ABSTRACT

Goods deliveries constitute an important part of road traffic in urban areas and the transport efficiency is often low due to congestion. An off-peak delivery pilot project in Stockholm seeks to evaluate the potential for commercial traffic to make use more off-peak hours, from the late evening to the early morning. This paper evaluates the transport efficiency of the off-peak pilot project in Stockholm, in terms of driving efficiency, delivery reliability, energy efficiency and service efficiency aspects. For each aspect, indicators are introduced and examined. The proposed evaluation framework uses vehicle Global Positioning System (GPS) probe data, fleet management data, and logistic information. The results suggest that shifting the deliveries to the off-peak hours can achieve better transport efficiency in all four aspects.

Keywords: Goods transport, urban freight, off-peak delivery, transport efficiency
INTRODUCTION

Congestion is a major problem in metropolitan areas throughout the world. Studies show that commercial traffic makes a significant contribution to congestion and environmental emissions in many large cities (1). The growing congestion also has an adverse effect on the freight industry, and stakeholders are increasingly being forced to consider switching delivery operations to less congested times of the day in order to ensure faster and reliable delivery services.

Shifting goods deliveries to less congested hours has a very long history. It was already implemented in ancient Rome when Julius Caesar proclaimed a ban on commercial deliveries during the daytime as a solution to ease congestion in the streets (2). In recent years, a number of studies focusing on commercial deliveries during off-peak hours have been carried out in large metropolitan areas, targeting goods receivers and carriers. Successful examples include the New York City Off-hour Delivery Project (3), (4) and the freight transport strategy in London during the Olympic games in 2012 (5). Similar studies have also taken place in the Netherlands (6), Spain, Ireland (7), and Belgium (8). A comprehensive literature review on various off-peak delivery projects around the world can be found in (9).

The off-hour delivery project in New York City is one of the broadest studies carried out on this topic. Starting 2002, the New York State Department of Transport set up a project team to study methods for encouraging off-peak deliveries in Manhattan and Brooklyn. The project emphasized the design of the delivery program and various productivity measures were evaluated. While studying the necessary conditions for off-peak urban freight distribution systems, it was found that the goods receivers play the dominant role in decisions about delivery time. The project successfully used GPS-enabled cell phones in the participating trucks to transmit location, velocity, date and time. It was found that average travel speeds were significantly higher during off-hours compared to daytime. Furthermore, the service times decreased during off-hours, since less time was lost to searching for parking and to locating and interacting with the personnel. It was concluded that if off-peak delivery can be fully implemented in the New York metropolitan area, the economic benefits are expected to be in the range of 147 to 193 million dollars per year due to increased productivity of the freight industry, travel time savings to road users, and environmental benefits to society.

In the studies carried out in Barcelona and Dublin (7), low noise trucks and loading equipment were employed for a few deliveries in large volume during the night hours instead of several smaller delivery trucks during the day. Although the projects in these two cities 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 delivery restrictions in urban areas was presented in (11). Scenarios such as delivery restrictions during both morning and afternoon peak hours for all commercial and grocery stores, as well as delivery restrictions during morning peak hours for 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 in both scenarios led to increases in average vehicle speeds, especially during morning peak hours.
In 2005-2006, inner city evening delivery was tested by two grocery companies in a pilot project in Stockholm (10), and dedicated routes were designed for the deliveries to the participating stores. The results showed that the possible timesavings were around 20-25% when the delivery starts after 18:00 compared to delivery at daytime.

Most of the above-mentioned studies have been done from the stakeholders’ perspective and focus on the policies for promoting off-peak deliveries and social-economic aspects. The incentives for carriers and receivers to adopt off-peak deliveries, and the long-term feasibility of such schemes, depend strongly on the transport efficiency impacts, including driving times, fuel consumption, delivery time reliability, etc. However, the collected evidence on the transport efficiency impacts of shifting goods deliveries to off-peak hours are still limited. The first aim of this paper is thus to propose a general methodological framework for evaluating the transport efficiency impacts of transferring goods deliveries from daytime to off-peak hours in urban areas. A set of indicators capturing different important aspects of transport efficiency for carriers and receivers is proposed. For each indicator, a set of sufficient data for evaluation is identified.

The second aim of the paper is to apply the methodology to evaluate the transport efficiency impacts of a recent off-peak pilot in Stockholm, Sweden, using various data sources collected in the project. The city of Stockholm initiated a new off-peak goods delivery project in 2014 in order to achieve a more efficient and environmentally friendly goods delivery system. The off-peak delivery pilot project is one of the actions for improving urban mobility in Stockholm (12), and is the first off-peak trial in the world using environmentally friendly vehicles. The goal of the pilot is to examine the feasibility of night delivery considering a number of factors, e.g. goods distribution times, environmental and noise aspects, workforce utilization, storage facilities and delivery vehicles, as well as working environment (13). 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, the city of Stockholm has issued special permits to two heavy delivery trucks to deliver goods in the inner city during the restricted time period. 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 have been designed and used in order to reduce the noise and vibration levels during delivery.

The paper is organized as follows. In the next section the general transport efficiency evaluation methodology is presented. The Stockholm off-peak pilot study is then introduced, followed by results from the evaluation. Finally, conclusions are drawn.

**METHODOLOGY**

This section presents a methodological framework for evaluating the transport efficiency impacts of shifting goods deliveries from daytime to off-peak hours.

**Aspects of Transport Efficiency**

Four aspects of transport efficiency are considered in this study: Driving efficiency, delivery reliability, energy efficiency and service efficiency. Each aspect is discussed in more detail below.
Driving Efficiency

Driving efficiency considers the efficiency with which goods can be delivered from warehouses to delivery points. Average speed is the most straightforward indicator for driving efficiency. In a congested urban network, delivery vehicles are forced to travel at low speeds and in stop-and-go conditions that significantly increase the time spent driving to each customer and reduce the number of customers that can be served during a shift. As pointed out in (4), it is unlikely for carriers passing the costs associated with congestion and toll 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 has been used increasingly as a congestion measure of road network quality (14). High reliability indicates good network performance, and carriers need to allocate less buffer time in order to arrive to the customers on time. Further, the customers do not need to keep larger stock in case the expected deliveries do not arrive on time. However, travel time variability is difficult to evaluate when the delivery routes and expected delivery time are not strictly constrained (15).

Energy Efficiency

Energy efficiency is measured by fuel consumption per driven kilometer. This indicator not only describes the effects of congestion (unnecessary stop-and-go), but also disturbances such as traffic lights and pedestrians. For the same reasons as for the driving efficiency aspect, energy efficiency is critical from carriers’ perspective, but it is also an important societal and environmental aspect as it is closely tied to emissions of CO2 and other pollutants.

Service Efficiency

The driving and energy efficiency indicators only 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 driver at the customer location (4), 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, this aspect is critical for both carriers and receivers.

Data Sources for Evaluation

Different data sources may be employed to evaluate the four aspects of transport efficiency. Three types of data sources 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 that are logged at certain intervals or events. From these basic data can be extracted the movement of the truck, and indicators such as driving time, average driving speed, arrival time at the customers, service time, etc. can be easily calculated. FMS data are thus valuable for evaluating all aspects of transport efficiency. However, the sampling frequency may be low (sometimes several minutes between reports), which can limit the usefulness of the data. Further, FMS data often contain additional information including fuel consumption, which is needed in order to evaluate the energy efficiency.

Fleet Management System (FMS) data are available in different formats and with different frequencies for both delivery trucks in the Stockholm pilot. Both systems provide information of vehicle locations, timestamps, and fuel consumption.

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 GPS coordinates (latitude, longitude and altitude). GPS data are thus valuable for evaluating all four aspects of transport efficiency.

In the Stockholm pilot study, GPS receivers were installed in both trucks to complement the FMS systems and record locations at the resolution of one hertz (one record per second). The GPS receivers were connected to the engine of the vehicle so that the GPS devices are switched on when the vehicle is in operation. Fuel level measurement systems were also installed and recorded the fuel consumption at the same frequency of the GPS receivers.

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 was provided by the goods receiver and includes the volume of goods in TPE (standard transport unit) delivered by the trucks to each delivery point every day.

The three different data sources provide all necessary information for computing the above-mentioned indicators of transport efficiency. The methodology for assessing the transport efficiency of off-peak deliveries is shown in Figure 1.
FIGURE 1 Flowchart of transport efficiency evaluation using different data sources.

CASE STUDY

This section describes the Stockholm off-peak pilot study and the data collection and analysis conducted to evaluate the transport efficiency impacts.

Study Area Description

Stockholm is a fast growing city, and the demand for goods that need to be distributed increases constantly. In 2010 almost 40 million tons of goods were transported by trucks in Stockholm County, and there are approximately 10,000 heavy vehicles (over 3.5 ton) on the roads every day (13). Data from the congestion charging system show that 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 (16). Delivery trucks frequently encounter the problem that the assigned loading/unloading places 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 2 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 (17), (18). The mean speed across days (solid line in Figure 2) 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 2 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.

Off-peak Pilot Study Description

Two heavy trucks specially designed to reduce noise and pollution were used in the pilot study. The first, denoted truck A in the following, is a hybrid diesel-electric truck. A zone management system is customized in the control unit so that the truck operates with only the electric motor in the inner city area (defined by the Stockholm congestion charging system) and with the diesel engine elsewhere. The second truck, denoted truck B, is gas-fueled.

The two trucks made delivery tours with different schemes. Truck A made dedicated deliveries of big volumes to specific receiver in every trip; the delivery route is shown in Figure 3(a). During the pilot study, three grocery stores in Stockholm inner city changed their delivery routines from daytime to off-peak hours on weekdays. The three stores are located at Sveavägen (Store 1), Sankt Eriksgatan (Store 2), and Södra Station (Store 3), and are displayed at the lower right corner in Figure 3(a) 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 work day evening during the measurement period, truck A went from the logistics company’s terminal to the warehouse located in the north of Stockholm (the red diamond in Figure 3(a)) 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 traveled 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.

Truck B made consolidated deliveries of small volumes to several customers in the city in one tour
both during daytime and off-peak hours (Figure 3(b)). The warehouse is located in the south of
Stockholm and shown as a red diamond in Figure 3(b), and the customers are different restaurants
and hotels that are spread out in the entire Stockholm region. Due to the business characteristics of
the customers, the delivery points of truck B were different from day to day.

Evaluation Design

Truck A (Dedicated Delivery to a Single Customer)

Ideally, all three types of data (GPS, FMS and logistics data) for both daytime and off-peak
deliveries to the same stores along the same routes should be collected and analyzed, so that a
direct comparison can be made in terms of the efficiency indicators. Comparison of deliveries on the same routes during both daytime and off-peak hours is essential, as congestion affects not only vehicle hours travelled but also vehicle kilometers travelled. In addition to the comparison between the observed daytime and off-peak deliveries, the travel time on the delivery route at different hours of a day should also be investigated in order to observe the overall traffic conditions. However, there are no deliveries to the stores served by truck A during daytime. 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, 2016 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. In total, five delivery trips were made to each of Store 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 in order to evaluate the transport efficiency indicators.

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 logs in/out, the driver’s activity changes into driving/working/resting, or making a stop. When the truck was moving, data were recorded every ten minutes. The FMS data reports the time of event, driver’s ID, driver’s activity, odometer, fuel level, accumulated duration, accumulated driving distance, accumulated fuel consumption, location address, latitude and longitude.

**Truck B (Consolidated Delivery to Various Customers)**

The delivery routes of truck B varied from day to day, which means it is not possible to compare the transport efficiency indicators along the same delivery routes as with truck A. On the other hand, the delivery routes cover the entire Stockholm region. The FMS data provided by the truck manufacturer were available on a continuous basis and give an overall picture of the traffic conditions at different times of the day. The FMS data include timestamp, odometer, fuel level, instantaneous speed, GPS coordinates, vehicle’s location, ignition status, and driver change. The data were recorded at the frequency of one record per minute. Thus, the FMS data of truck B are used to study the general transport efficiency between daytime and off-peak hours in the Stockholm region. 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.
RESULTS

Table 1 summarizes the evaluation of the four aspects of transport efficiency for both truck A (dedicated deliveries) and truck B (consolidated deliveries) in the Stockholm pilot. The results are discussed in more detail below.

TABLE 1 Transport efficiency indicators.

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<tr>
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<th>Truck A (dedicated delivery)</th>
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<th>Truck B (consolidated delivery)</th>
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<td>Off-peak Delivery (10PM-6AM)</td>
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<td>Average speed (km/h)</td>
<td>62.08</td>
<td>64.71</td>
<td>58.95</td>
<td>46.00</td>
<td>64.37</td>
<td>50.74</td>
<td>22.16</td>
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<td>Delivery Reliability</td>
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<td>Store 2</td>
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<tr>
<td>Travel time (minutes)</td>
<td>31.23</td>
<td>29.02</td>
<td>41.21</td>
<td>44.17</td>
<td>29.55</td>
<td>44.67</td>
<td>2.28</td>
<td>1.80</td>
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<td>Standard deviation of travel time (minutes)</td>
<td>2.28</td>
<td>1.80</td>
<td>5.29</td>
<td>12.00</td>
<td>3.05</td>
<td>2.37</td>
<td>2.28</td>
<td>1.80</td>
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<td>Energy Efficiency</td>
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<td>Store 3</td>
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<td>Fuel consumption (liter/km)</td>
<td>0.29</td>
<td>0.28</td>
<td>0.29</td>
<td>0.26</td>
<td>0.29</td>
<td>0.27</td>
<td>0.27</td>
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<td>Service Efficiency</td>
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<tr>
<td>Service time (minutes)</td>
<td>46.44</td>
<td>46.17</td>
<td>51.66</td>
<td>46.44</td>
<td>49.85</td>
<td>51.66</td>
<td>14.35</td>
<td>18.45</td>
</tr>
<tr>
<td>Service speed (TPE/h)</td>
<td>27.63</td>
<td>20.90</td>
<td>21.39</td>
<td>27.63</td>
<td>20.90</td>
<td>21.39</td>
<td>3.73</td>
<td>3.54</td>
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<tr>
<td>Number of service stops per driving hour</td>
<td>3.73</td>
<td>3.54</td>
<td>3.73</td>
<td>7.11</td>
<td>2.07</td>
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Driving Efficiency

The distribution of driving speeds of both trucks are depicted as box-and-whisker plots in Figure 4(a) and 4(b), 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, and observations beyond the whisker length are considered as outliers (marked with red “+” signs in the figures).

For truck A, the delivery trips from the warehouse to the stores are used to compute the transport efficiency indicators. The transport efficiency during off-peak hours was monitored in several periods during the pilot study and shows consistency over time. During the measurement period where baseline 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.

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 difference in average speed, 64.7 km/h versus 64.4 km/h. Finally for Store 3, truck A travels with higher speed during the off-peak hours (59.0 km/h) compared to in daytime (50.7 km/h).

The average speeds for off-peak, daytime overall, and the four individual daytime intervals for truck B are shown in a box-and-whisker plot in Figure 4(b). 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. With close examination of the GPS coordinates in the morning peak hours, it is observed that the delivery truck was 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 specially designed based on the customers’ location to avoid congestion. 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 speeds of truck A (a) and truck B (b), and arrival time of truck A at the stores during off-peak hours (c) and daytime (d).

Delivery Reliability

The distributions of the arrival times of truck A to the three stores are shown as box-and-whisker plots in Figure 4(c) for off-peak hours and Figure 4(d) for daytime. Looking closely at the daytime trips in Figure 4(d), 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, which is
consistent with the network conditions shown in Figure 2. The delivery trips to Store 3 were completed around 15:00 when the traffic flow starts to increase (see Figure 2), 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. This shows that the road network is congested during the delivery periods, which causes low delivery reliability. For the delivery trips to Store 2, there is no significant difference in the mean and standard deviation of travel time. This agrees with the finding that there is little travel time variability in the middle of the day. Finally for the deliveries to Store 3, the travel time is marginally longer in the day compared to in the night (44.67 min versus 41.21 min) as the traffic begins to increase in the afternoon.

The delivery reliability aspect cannot be studied for truck B since the delivery routes are different from day to day.

Energy Efficiency

The fuel consumption of the hybrid diesel-electric truck A in off-peak hours is 0.28 liter/km. 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 we are unable to draw conclusions with respect to the energy efficiency aspect using the dataset.

For the gas-powered truck B, the fuel consumption during off-peak and daytime are 0.26 and 0.27 liter/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 a box-and-whisker plot in Figure 5(b). The fuel consumptions is higher for all daytime intervals compared to the off-peak hours. Moreover, the fuel consumption in the interval 15:00 – 18:00 is the highest (0.31 liter/km compared to 0.27 liter/km for daytime on average) because of the congestion.
FIGURE 5 Fuel consumption of truck A (electric-diesel hybrid) (a) and truck B (gas) (b).

Service Efficiency

In 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, and the four individual daytime intervals are shown as box-and-whisker plots in Figure 6(a). 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 previous off-peak delivery studies where the drivers may need to handle the delivery process on their own. Service times are the highest during the morning peak hours, 6:00–10:00, 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 listed in Table 1 and shown in a boxplot in Figure 6(b). The number of stops is in general higher during off-peak hours than during daytime, 3.73 versus 3.58 stops per driving hour. This implies that the truck can make more delivery stops 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 optimized so that the truck delivers to locations with concentrated customers in order to avoid getting stuck in the afternoon congestion.

**FIGURE 6** Service time at the stops (a) and number of service stops per driving hour (b) of truck B.

**CONCLUSIONS**

The paper presented a framework for evaluating the transport efficiency impacts of transferring goods deliveries from daytime to off-peak hours in urban areas. Four aspects of transport efficiency were considered: driving efficiency, delivery reliability, energy efficiency and service efficiency. These efficiency aspects were evaluated using data collected from two delivery trucks.
in the off-peak delivery pilot project in Stockholm, Sweden. Two delivery schemes were employed in the off-peak pilot: dedicated deliveries in order to study the efficiency aspects on the same delivery routes, and consolidated deliveries for evaluating the efficiency in the entire urban network.

The evaluation of the 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 in off-peak is ca. 59% higher than in the afternoon peak based on data from the consolidated deliveries. However, no definitive conclusion can be drawn regarding service efficiency aspect using the dataset from the pilot project.

Moreover, the evaluation highlighted that the delivery route of the truck making consolidated deliveries is already optimized in order to meet customers’ demand and at the same time avoid congestion. The comparison conducted in the case study is between a regular delivery route in off-peak and an optimized route during daytime. Thus, better performance in transport efficiency for off-peak delivery is expected while using the same delivery route.

This study focuses on the transport efficiency aspects of switching goods deliveries from daytime to off-peak hours. It should be emphasized that a full evaluation of the impacts of off-peak schemes such as the Stockholm pilot should include other aspects such as stakeholders’ satisfaction (carriers, receivers, authorities, the general public, etc.), noise measurements, environmental impacts, and cost-benefit analysis. Once such a comprehensive assessment is carried out, it may 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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