, specially
designed 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 off-peak 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 receivers are defined. For each indicator, a set of sufficient data for the evaluation is identified. Taking advantage of emerging sensing technologies such as vehicle GPS probe data and Fleet Management System data, the methodology is applied to the Stockholm off-peak pilot. The evaluation provides insights to assist planners, decision makers and local authorities for the design and implementation of effective policy initiatives.

The paper is organized as follows. Section 2 provides a review of 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 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 focusing on commercial deliveries during off-peak hours have been carried out in large urban areas, targeting goods receivers and carriers; see Sánchez-Díaz et al. (2016) for a comprehensive review. 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 taken place 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 receivers play the dominant role in decisions about delivery time. The project used GPS-enabled 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 off-peak delivery in the New York metropolitan area has potential economic benefits in the range of 147 to 193 million dollars per year from increased productivity of the freight industry, travel time savings to road users, and environmental benefits to society. A recent study shows that the reduction of the emissions per kilometre in New York City due to a shift to off-peak hours can 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 during night hours instead of several smaller delivery trucks during the day. Although the projects provided evidence of noise reduction during both traffic and deliveries, no quantitative analysis has been presented on the transport efficiency effects in the distribution process.

A framework for quantifying the traffic effects of restrictions with respect to delivery receiver 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.

In 2005-2006, an inner city evening delivery scheme was tested by two grocery companies in a pilot project in Stockholm (Blinge and Franzén, 2007), with dedicated routes designed for the deliveries to the participating stores. The results showed that the possible time savings were around 20-25% when the delivery starts after 18:00 compared to daytime delivery.

Most of the above-mentioned studies focus on policies for promoting off-peak deliveries. The incentives for carriers and receivers 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. However, the available evidence on the transport efficiency impacts of shifting goods deliveries to off-peak hours is still limited. As pointed out by van Duin and Quak (2007) and Cui et al. (2015), urban freight policy is frequently based on insufficient analysis and evaluation regardless of local characteristics and dynamics. It is necessary to have a systematic evaluation approach in order to increase the understanding of off-peak urban distribution logistics.

3. Stockholm off-peak pilot project

3.1. Study area description

Stockholm is a fast growing city, 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 ton) on the roads every day (Stockholms Stad, 2014a). In 2006, light and heavy vehicles accounted for 17% of all traffic entering the city, and 19% of the traffic exiting the city during the congestion charging hours (Transek, 2006). Delivery trucks in Stockholm frequently encounter the problem that the assigned loading/unloading spaces are occupied by other vehicles so that the trucks have to drive around the area in search for other parking options or wait until the assigned space is free.

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 Jenelius and Koutsopoulos (2013) and Rahmani and Koutsopoulos (2013). 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 where the speed drops to ca. 31 km/h, and the other is at 16:30 in the afternoon.
where 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 are 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.](image)

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 night delivery considering factors such as delivery times, environmental and noise aspects, 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 6:00 due to concerns for 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 to two heavy delivery trucks to deliver goods during the restricted time period. The shippers and receivers of the goods deliveries were closely involved in the project and committed to adjusting the deliveries to off-peak hours. The two trucks were specially designed to reduce noise and pollution. Moreover, various noise-reducing cargo handling technologies, such as silent
forklifts and roll cages, and increased noise awareness during deliveries for the drivers were designed and used in order to reduce noise and vibration levels during delivery.

The two trucks in the pilot study made delivery tours according to different schemes. 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) and with the diesel engine elsewhere. Truck A made dedicated large volume deliveries to one of three grocery stores in Stockholm inner city with each trip; 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 green star and a pink cross, respectively. The stores were selected by the store chain company based on the feasibility of receiving goods during off-peak hours.

Every weekday evening during the pilot, truck A travelled from the logistics company’s terminal to the warehouse located in the north of Stockholm to load the goods, and drove to the first store. After completing the delivery, 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. The goods delivered to Store 1 were received by the store personnel, while the deliveries at Store 2 and 3 were unassisted. Specially designed goods-receiving equipment was installed at these two stores and the driver could easily unload the truck. The delivery schedule for the involved three stores was different on weekends. Most part of truck A’s delivery route is on highways.

The second vehicle, denoted truck B, is gas-fuelled. 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 (Figure 2, right). The warehouse is located in the south of Stockholm and shown as a red diamond in the figure, and the customers are different restaurants and hotels that are dispersed in the entire Stockholm region. Due to the business characteristics of the customers, the delivery points of truck B varied from day to day.
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 aspect 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 is the most straightforward indicator 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 driving time and reduces the number of customers that can be served during a 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, thus this aspect is important from the carriers’ perspective since it directly reflect 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 used as a measure 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 to the customers on time. Further, customers need to keep smaller stocks in case the expected deliveries do not arrive on time. Therefore, the aspect is important from both carriers and receivers’ point of view. However, travel time variability is difficult to evaluate when the delivery routes and expected delivery time are not strictly constrained (Figliozzi, 2010).

**Energy efficiency**

Energy efficiency is measured by fuel consumption per driven distance. 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 greenhouse emissions 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. Thus, service efficiency is 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 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 receiver and other related activities. Service speed is defined as the goods volume delivered divided by the service time. For the goods receivers, long service time and low service speed indicate longer time for the personnel to receive goods, which can lead disturbances to their regular business. Thus, these two indicators are critical for both carriers and receivers. Further, the indicator of number of service stops versus driving time is introduced in our study to examine the characteristics of the delivery service. Larger number of service stops per unit driving time means the carriers can serve more customers in 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. Data sources for evaluation

New sensing technologies have made it possible to continuously measure and monitor the proposed indicators of transport efficiency. Three types of data collection methods were used in the Stockholm off-peak pilot project and are discussed below.

**Fleet Management System data**

Commercial vehicles are commonly equipped with a Fleet Management System (FMS) that collects various kinds of data about the vehicle status. At minimum, FMS data typically contain vehicle locations and associated time stamps that 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 the customers, and service time may be calculated. Further, FMS data often contain additional information including fuel consumption, which is needed in order to evaluate the 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 is moving, data are 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, a GPS receiver was installed 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. Fuel level measurement system was also installed and recorded the fuel consumption at the same frequency of 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 receiver. In the Stockholm pilot, the logistics data were provided by the goods receivers 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.
4.3. 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, artificial daytime delivery trips were carried out with truck A during a data collection period between May 9th and May 22nd, 2016. During this period, truck A traversed exactly the same delivery routes to the three stores as during the off-peak hours, although no goods were unloaded at the delivery points. In total, five delivery trips were made to each of stores 1, 2 and 3 during daytime, and 10, 10 and 9 trips in off-peak hours were made to each store during the measurement period, respectively. 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 vehicle’s load. In the artificial daytime delivery trips truck A carried some goods. However, there is no exact report regarding the actual volume carried, and it is not possible to evaluate the energy efficiency dimension based on the dataset.

For truck B, the delivery routes cover the entire Stockholm region which gives an overall picture of freight transport efficiency. 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 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>
<thead>
<tr>
<th>Delivery vehicle</th>
<th>Off-peak service</th>
<th>Daytime reference</th>
<th>Efficiency dimension evaluated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck A</td>
<td>Dedicated delivery to single off-peak customers</td>
<td>Artificial delivery on off-peak routes (five days between 9 May and 22 May, 2016)</td>
<td>Driving efficiency (static routes) Delivery reliability</td>
</tr>
<tr>
<td>Truck B</td>
<td>Consolidated delivery to multiple off-peak customers, varying day-to-day</td>
<td>Consolidated delivery to multiple daytime customers, varying day-to-day (244 days between 24 September 2015 and 24 July 2016)</td>
<td>Driving efficiency (dynamic routes) Energy efficiency Service efficiency</td>
</tr>
</tbody>
</table>

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. During the measurement period where reference daytime data are available, the sample size of daytime deliveries is small and the differences not statistically significant. However, we can observe an overall improvement in driving efficiency during off-peak hours compared to daytime as shown in the left diagram in Figure 4. The driving speed to Store 1 is markedly higher during the off-peak hour deliveries compared to daytime, 62.1 km/h versus 46.0 km/h (approximately 31% higher). For the delivery trips to Store 2, there is no significant difference in average speed, 64.7 km/h versus 64.4 km/h. Finally for Store 3, truck A travels at higher speed during the off-peak hours (59.0 km/h) compared to during daytime (50.7 km/h).

For truck B, the average speeds for off-peak, daytime overall, and the four individual daytime intervals are shown in Figure 4 right. The average speeds during off-peak and daytime deliveries are 22.2 and 18.8 km/h, respectively. The results show that in general, off-peak deliveries yield better driving efficiency compared to daytime deliveries. There is evidence of severe congestion
during the period 15:00-18:00 with the average speed of 14.0 km/h, and the speed during off-peak hours is ca. 59% higher than the afternoon peak hours. However, 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 the traffic condition in Stockholm at that time. Closer examination of the GPS coordinates in the morning peak hours shows that the delivery truck spent most of the time in the suburban areas of Stockholm. Interviews with the manager of the delivery company confirm that the delivery schedule of truck B is specifically designed to avoid congestion based on the customers’ locations. The truck delivers to customers located in the suburban areas in Stockholm with large delivery volumes during the morning peak hours. 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.

![Figure 4. Driving speed. Left: truck A. Right: truck B.](image)

5.2. Delivery reliability

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 and daytime. Looking closely at the daytime trips in the right diagram in Figure 5, the delivery trips to Store 1 are made between 8:00 to 10:00, which is in the morning peak, thus the driving speed has much higher variance compared to trips to Store 2 and 3. Interviews with the manager of the logistics company confirms that traffic conditions on the delivery routes are mostly congested between 7:00-9:00 in the morning, and not congested during the middle of the day. Thus, the truck travels at free flow speed to Store 2 during daytime. The delivery trips to Store 3 were completed around 15:00 when the traffic flow starts to increase (see Figure 1), thus the average driving speed is slightly lower than the trips during off-peak hours.

For the dedicated deliveries, the travel time to Store 1 in daytime is almost 1.5 times longer than during off-peak hours (44.2 minutes compared to 31.2 minutes), and the variance of travel time in daytime is also much higher (Table 2). This shows that the delivery route is congested during the delivery periods, which causes low delivery reliability. For the delivery trips to Store 2, there is no much difference in the mean and standard deviation of travel time. This indicates low travel time variability in the middle of the day on this delivery route. Most part of the delivery route is on highway thus the trips are not much affected by the congestions in inner city. Finally for the
deliveries to Store 3, the travel time is marginally longer during daytime compared to at night (44.67 min versus 41.21 min) as the traffic begins to increase in the afternoon.

5.3. Energy efficiency

Figure 6, left diagram, shows the fuel consumption of truck A in off-peak hours. Overall, the average fuel consumption for off-peak hours is 28.67 litres/100 km.

For truck B, the fuel consumption during off-peak and daytime is 25.16 litres/100 km and 27.23 litres/100 km, respectively. The results show a tendency toward the off-peak deliveries having better energy efficiency compared to regular hour deliveries. Further, the average fuel consumption for off-peak, daytime, and the four individual daytime intervals are also shown in the right diagram in Figure 6. The fuel consumption is higher during all daytime intervals compared to the off-peak hours. Moreover, the fuel consumption in the interval 15:00-18:00 is the highest (30.96 litres/100 km compared to 27.23 litres/100 km for daytime on average) because of the congestion.
5.4. Service efficiency

On the artificial daytime trips generated 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 Store 2 (20.9 TPE/h) and 3 (21.4 TPE/h). This could be explained by the unloading process at Store 1 being assisted by the store personnel; while those at the other stores are automated through the equipment.

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 average service time per stop in daytime in overall is slightly shorter than during off-peak hours (13.9 minutes compared to 14.4 minutes). The results are in agreement with experiences from most of the previous off-peak delivery studies where the drivers may need to handle the unloading process on their own. Service times are the highest during the morning peak hours, 6:00-10:00. Using the FMS data from a typical day, the service times at the receivers in this period are indicated in Figure 8 left. We observe in the figure that the customers are located in the suburban area in Stockholm and the service time at each stop is relatively long, which confirms the information provided by the manager that the truck makes deliveries with large volume during this time period.

Finally, the number of service stops per driving hour is shown in Figure 7, right. The number of stops is in general higher during off-peak hours than during daytime overall, 3.73 versus 3.58 stops per driving hour. This implies 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, definitive conclusions regarding service efficiency cannot be drawn using the dataset since the delivery
routes and goods volumes are not the same during off-peak hours and daytime.

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 during the day, 7.11 stops per hour. This could be explained by the delivery routes during daytime being adjusted so that the truck delivers to locations with concentrated customers in order to avoid getting stuck in the afternoon congestion. Figure 8, right diagram, shows the service locations and times in the afternoon peak, and we observe that the customers are located in the city centre and the service time at each location is low.

Figure 7. Service efficiency indicators of truck B. Left: service time. Right: number of service stops per driving time.
Figure 8. Delivery stops (in red dots) and stop time of truck B. 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.

<table>
<thead>
<tr>
<th></th>
<th>Truck A (dedicated delivery)</th>
<th>Truck B (consolidated delivery)</th>
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<tbody>
<tr>
<td></td>
<td>Off-peak delivery (10PM-6AM)</td>
<td>Daytime delivery (6AM-10PM)</td>
</tr>
<tr>
<td></td>
<td>Store 1</td>
<td>Store 2</td>
</tr>
<tr>
<td><strong>Driving efficiency</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>62.08</td>
<td>64.71</td>
</tr>
<tr>
<td><strong>Delivery reliability</strong></td>
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<td></td>
</tr>
<tr>
<td>Travel time (minutes)</td>
<td>31.23</td>
<td>29.02</td>
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<tr>
<td>Standard deviation of travel time (minutes)</td>
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<td>1.80</td>
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<td><strong>Energy efficiency</strong></td>
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<td>Fuel consumption (liter/100 km)</td>
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<td>28.22</td>
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<td><strong>Service efficiency</strong></td>
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<td>Service time (minutes)</td>
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<td>Service speed (TPE/h)</td>
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</table>

6. Discussion and conclusion

The paper evaluated the transport efficiency impacts of transferring urban goods deliveries from daytime to off-peak hours 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 data collected from two delivery trucks in the Stockholm off-peak pilot. The two trucks employed different delivery schemes: one truck made dedicated deliveries to a low number of large customers each night, and was used to study the efficiency aspects on the same delivery routes; the other truck made consolidated deliveries to a large number of varying small customers, and was used for evaluating the overall efficiency impacts in the urban network.
The evaluation of the Stockholm pilot study showed that off-peak deliveries in general have better performance regarding driving efficiency, delivery reliability and energy efficiency. The driving speed on the same delivery route in off-peak is approximately 31% higher than in the morning peak using the data from the truck making dedicated deliveries, and the driving speed in the entire urban network during off-peak is ca. 59% higher than in the afternoon peak based on data from the consolidated deliveries. No definitive conclusion can be drawn regarding service efficiency based on the dataset from the pilot project.

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, which is likely because congestion levels in inner city Stockholm are relatively modest. Moreover, the evaluation highlights that the delivery 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. Thus, larger positive impacts on transport efficiency of off-peak delivery are expected when using the same delivery routes during both periods. It is worth some discussion whether to compare transport efficiency impacts on the exact same delivery routes. As in the dedicated delivery using truck A, it is straightforward to compare the transport efficiency dimensions and interpret the results with the same delivery routes. However, the daytime trips of dedicated deliveries in this study are artificial, and the delivery routes and schedules would be different in reality. Before the Stockholm pilot, the deliveries to the involved three stores were provided by several trucks in multiple trips every day in order to meet the demands of the stores without disturbing the regular business. Thus, evaluation using different delivery routes during daytime/off-peak as with the consolidated deliveries are more realistic though more difficult to compare.

This study focused on the transport efficiency aspects from shifting goods deliveries from daytime to off-peak hours. It should be emphasized that a full evaluation of the impacts of off-peak strategies, such as the Stockholm pilot, should include other aspects such as stakeholder satisfaction (carriers, receivers, authorities, the general public, etc.), noise measurement, and environmental impacts. Cost-benefit analysis may also be an appropriate tool for evaluating such policies. A comprehensive assessment framework may also act as decision-support for policy makers. For the Stockholm pilot study, research on most of these aspects is currently ongoing.

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