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Impact of Congestion Pricing Schemes on Costs and Emissions of Commercial Fleets in Urban Areas

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Abstract

As urbanization increases, municipalities across the world have become aware of the negative impacts of road-based transportation, which include traffic congestion and air pollution. As a result, several cities have introduced tolling schemes to discourage vehicles from entering the inner city. However, little research has been done to examine the impact of tolling schemes on the routing of commercial fleets, especially on the resulting costs and emissions. In this study, we investigate a vehicle routing problem considering different congestion charge schemes for several city types. We design comprehensive computational experiments to investigate whether different types of tolling schemes work in the way municipalities expect and what factors affect the performance of the congestion charge schemes. We compare the impact on a company's total costs, fuel usage (which drives emissions), and delivery tour plans. Our experimental results demonstrate that some congestion pricing schemes may even increase the emissions in the city center, and higher congestion charges may not necessarily lead to lower emissions.

Key words: emissions, vehicle routing, green logistics, driver costs, urban logistics, congestion zones

1 Motivation

Governments across the globe have become concerned about the level of emissions in their city centers. These emissions pollute the air and create problems for the citizens and the environment. To control emissions in city centers, municipalities have come up with a large variety of emission policies. Many cities have limited the types of engines that can be used in vehicles within the city center. Engines often must meet specific emission standards such as described by Euro 5 or Euro 6 guidelines [EUEnvironment, 2016]. Recently, some municipalities in Germany were forced to ban vehicles with diesel engines from their city centers, "after authorities have failed to meet their duty on lowering emissions levels" [Behrmann, 2017]. Many city governments have limited the times of the day when vehicles of certain types can enter the city center, and some are experimenting with different types of congestion charges to discourage vehicles from entering the inner city, especially at peak times. In our literature review, we present some of the congestion charge policies currently being tested all over the world.

In this paper, we are particularly interested in understanding the impact of congestion charges on the routing of commercial fleets in urban areas. We are interested in how different kinds of congestion charge schemes perform from both the municipality's as well as the commercial fleet operator's perspective. While the role of the municipality is to ensure a reduction of emissions, operators of commercial fleets are mainly interested in keeping their costs as low as possible. Operators of commercial fleets have to consider congestion charges in their route planning, because they can increase the cost of routing significantly. This may lead to situations where certain types of congestion charge schemes can even cause an unintended increase of emissions in the city center. Furthermore, some types of congestion charge schemes may lead to an increase of commercial traffic in the vicinity of the city center, counteracting the good intentions of the policy. As urbanization increases, it is important to develop an understanding of how these pricing tools should be used.

Since current congestion charge schemes vary in terms of fees, times, geographical area, etc., it is challenging to create vehicle routing instances and techniques to compare their effectiveness. Hence, little research has been done to examine the impact of congestion charge schemes on the routing of commercial fleets and the resulting emissions that occur in city centers. The main exception is Wen and Eglese [2015] who look at how to minimize total costs when routing vehicles to customers in a city with a fixed daily charge for entering the city center, as exists in the city of London. They find that deliveries in the inner city should be concentrated onto as few vehicles as possible to minimize cost, and they examine the resulting emissions. Still, there are more types of congestion charges that need to be investigated systematically and more instance types to consider.

To compare different types of congestion charge schemes, we extend the routing heuristic from Wen and Eglese [2015] to handle temporal and spatial congestion charge schemes. We apply this modified heuristic to cities of different sizes with varying congestion zone sizes. We analyze metrics relevant for the fleet operator such as the total cost of a route plan. We also analyze metrics that are relevant for the municipality such as total fuel consumption as an approximation of emissions. We also want to understand the impact of the different congestion charge schemes with and without the impact of time windows. We understand that only when the carrier and receiver have integrated operations would the carrier likely be able to have such flexibility on the delivery times at customers, but it is important to understand the value of such flexibility.

The goal of our study is to develop an understanding of how different congestion charge schemes impact key business and environmental metrics and the routing of the vehicles. We compare the results to those found with no congestion charges. Our results are somewhat surprising. We find that many of the congestion charge schemes that are in place actually increase total emissions because vehicles drive farther distances to avoid the city center. We find that one charge scheme does a better job of mitigating the travel into the city center and reducing total emissions than the others. Generally, our results demonstrate the importance of adapted routing schemes for controlling the cost of commercial fleets' operators as well as for the development of effective congestion charge schemes.

The paper begins with a literature review including various examples of congestion charge schemes. We then present our model of an artificial city and how we implement the different congestion charge schemes in Section 3. Section 4 presents the solution methodology that we use to plan the routes for a fleet of commercial vehicles. The experimental design is presented in Section 5, including the design of different city sizes and the modeling of peak hour travel times. Section 6 discusses metrics and experimental results in detail, and Section 7 concludes the paper.

2 Literature Review

Technological advancements such as GPS tracking have led to a variety of congestion charging schemes, see de Palma and Lindsey [2011] for an overview of scheme variants and technologies used. In the following, we discuss the various congestion charge schemes in detail and then discuss related research on the effectiveness of congestion charge schemes.

2.1 Congestion Pricing Schemes

The list of cities and towns apply congestion charges includes Singapore, London, Milan, Stockholm, Gothenburg (Sweden), Valletta (Malta), and Durham (England).

Vehicle Type	Tolling Time	Rate Range (for passing a gantry)
Passenger Cars/Light Goods Vehicles/Taxis	7am-10am,12pm-8pm	S$0.5 – S$0.6
Motorcycles	7am-10am,12pm-8pm	S$0.25 – S$3
Heavy Goods Vehicles and Small Buses	7am-10am,12pm-8pm	S$0.75 – S$9
Very Heavy Goods Vehicles and Small Buses	7am-10am,12pm-8pm	S$1 – S$12

Table 1: Congestion Charge Rate for Different Classes of Vehicles in Singapore

Singapore introduced the first congestion charge scheme in the world to its Central Business District (CBD) in 1975. In 1998, assisted by the technological advances in electronic detection, electronic toll collection, and video surveillance, Singapore started using an Electronic Road Pricing (ERP) system to manage road pricing. There are ERP gantries at all roads entering Singapore's CBD and along roads with heavy traffic in the CBD. Vehicles have to pay a fee every time they pass a gantry. The tolling times are 7am-10am and 12pm-8pm on all weekdays and Saturdays except public holidays. The charge depends on the location of the gantry, the time of the gantry is passed, as well as the vehicle type. Table 1 summarizes the congestion charge rates effective from February 20th, 2017 [Singapore, 2017]. As shown in the table, the heavier the vehicle, the higher the rate.

Following Singapore, London introduced its congestion charge scheme on February 17, 2003 [London, 2017a]. Unlike Singapore, a daily fee of £11.5 is applied for entering the congestion zone in central London between 7am and 6pm from Mondays to Fridays except public holidays. The fee is charged only once per day regardless of the number of times the vehicle crosses into the city center. Discounts are applicable to vehicle types. For example, two-wheeled motorbikes and mopeds, emergency service vehicles, vehicles used by disabled people, taxis and hired vehicles, vehicles with 9 or more seats, and vehicles emitting 75g/km or less of CO_2 and meeting the Euro 5 standard for air quality are qualified for 100% discount. Residents living within or very close to the congestion zone can apply for a 90% discount if they pay the charge using the automated payment system[London, 2017b]. The city of Durham, England also collects a daily fee of £2 from 10am-4pm Monday to Saturday for entering the Durham peninsula [Durham, 2017].

The city of Milan launched a congestion charge scheme for entering its historical center (an area of 8.2 km^2 with 77,000 residents, referred to as Area C) on January 16, 2012. Area C is accessible through 43 gates monitored by cameras, 7 of which are used exclusively for public transportation. To enter Area C on Monday, Tuesday, Wednesday and Friday from 7:30am to 7:30pm, and on Thursday from 7:30am to 6pm,

Tolling Time	$Rate_1$	$Rate_2$	Tolling Time	$Rate_1$	$Rate_2$
06:30 – 06:59	kr15	kr15	15:00 – 15:29	kr15	kr15
07:00 – 07:29	kr25	kr22	15:30 – 15:59	kr25	kr22
07:30 – 08:29	kr35	kr30	16:00 – 17:29	kr35	kr30
08:30 – 08:59	kr25	kr22	17:30 – 17:59	kr25	kr22
09:00 – 09:29	kr15	kr15	18:00 – 18:29	kr15	kr15
09:30 – 14:59	kr11	kr11			

[1] $Rate_1$: rate for central Stockholm
[2] $Rate_2$: rate for Essingeleden (motorway into Stockholm)

Table 2: Congestion Charge Rate in Stockholm

Tolling Time	Rate	Tolling Time	Rate
06:00 – 06:29	kr9	15:00 – 15:29	kr16
06:30 – 06:59	kr16	15:30 – 16:59	kr22
07:00 – 07:59	kr22	17:00 – 17:59	kr16
08:00 – 08:29	kr16	18:00 – 18:29	kr9
08:30 – 14:59	kr9		

Table 3: Congestion Charge Rate in Gothenburg

each vehicle has to pay a daily fee of €5. Residents have 40 free daily entries per year and then have to pay a reduced daily tariff of €2 [Milan, 2017a]. Exemptions apply to electric vehicles, hybrid vehicles, motorcycles, scooters, public utilities' vehicles, vehicles transporting disabled people, and police and emergency vehicles. The access to Area C is forbidden to "Euro 0" petrol vehicles and "Euro 0, 1, 2, 3" diesel vehicles.[Milan, 2017b]

In Sweden, the cities of Stockholm and Gothenburg introduced congestion charge schemes to reduce traffic in their city centers in 2006 and 2013, respectively. Cars, trucks, and buses have to pay to enter the congestion zone between 6am and 6:29pm Mondays to Fridays. Each vehicle is charged every time it passes a control point to enter the congestion zone. The charged amount depends on the time of entering and there is a maximum daily charge of 105 krona and 60 krona in Stockholm and Gothenburg, respectively [Sweden, 2017]. The fee is not collected on weekends, public holidays, the day before public holidays, and the month of July. Emergency vehicles, buses with a total weight of at least 14 tons, motorbikes, mopeds, and cars with disabled parking permit are not charged. Tables 2 and 3 present the time-dependent per entry congestion charges in Stockholm and Gothenburg, respectively.

Valletta, Malta launched a Controlled Vehicular Access (CVA) system in 2007. There are 8 entry points and 8 exit points located on the CVA boundary [Malta, 2017a]. The congestion charge depends on the length

Tolling Time	Criteria	Rate
8am to 6pm	First 30 minutes	free
Entrance before 2pm	Over 30 minutes up to 60 minutes	€0.82
Monday to Friday	Over 60 minutes	€0.82 per hour (maximum €6.52)

Table 4: Congestion Charge Rate in Malta

City/Town	Tolling Time	Charge Type	Time-Dependent	Max Amount
Singapore	7am – 10am, 12pm – 8pm	per gantry	Yes	No
London	7am – 6pm	per day	N/A	N/A
Durham	10am – 4pm	per day	N/A	N/A
Milan	7:30am – 7:30pm or 7:30am – 6pm	per day	N/A	N/A
Stockholm	6am – 6:29pm	per entry	Yes	Yes
Gothenburg	6am – 6:29pm	per entry	Yes	Yes
Valletta	8am – 6pm	per time in the zone	No	Yes

Table 5: Summary of Congestion Charge Schemes

of time that a vehicle spends in the CVA region, i.e., the time between when a vehicle enters and exits the CVA region via an entry point and an exit point. Table 4 summarizes the congestion charge scheme in Malta [Malta, 2017b]. A vehicle needs to pay a toll for accessing the congestion zone between 8am and 6pm on Monday to Friday if the entrance time is before 2pm. For the first 30 minutes of access to the congestion charge zone, no fee needs to be paid. For accessing the zone over 30 minutes and up to 60 minutes, a fee of €0.82 is collected. For access over 60 minutes, the charge is €0.82 per hour with a maximum charge of €6.52. Exemptions are available to emergency vehicles, electric vehicles, motorcycles, and vehicles capable of carrying 10 or more people.

In Table 5, we summarize the congestion charge schemes from the cities and towns that we discussed above. The second column of the table presents the tolling time for the cities/towns. The third and fourth columns illustrate whether the congestion charge is a fixed per day charge (London, Milan, and Durham), a per gantry charge with the rate depending on the time of passing the gantry (Singapore), a per entry charge with the precise rate depending on the time of entering the charge zone (Stockholm, and Gothenburg), or a per entry charge with the rate depending on the amount of time spent in the zone (Valletta). The fifth column indicates whether there is a maximum charge amount if a toll is collected every time a vehicle enters the zone.

2.2 Effectiveness of Congestion Charge Schemes

There are many studies that focus on the evaluation of road network pricing schemes (see Tsekeris and Voß [2009] for a review). A few of them investigate the impact of road pricing on the planning and operations of freight carriers. For example, Holguin-Veras et al. [2006] investigate the impact of road pricing policies enforced by the Port Authority of New York and the state of New Jersey. They conduct an empirical study with data from the port to analyze the carriers' responses to the increases in road tolls during peak hours, which include productivity increases, cost transfer, and change in facility usages. Holguin-Veras [2011] propose analytical formulations to study the impact of time and dependent road pricing on both the freight carriers' and the receivers' behaviors. They find that introducing tolling schemes will not lead to the most efficient operation (off-hour deliveries) because of the receivers' opposition. Anderson et al. [2005] investigate whether congestion charges and other related policies can change logistic carriers' activities in urban distribution operation. They find out that congestion charges change the proportion of vehicles that enter the charge area. They conduct this research via developing a database model and working closely with distribution companies. No mathematical formulations are presented.

Some studies present analytical models to determine road tolling schemes with various objectives. For instance, Zhang and Yang [2004] propose a mixed integer programming model to optimally select toll levels and toll locations with an objective to maximize social welfare. They consider both single-layered and double-layered cordon pricing strategies. The single-layered cordon divides the network into the tolling area and the non-tolling area, similar to the definition of the congestion zone in our work. The double-layered cordon consists of two disjoint closed loops and the vehicles have to pay toll charges once crossing a closed loop of the cordon. Chen et al. [2011] present a two-phase optimization approach to identify a time-varying tolling pattern that leads to the optimal truck arrival pattern at ports. In the first stage, they analyze the time-dependent truck queueing processes and propose an analytical model to minimize the trucks' waiting times at the port and the difference between the truckers' assigned arrival times and their preferred arrival times. In the second stage, they develop a toll-setting model to obtain the time-varying toll pattern which adjusts the truck's arrival time to the desired system-optimal arrival pattern. Teo et al. [2014] use multi-agent systems with reinforcement learning to evaluate the influence of a joint freight scheme on the major stakeholders in city logistics. Their freight scheme includes a distance-based road pricing and load factor control scheme, and the stakeholders include carriers, shippers, administrators and customers. They optimize the carriers' routing decisions through a vehicle routing model with soft time windows. The computational experiment is conducted by using real network data from Osaka, Japan. Experimental results show that the joint scheme is able to reduce costs of shippers and carriers as well as improve emissions. Wen and Eglese [2016] propose a bi-level road pricing model to minimize the CO_2 equivalent emissions and the total travel time of vehicles in a small road network. The upper level of the model decides the level of toll that minimizes the CO_2 equivalent emissions, while the lower level of the model allows the users to choose their routes and departure times to react to the change of toll level. They assume that all vehicles' origin and destinations are the same and only consider two alternative routes for the vehicles. The routes are selected such that the dynamic user equilibrium is achieved for the whole traffic network given the current toll level.

The most closely related literature to the work in this paper are the studies by Wen et al. [2014] and Wen and Eglese [2015]. Wen et al. [2014] focus on finding minimum cost routes between pairs of nodes while they consider congestion through a time-varying road network and a fixed daily congestion charge. Two heuristics are proposed to solve the minimum cost path problem. Similar to our work, Wen et al. [2014] consider congestion charges in a routing problem. However, their problem is not to route a fleet of vehicles to serve customers but finding paths between nodes, and they only consider one congestion charge type. In Wen and Eglese [2015], a vehicle routing problem is solved with an objective to minimize the total travel costs, which include fuel cost, driver cost and a daily congestion charge. The LANCOST heuristic is proposed to solve the problem. Our work is similar to theirs in terms of routing a fleet of vehicles to serve customers and applying the LANCOST heuristic to solve the problem. However, we consider several types of congestion charges and different city and congestion zone instances. Further, we integrate the decisions of crossing the congestion zone by paying a toll versus avoiding the zone by taking a detour into the route building, at the presence of various charge schemes.

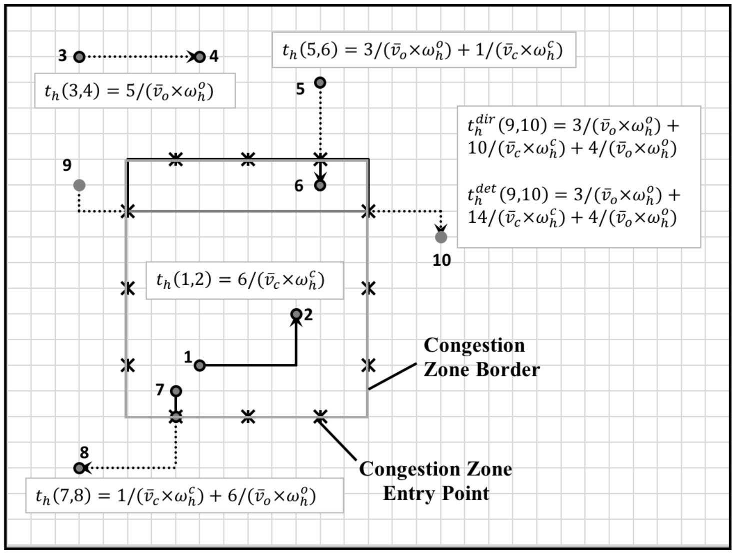
In contrast to the majority of the above papers which address different problem and/or employ different research approaches as we do, we explicitly investigate the cost objectives of fleet operators with adapted routing techniques by systematically including different congestion charge schemes and evaluate the results from both an operator's as well as the municipality's perspective.

3 Model

Similar to Wen and Eglese [2015], we consider a single-depot vehicle routing problem with a time-dependent road network where each vehicle starts and ends its route at a depot. As in Wen and Eglese [2015], the set of customers that need to be visited is denoted by N, and the depot is represented by 0. For each customer in N, we assume a fixed service time s. We consider both when each customer has a time window that dictates when they can be visited and when each customer can be visited at any time during a day. We denote by the set K a homogeneous fleet of vehicles that will serve the customers. We assume all vehicles begin their day at a pre-specified time τ, and each driver works for a maximum duration D. Unlike Wen and Eglese [2015], we ignore delivery size and vehicle capacity, because time limitations are typically more constraining with urban deliveries.

We assume that the travel time between locations are known and are time-dependent. Specifically, the travel time between two customers depends on the time the vehicle starts its travel. As in Wen and Eglese [2015], we define the travel time between location i and j $(i, j \in N \cup \{0\})$ as $t_h(i, j)$, where h is the time the vehicle leaves customer i. We approximate the distance d_{ij} between locations i and j via the Manhattan distance between their coordinates, calculated as $|x_i - x_j| + |y_i - y_j|$, where (x_i, y_i) and (x_j, y_j) are the coordinates of locations i and j, respectively. Distances are measured rectilinearly to represent travel in a city. The time-dependent travel times are computed as $t_h(i, j) = d_{ij}/v_h(i, j), \forall i, j \in N \cup \{0\}$, where $v_h(i, j)$ is the speed for traveling from i to j at start time h. In this study, we approximate $v_h(i, j)$ via the average speed of traveling along the path and a time-dependent speed factor identified in Ehmke et al. [2012]. Specifically, if both locations i and j are within the congestion zone, we set $t_h(i, j) = d_{ij}/(\bar{v}_c \times \omega_h^c)$, where $\bar{v}_c$ is the average speed of traveling within the congestion zone and ω_h^c is the corresponding speed factor for the start time of h (we refer the readers to Ehmke et al. [2012] for more details). This situation is demonstrated by path (1, 2) in Figure 1. If location i is in the congestion zone and location j is outside the zone, $t_h(i, j) = d_{ip^o}/(\bar{v}_c \times \omega_h^c) + d_{p^o j}/(\bar{v}_o \times \omega_h^o)$, where p^o is the point on the border that the vehicle leaves the congestion zone, $\bar{v}_o$ is the average speed of traveling outside the congestion zone, and ω_h^o is the corresponding

Figure 1: Computation of Travel Distances and Travel Times



speed factor. We demonstrate this situation via path (7, 8) in Figure 1. If location i is outside the zone and location j is in the zone, then $t_h(i,j) = d_{ip^e}/(\bar{v}_o \times \omega_h^o) + d_{p^e j}/(\bar{v}_c \times \omega_h^c)$ with p^e being the point on the border where the vehicle enters the zone. This situation corresponds to path (5, 6) in the figure. In this study, we assume that the vehicle can only enter or leave the congestion zone via one of several points located on the border of the congestion charge zone. We will discuss the details in Section 5. If both i and j are outside the congestion zone, we consider two situations. One is that the rectilinear path between i and j does not cross the congestion zone, then $t_h(i,j) = d_{ij}/(\bar{v}_c \times \omega_h^o)$, which is denoted by path (3, 4) in Figure 1. The other situation is that the path (i, j) crosses the congestion zone, which is denoted by path (9, 10) in Figure 1. In this case, we assume that a vehicle can either pay the congestion charge and take the direct path to cross the zone, or take a detour. We assume that the vehicle will take a detour along the border of the congestion charge zone. If the vehicle takes the direct path, $t_h^{dir}(i,j) = d_{ip^e}/(\bar{v}_o \times \omega_h^o) + d_{p^e p^o}/(\bar{v}_c \times \omega_h^c) + d_{p^e j}/(\bar{v}_o \times \omega_h^o)$. If the vehicle detours, $t_h^{det}(i,j) = d_{ip^e}/(\bar{v}_o \times \omega_h^o) + d'_{p^e p^o}/(\bar{v}_c \times \omega_h^c) + d_{p^o j}/(\bar{v}_o \times \omega_h^o)$, where $d'_{p^e p^o}$ is the distance of traveling along the congestion zone border from entrance point p^e and exit point p^o. Whether the vehicle chooses to take the direct path or take the detour depends on the total cost associated with the choice, which we will discuss in more detail below.

Let $\nu^k = (\nu_1^k, \nu_2^k, \ldots, \nu_{m_k}^k)$ represent the sequence of locations visited by vehicle $k \in K$. We note that the first and the last location in the sequence is the depot (i.e., $\nu_1^k = \nu_{m_k}^k = 0$), and $\nu_p^k \in N$ for $p = 2, ..., m_k - 1$.

We denote by $e(\nu_p^k)$ and $l(\nu_p^k)$ the beginning and end of the time window at customer ν_p^k, respectively. Let $\chi(\nu_p^k)$ be the time that vehicle k arrives at customer ν_p^k. Then $\chi(\nu_p^k) = \max\left\{e(\nu_p^k), \chi(\nu_{p-1}^k)+s+t_h(\nu_{p-1}^k, \nu_p^k)\right\}$ and $\chi(0) = \tau$. Let $\eta(\nu_p^k)$ be the time that vehicle k spends waiting at customer ν_p^k. Then we have $\eta(\nu_p^k) = \max\left\{0, e(\nu_p^k) - \chi(\nu_p^k)\right\}$. The constraints on the arrival times at customers are:

$$e(\nu_p^k) \leq \chi(\nu_p^k) \leq l(\nu_p^l), \forall \nu_p^k \in N. \tag{1}$$

After arriving at a customer, each vehicle incurs the service time and then immediately begins to travel to the next customer in the sequence. When leaving the depot at time τ, each vehicle has to return to the depot by time $\tau + D$. Specifically,

$$\sum_{p=1}^{m_k-1} t_h(\nu_p^k, \nu_{p+1}^k) + (m_k - 2)s + \sum_{p=2}^{m_k-1} \eta(\nu_p^k) \leq D, \forall k \in K. \tag{2}$$

Inequality (2) ensures that the total travel time and service time is smaller than the total available working time D.

Let $c_h(i,j)$ represent the total costs for traveling from location i to j $\forall i,j \in N \cup \{0\}$, when the travel starts at time h. The total costs consist of the driver cost, fuel cost, and the congestion charge. Let $L_h(i,j)$, $F_h(i,j)$ and $CC_h(i,j)$ represent the driver cost, fuel cost, and congestion charge, respectively. The driver cost is proportional to the sum of the travel time and the service time, i.e., the driver's working time during the day. The fuel cost is calculated via the fuel formula presented in Franceschetti et al. [2013], which is $F_h(i,j) = \lambda\big(fUW\frac{d_{ij}}{v_h(i,j)} + \gamma\beta d_{ij} v_h(i,j)^2 + \gamma\alpha(\mu + l)d_{ij}\big)$. In the formula, U is the engine speed, W is the engine displacement, f is the engine fiction, μ is the curb weight, and α, β, γ and λ are the products of other parameters introduced in Franceschetti et al. [2013]. We set $U = 33, W = 5, g = 0.2, \alpha = 0.0981, \beta = 1.6487, \gamma = 0.0028$ and $\lambda = 1/32428$ as in Franceschetti et al. [2013]. We consider "standard" freight vehicles with a gross weight of $\mu = 6350$. We ignore the dependency of the fuel consumption on the load carried by a vehicle and set $l = 0$. We ignore the load on the vehicle since we are assuming the delivery of lightweight packages where, as mentioned earlier, time is more limiting than vehicle capacity. For $CC_h(i,j)$, we consider four types of congestion charge schemes as follows.

1. Daily Fee

In this scheme (*daily*), we assume that a fixed daily entry fee needs to be paid for entering the congestion charge zone (as in London, Milan, and Durham). When executing the route plan ν^k, each vehicle $k \in K$ pays the toll the first time it enters the zone. Let C_d denote the fixed daily fee. Let $N_c \in N$ denote the set of customers located in the congestion charge zone. Let $\nu^k_{p_0}$ be the first customer in the congestion charge zone served by vehicle k. Thus, if $i \in \{N \setminus N_c\}$ and $j = \nu^k_{p_0}$, $CC_h(i,j) = C_d$. Otherwise, $CC_h(i,j) = 0$. In our experiments, we will consider different prices for daily fees.

2. Per Entry Fee

In this scheme, we consider that a charge will be collected each time a vehicle enters the congestion charge zone (as in Stockholm and Gothenburg). We consider two types of per entry fees. One is a fixed charge such that the same amount of fee will be collected per entrance (*fixed entry*). The other is a time-dependent congestion charge such that a higher fee will be collected during peak hours (*t-d entry*). Let C^f_e and C^h_e represent the fixed and time-dependent per entry fees, respectively. We assume that the time-dependent fee is based on the fixed fee and the speed factors introduced in Franceschetti et al. [2013]. Specifically, $C^h_e = \frac{C^f_e}{\omega^c_h}$. In general, we have $CC_h(i,j) = C_e$, $\forall i \in \{N \setminus N_c\}, j \in N_c$, where $C_e = C^f_e$ or $C_e = C^h_e$. Otherwise, $CC_h(i,j) = 0$.

3. Per Minute Fee

In this scheme, the vehicle needs to pay a fee based on the amount of time it spends in the congestion charge zone (as in Valletta). We consider a fixed per minute fee (*fixed min*) and a time-dependent per minute fee (*t-d min*), denoted as C^f_m and C^h_m, respectively, where $C^h_m = \frac{C^f_m}{\omega^c_h}$. For all $i \in N, j \in N_c$, $CC_h(i,j) = C_m \times (\tilde{t}_h(i,j) + s)$, where $C_m = C^f_m$ or $C_m = C^h_m$, and $\tilde{t}_h(i,j)$ is the time that the vehicle spends in the congestion zone when traveling from location i to j.

4. Per Gantry Fee

Similar to the congestion charge scheme in Singapore, we consider that there are several gantries located within the congestion charge zone. Each time a vehicle passes a gantry, a fee needs to be paid (*gantry*). We assume that the same amount of fee is charged for each gantry, denoted by C_g. Thus, $CC_h(i,j) = C_g \times \delta_{ij}$ for all $i \in N, j \in N_c$, where δ_{ij} is the number of gantries that a vehicle passes when traveling from location

i to j.

The objective is to minimize the total traveling costs of all vehicles, i.e.,

$$\min \sum_{k \in K} \sum_{p=1}^{m_k - 1} c_h(\nu_p^k, \nu_{p+1}^k), \tag{3}$$

where $c_h(\nu_p^k, \nu_{p+1}^k) = F_h(\nu_p^k, \nu_{p+1}^k) + L_h(\nu_p^k, \nu_{p+1}^k) + CC_h(\nu_p^k, \nu_{p+1}^k)$. Compared with Wen and Eglese [2015], we use more detailed fuel consumption models, we consider more congestion charge schemes, and we also evaluate the effectiveness of the different congestion charge schemes from a policy perspective.

4 Methodology

We extend the LANCOST heuristic proposed by Wen and Eglese [2015] to solve the resulting vehicle routing problems. The LANCOST algorithm is based on LANTIME, a tabu search based algorithm solving the least time VRP problem with multiple vehicles and time-dependent travel speeds. Algorithm 1 outlines our LANCOST implementation.

Algorithm 1: LANCOST Algorithm

1: $x_{now} \leftarrow initialize()$, $x^* = x_{now}$, $count = 0$
2: Set tabu list to empty and long-term memory values to zero
3: **while** $count < iterationMax$ **do**
4:     $g \leftarrow Random(1, G)$
5:     **while** $N_g(x_{now})$ is not exhausted **do**
6:         $x_{trial} \leftarrow N_k(x_{now})$
7:         **if** x_{trial} is the first trial solution in $N_k(x_{now})$ **then**
8:             $x_{best} = x_{trial}$
9:         **if** $P(x_{trial}) = 0$ and $f(x_{trial}) < f(x^*)$, **then**
10:             $f(x_{best}) = f(x_{trial}), P(x_{best}) = P(x_{trial}), x_{best} = x_{trial}$, go to Line 16
11:         **else if** move from x_{now} to x_{trial} is not set tabu, **then**
12:             **if** $\Phi(x_{trial}) < \Phi(x_{now})$ **then**
13:                 $f(x_{best}) = f(x_{trial})$, $P(x_{best}) = P(x_{trial})$, $x_{best} = x_{trial}$, go to Line 16
14:             **else if** $\Phi(x_{trial}) < \Phi(x_{best})$ **then**
15:                 $M(x_{best}) = M(x_{trial})$, $f(x_{best}) = f(x_{trial})$, $P(x_{best}) = P(x_{trial})$, $x_{best} = x_{trial}$
16:     $x_{now} = x_{best}$, $count = count + 1$
17:     Update tabu list and long-term memory values
18:     **if** $P(x_{best}) = 0$ and $f(x_{now}) < f(x^*)$, **then**
19:         $x^* = x_{now}$
20: **for** $k \in K$ **do**
21:     2-Opt(x_k^*)

Line 1 of Algorithm 1 initializes the search with a solution generated via a parallel insertion algorithm as introduced by Potvin and Rousseau [1993], which ensures the solution to be feasible. We represent by x_{now} the best solution found so far given that some feasibility constraint may be violated and by x^* the best feasible solution. In Line 2, we initialize the tabu list with an empty set and set the long-term memory values to zero. Line 3 states the termination criteria of the LANCOST. We determined that setting $iterationMax = 1000$ results in robust performance.

In the algorithm, four neighborhoods are considered: cross exchange, one exchange, swap, and insertion/removal. We refer the readers to Maden et al. [2010] for a detailed illustration of the neighborhoods. In line 4, $Random(1, G)$ randomly selects a neighborhood out of the $G(= 4)$ different neighborhoods to explore in the current iteration, based on probabilities assigned in advance. After a preliminary test, we determined that setting the probabilities of assigning cross exchange, one exchange, swap, and insertion/removal as 1/6, 1/3, 1/3, and 1/6 would lead to robust performance with reasonable computational efforts. Line 6 generates a neighborhood solution of x_{now}, and line 8 initializes the best solution in the current neighborhood. We measure the feasibility of a solution via function $P(x)$, where $P(x)$ is measured as the sum of the extra time from each vehicle, i.e., the total time spent by the vehicle (including the travel time and service time) exceeding the working allowance D.

The objective function $f(x)$ is calculated via $\sum_{k\in K}\sum_{p=1}^{m_k-1} F_h(\nu_p^k, \nu_{p+1}^k) + L_h(\nu_p^k, \nu_{p+1}^k) + CC_h(\nu_p^k, \nu_{p+1}^k)$, where the solution x consists of k routes, each denoted as $(\nu_1^k, \nu_2^k, \dots, \nu_{m_k}^k)$. We note that if the rectilinear path from the pth location to the $(p + 1)$th location crosses the congestion zone and there is a per-entry, per-time, per-gantry congestion charge, or a per-day charge that has not been paid yet, we compare the total costs of taking the rectilinear path with that of taking a detour around the congestion zone. Specifically, we represent by $F_h^r(\nu_p^k, \nu_{p+1}^k)$ and $L_h^r(\nu_p^k, \nu_{p+1}^k)$ the fuel cost and labor cost if vehicle k takes the rectilinear path from the pth location to the $(p + 1)$th location, respectively. Let $F_h^d(\nu_p^k, \nu_{p+1}^k)$, $L_h^d(\nu_p^k, \nu_{p+1}^k)$ represent the fuel cost and labor cost if vehicle k takes the detour, respectively. If $F_h^r(\nu_p^k, \nu_{p+1}^k) + L_h^r(\nu_p^k, \nu_{p+1}^k) + CC_h(\nu_p^k, \nu_{p+1}^k) < F_h^d(\nu_p^k, \nu_{p+1}^k) + L_h^d(\nu_p^k, \nu_{p+1}^k)$, the vehicle will pay the congestion charge and take the rectilinear path. Otherwise, it will avoid entering the congestion zone and take the detour.

Line 9 through line 15 explore the current neighborhood in the tabu search. If the current solution x_{trial} is feasible and it is better than the best feasible solution x^* found in previous iterations, then we update

x_{now}, x^*, the tabu list and long-term memory tables (line 16 through line 19) and start searching another neighborhood. If the move from x_{now} to x_{trial} is not tabu, we decide whether to update x_{now} and switch to another neighborhood or to keep searching the current neighborhood (line 12 through line 15) based on the tabu search objective $\Phi(x) = M(x)f(x) + \rho P(x) - \sigma \sum_{k \in K} (\frac{n_k(x)}{c})^2$, where $M(x)$ is the long-term memory cost that is calculated as

$$M(x) = \frac{\sum tallyCount/numberCustomerInvolved}{currentIterationNumber} \times \theta + 1. \tag{4}$$

Equation (4) states the calculation of the long-term memory $M(x)$. In the equation, *tallyCount* tracks the number of times that a customer is involved in the current move, $\sum tallyCount$ is the sum of tally counts from all customers involved in the current move, *numberCustomerInvolved* is the total number of customers involved in the move, *currentIterationNumber* is the current iteration number, and θ is a constant parameter. We set the value of θ to 0.5. The value of ρ is initially set to 1 and updated every ξ iterations. If all previous ξ iterations are infeasible, we update ρ as $\rho = 2\rho$. If all previous ξ iterations are feasible, then $\rho = \rho/2$. We set $\xi = 20$ in our experiments.

The third part of $\Phi(x)$, $\sigma \sum_{k \in K} (\frac{n_k(x)}{c})^2$, is employed to minimize the number of vehicles entering the congestion charge zone. Specifically, c is the total number of customers located in the congestion charge zone that needs to be served, $n_k(x)$ is the number of in-zone customers served by vehicle k in solution x, and σ is a parameter. We set $\sigma = 100$ in our experiments. After finishing the tabu search, we implement a 2-opt heuristic to improve each individual route in the best solution x^*, as in line 20 and line 21, where x^*_k corresponds to the route for vehicle k in solution x^*.

5 Experimental Design

In our computational experiments, we aim at analyzing the impact of different congestion charge schemes on the total costs of commercial fleets, emissions (driven by fuel usage), and delivery tour plans, while considering different city sizes and congestion zone types. In the following, we discuss the design of our experiments.

City Type	City Size	Large Congestion Zone Size	Small Congestion Zone Size
Large	30km × 30km	15km × 15km	6km × 6km
Medium	20km × 20km	10km × 10km	4km × 4km
Small	10km × 10km	5km × 5km	2km × 2km

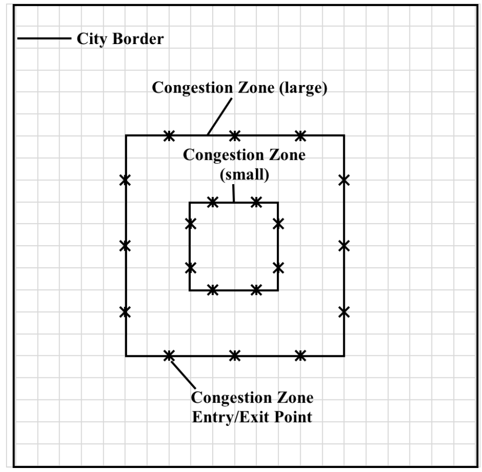
Table 6: Geographical Information

To imitate different city sizes, we assume that customers are distributed across a square area of three different magnitudes. We consider a *large city* of size 900km^2 (30km × 30km), a *medium city* of size 400km^2 (20km × 20km), and a *small city* of size 100km^2 (10km × 10km). The large city is about the size of Berlin (city area: 891km^2, Reuter and Erb [2016]), or the average size of Singapore (city area: 719.1km^2, Singapore [2014]) and Hong Kong (land area: 1104km^2, Singapore [2014]). The medium city is close to the size of Stockholm (urban area: 381km^2, Stockholm [2017]). The small city area is about the size of Florence (city area: 104 km^2, Silver et al. [2017]) or half the size of Milan (city area: 181.76km^2, Milan [2017c]).

For each city size, we experiment with two different congestion zone sizes. Each congestion zone covers the same percentage of the city area, where the *large* congestion zone covers 25% and the *small* congestion zone covers 15%. Figure 2 provides an example of a city and the two variants of congestion zones. For the large city, each grid in the figure represents 1.5 kilometers, while for medium and small cities, it represents 1 and 0.5 kilometers, respectively. We assume that a vehicle can only enter or exit a congestion zone via one of the control points located on the border of the zone. Each control point can serve both as an entry and an exit point for the congestion zone. As shown in the figure, for the large congestion zone, there are three entries/exits on each side of the square, while for the small congestion zone, there are only two on each side. Rectilinear distances represent travel in a city and accommodate the use of these entry points. In Table 6, we summarize the sizes of cities and the corresponding congestion zones. Columns 1 and 2 of the table present the city type (large, medium, small) and the size of each city type in kilometers, respectively. Columns 3 and 4 present the sizes of a large congestion zone (congestion zone 1) and a small zone (congestion zone 2) for each city type in kilometers, respectively.

For each city and zone size combination, we randomly generate five 100-customer instances. For a large congestion zone, we generate 25 customers outside the zone and 75 customers within the zone. For a small congestion zone, we generate 50 customers outside the zone and 50 customers in the zone. For each instance,

Figure 2: City and Congestion Zones



we consider 10 different departure times, which are 6am, 7am, 8am, 9am, 10am, 11am, 12pm, 2pm, 4pm, and 5pm, to see how the results change at different times of day given changes in fee structures and congestion. We assume the customers in each instance can be served with any of the start times considered, which may not always be feasible in practice, but such experiments provide an idea of how the costs of serving customers can change if served at different times of the day when possible. We assume a service time of 10 minutes at each customer. We assume 8 hours of working time ($D = 8$ hours). We set the traveling speed within the congestion zone and along the border of the zone as $\bar{v}_c = 20km/h$ and outside the zone as $\bar{v}_o = 40km/h$. The setting of average speeds is based on the real traffic conditions in cities with a high congestion level. For example, the average speeds for traveling on different traffic corridors in Milan range from 17 km/h to 42 km/h (MilanTraffic [2016]). The values of the time-dependent speed factors ω_h^c and ω_h^o are presented in Table 7. These were taken from empirical taxi data that was analyzed for a German metropolitan area in Ehmke et al. [2012]. We assume a driver's salary is \$11.46 per hour and a fuel price of \$1.19 per liter, based on information from Ehmke et al. [2016]. Each instance is computed five times on 2.6-GHz Intel Xeon processors with 512 GB of RAM, and we report the best result of the five runs. For each run, we let the extended LANCOST heuristic iterate 1000 times, which requires an average run time of 1420 seconds.

We consider three daily congestion basis fee levels, namely \$18, \$12, and \$6, where \$18 is based on the per-day congestion charge in the city of London, and \$6 is based on the congestion charge in Milan. We use the Big Mac index [BigMacIndex, 2017] to convert congestion charges from other currencies into dollars. To

time	ω_h^c	ω_h^o	time	ω_h^c	ω_h^c	time	ω_h^c	ω_h^o
12am–1am	1.032	1.3304	8am–9am	0.9468	0.711	4pm–5pm	0.9399	0.6289
1am–2am	1.0538	1.4884	9am–10am	0.9721	0.7398	5pm–6pm	0.9308	0.6111
2am–3am	1.0658	1.5416	10am–11am	0.9808	0.7781	6pm–7pm	0.9482	0.6964
3am–4am	1.0634	1.5455	11am–12pm	0.9811	0.7977	7pm–8pm	0.9843	0.8629
4am–5am	1.0754	1.5274	12pm–1pm	0.9823	0.7983	8pm–9pm	1.0098	1.0407
5am–6am	1.0724	1.3163	1pm–2pm	0.9859	0.7888	9pm–10pm	1.014	1.1189
6am–7am	1.0357	1.0393	2pm–3pm	0.9814	0.7531	10pm–11pm	0.991	1.174
7am–8am	0.9786	0.7918	3pm–4pm	0.968	0.6969	11pm–12am	1.0066	1.2228

Table 7: Speed Factors

fee size	C_d	C_e^f	C_m^f	C_g
high	\$18/day	\$17/entry	\$0.06/minute	\$0.42/gantry
medium	\$12/day	\$11/entry	\$0.04/minute	\$0.28/gantry
low	\$6/day	\$6/entry	\$0.02/minute	\$0.14/gantry

Table 8: Congestion Charges

make fees from different congestion charge schemes comparable, we base the per-entry fee, per-minute fee, and per-gantry fees on the results from using daily fees. The particular fees are derived as follows:

- Per-entry fee: We compute the average number of congestion zone entrances $\bar{n}_e$ and divide $\overline{CC}$ by $\bar{n}_e$ to approximate a per-entry fixed fee C_e^f such that the total congestion charge based on the per-entry fee is roughly equivalent to that based on the given daily fee. We repeat this for all daily fees.

- Per-minute fee: We compute the average duration (travel time plus service time) in minutes $\bar{n}_t$ that the vehicles spend in the congestion zone. We approximate a fixed per-minute fee C_m^f by $\overline{CC}/\bar{n}_t$.

- Gantry: We assume that there is a gantry located at each grid point within the congestion zone (see Figure 2, for example). Thus, for the per gantry congestion fee, we compute the average number of gantries $\bar{n}_g$ passed by the vehicles and approximate C_g by $\overline{CC}/\bar{n}_g$.

In Table 8, we summarize the congestion charges that are used in our experiments. We note that C_e^h and C_m^h are obtained based on C_e^f and C_m^f, respectively, via the methods discussed in Section 3.

For most of our experiments, we assume customers can receive a delivery at any time of day. This maximizes the impact optimization can have on the application of the different congestion charges. We also perform several experiments with time windows at customers. For these experiments, we consider three start times that the vehicles will leave the depot: 6am, 2pm and 5pm.

6 Computational Experiments

In this section, we present the results of our computational experiments. First, we introduce the metrics that we use for discussion. Then, we introduce the results for the medium sized city with a large congestion zone as our base case. We analyze what happens for different city sizes, different congestion zone sizes, and different departure times. All results are discussed both from the perspective of the fleet operator and the perspective of the municipality.

6.1 Metrics

In our experiments, we record the following metrics that are especially relevant for operators of commercial fleets:

- *cost*: total operational costs for one day, consisting of driver costs for spending the drivers' time for travel and service, fuel cost, and congestion fees in US dollars,
- *drive*: total driving time for all drivers in hours,
- *fuel*: total fuel used in liters, where fuel usage depends on the speed and distance of travel, as well as the vehicles' features, and
- *number of vehicles*: number of vehicles required to serve all customers feasibly given the problem constraints.

In addition to traditional vehicle routing metrics, we present the following metrics that help us analyze the effectiveness of congestion charge schemes from the perspective of the municipality:

- *dist in zone*: the distance traveled in the congestion zone in kilometers,
- *drive in zone*: the total driving time for all drivers in the congestion zone in hours,
- *fuel in zone*: total fuel used in the congestion zone in liters,
- *veh enter*: number of vehicles entering the congestion zone, and
- *times enter*: number of times vehicles enter the congestion zone.

Assuming that *fuel in zone* is an approximation for emissions that should be reduced within the congestion charge zone, it will be particularly interesting to see how the different congestion charge schemes support the minimization of emissions while increasing the costs of fleet operators.

6.2 Base Case

For our base case, we begin with the results for the medium sized city with a large congestion zone in Table 9 without time windows. The first two columns reflect the fee being charged (*fee*) for entering the congestion zone and the charging scheme (*scheme*), respectively. The remaining columns are the values as defined above averaged across five different customer instances and 10 departure times. In the first row, we report the values found with no congestion fees collected, while in subsequent rows, we report the percentage change in the listed metrics relative to the metrics obtained with no congestion fees charged. This helps us understand how different congestion charge schemes change the solution, especially their financial and environmental impact. The last row denotes the average number of vehicles required. This number does not vary across the different fees or charging schemes for the same instance type.

Table 9: Average Metrics for Medium Sized City, Large Congestion Zone

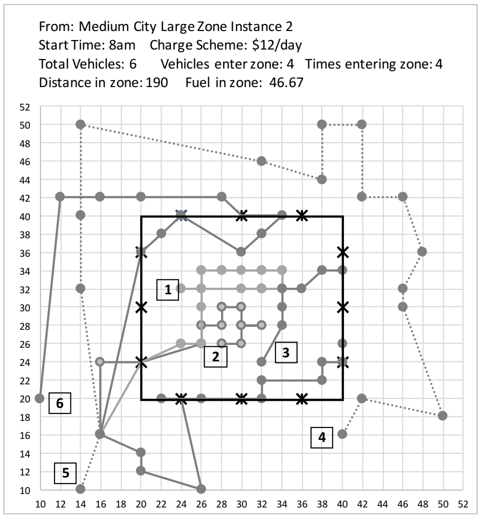
fee	scheme	cost	dist in zone	drive	drive in zone	fuel	fuel in zone	veh enter	times enter
no	no	524.65	168.24	18.71	8.65	100.56	41.44	4.38	4.54
18	daily	13.99%	0.03%	1.09%	-0.16%	0.77%	-0.11%	-10.00%	-9.63%
17	fixed entry	13.12%	-0.78%	1.08%	-1.00%	0.76%	-0.94%	-11.00%	-13.93%
17	t-d entry	13.16%	-1.46%	0.31%	-1.62%	0.25%	-1.58%	-10.50%	-13.43%
0.06	fixed min	14.30%	-3.42%	-0.13%	-3.42%	0.14%	-3.42%	0.07%	0.33%
0.06	t-d min	14.55%	-4.21%	-0.09%	-4.27%	0.21%	-4.25%	-1.40%	-3.67%
0.42	gantry	12.70%	-7.63%	0.27%	-7.70%	0.88%	-7.68%	-0.63%	-1.77%
12	daily	9.14%	-0.51%	0.38%	-0.69%	0.21%	-0.64%	-10.00%	-8.27%
11	fixed entry	8.53%	-0.75%	0.35%	-0.91%	0.26%	-0.86%	-8.60%	-11.53%
11	t-d entry	7.98%	-0.28%	0.41%	-0.44%	0.26%	-0.40%	-8.60%	-11.43%
0.04	fixed min	9.45%	-2.98%	-0.28%	-2.99%	0.00%	-2.99%	0.10%	0.73%
0.04	t-d min	9.63%	-3.43%	-0.23%	-3.48%	0.00%	-3.46%	-1.50%	-1.57%
0.28	gantry	8.49%	-6.31%	-0.03%	-6.30%	0.52%	-6.31%	-0.33%	-2.13%
6	daily	4.68%	0.87%	0.14%	0.79%	-0.03%	0.81%	-6.90%	-6.00%
6	fixed entry	4.60%	-1.71%	-0.07%	-1.78%	0.02%	-1.76%	-6.80%	-9.73%
6	t-d entry	4.89%	-0.91%	0.21%	-1.01%	0.21%	-0.99%	-7.03%	-9.87%
0.02	fixed min	4.82%	-2.11%	-0.04%	-2.10%	0.15%	-2.10%	1.17%	1.47%
0.02	t-d min	4.80%	-1.67%	-0.20%	-1.65%	-0.07%	-1.66%	0.17%	-0.67%
0.14	gantry	4.30%	-3.02%	-0.13%	-3.07%	0.08%	-3.06%	0.67%	0.60%
									average number of vehicles: 5.68

In order to serve all customers in our medium sized city within an 8-hour delivery period, a fleet of 5.68 vehicles is required on average, while each vehicle visits 17.6 customers on average. With no congestion fees, this leads to a total operational cost of \$524.65 and a fuel consumption of 100.56 liters in total, whereas about 2/5 of the fuel is consumed within the congestion zone. With congestion charges in place, the total number of vehicles required remains the same, but the total operational cost increases by about 4% to 14% depending on the type of the congestion charge scheme. Although the total operational costs increase between about 4% and 14%, there is not a parallel increase in the total time that vehicles are on the road, and there is also not a significant amount of variation (between a reduction of 0.28% and an increase of 1.09%). That is, while congestion charges generally increase operational costs, considering congestion charge schemes in vehicle routing procedures allows fleet operators to find alternative routes that are almost as time-efficient as the no fee options.

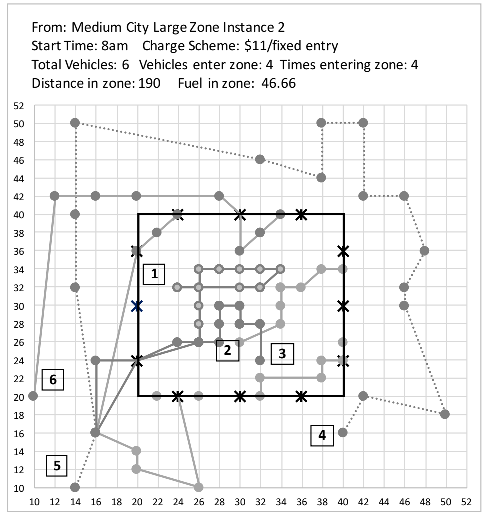
Analyzing the different types of schemes, some key observations are that daily entrance fees only decrease the distance traveled in zone for the medium \$12 daily fee, and even then, it is the least reduction in distance across all schemes and fees. Similarly, compared with other schemes, the daily charge scheme creates the least reduction in *fuel in zone* with the \$12 and \$18 fees and actually increases it with the \$6 daily fee. This is quite surprising since daily entrance fees are one of the more widely used ideas for reducing congestion. All other congestion charge schemes and fees lead to consistent reductions in *dist in zone*, *drive in zone*, and *fuel in zone*. As expected, larger fees usually lead to bigger reductions in these metrics. This suggests that larger fees are needed to drive companies to make significant changes in their routing plans to reduce emissions in the congestion zone. The only exception comes from the per entry fees. When the fee is high, the vehicles may travel for a longer distance within the zone after entering to take advantage of the fees paid. In this case, a higher fee (\$17 per entry) may lead to greater distance travelled in zone than a lower fee (\$6 per entry). Interestingly, gantry schemes have the largest impact on *dist in zone*, *drive in zone*, and *fuel in zone*. They lead to reductions in these metrics by over 7% for high fees, over 6% for medium fees, and over 3% with low fees. The next highest impact comes from the per minute fees with reductions in metrics by approximately half of what is achieved by gantries. Although most charge schemes reduce the emissions within the congestion zone, most of them increase the total emissions. While the distance travelled in zone is reduced by introducing congestion charges, the vehicles need to travel more outside the zone to complete the delivery service.

The *veh enter* column shows that with no congestion charges, 4.38 vehicles on average enter the congestion zone. The daily entry and per entry charges create the largest change in the number of vehicles entering the zone with values such as -10% and -11% for the highest fees. Similarly, these congestion charge schemes create the largest reductions in the average number of times that vehicles enter the congestion zone. As expected, the per entry fees make the biggest impact on the number of entrances to the congestion zone. The per minute and per gantry methods do not reduce the above two metrics or only reduce them slightly (between a reduction of 3.67% and an increase of 0.33% for *times enter* with the highest fees), but have a bigger impact on *drive in zone* and *fuel in zone*, which means having more vehicles enter the zone can still translate to savings in key metrics due to how the vehicles are used. Having fewer vehicles or entrances to the zone can translate to less efficient use of the vehicles rather than shorter distance travelled in zone via letting more vehicles enter the zone.

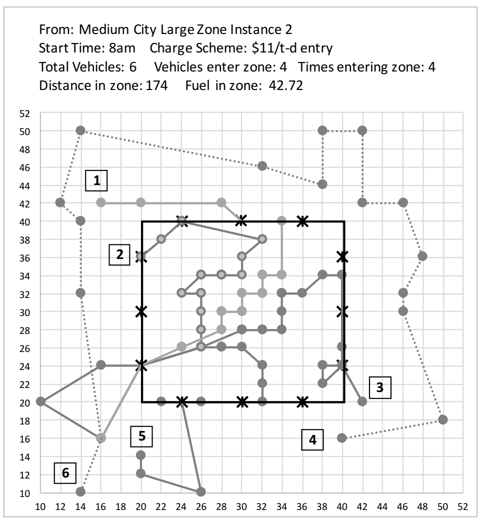
To see how the different congestion charge schemes affect the particular structure of routes, we next examine the detailed results for one instance in Figure 3. Here, we show the routes from different vehicles, omitting the travel to and from the depot. Routes are drawn with solid lines if the vehicles enter the congestion zone and are dashed if the associated vehicle remains outside the congestion zone. The large dots on the graphs represent the location of the customers. In Figure 3, the congestion charge schemes corresponding to graphs (a) through (f) are based on the medium fees: $12 daily, $11 fixed entry, $11 t-d entry, $0.04 per minute (fixed min), $0.04 per minute (t-d min), and $0.28 per gantry, respectively. We consider the same start time of 8am for all routes. As shown in the figures, each solution uses six vehicles. Although the number of vehicles entering the congestion charge zone are the same for all schemes in this instance, the travelled distance and the fuel consumption in the zone are quite different. The distance traveled within the congestion zone from the daily and fixed entry charge schemes are the most at 190 km, and these schemes also produce the highest fuel consumption (with 46.67 and 46.66 liters of fuel used, respectively). The least travel distance and emissions within the congestion charge zone is provided by the gantry congestion charge scheme, followed by the time-dependent per entry charge, the fixed and time-dependent per minute charge. With different charging schemes, the vehicles are routed differently within the congestion zone, leading to various emission levels. We note that even though it is easy to see that the



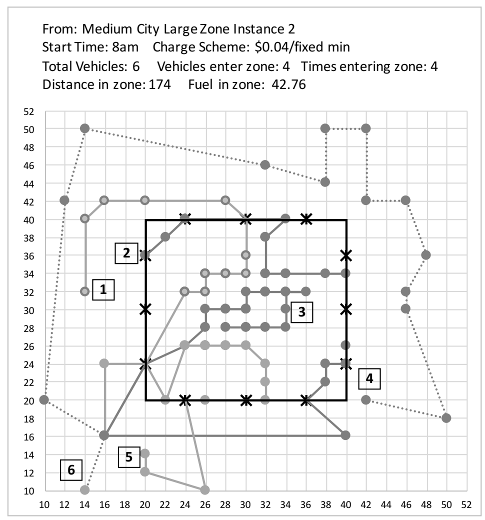
(a) daily



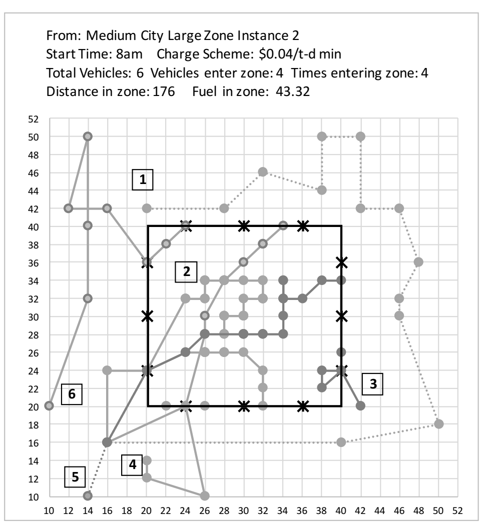
(b) fixed entry



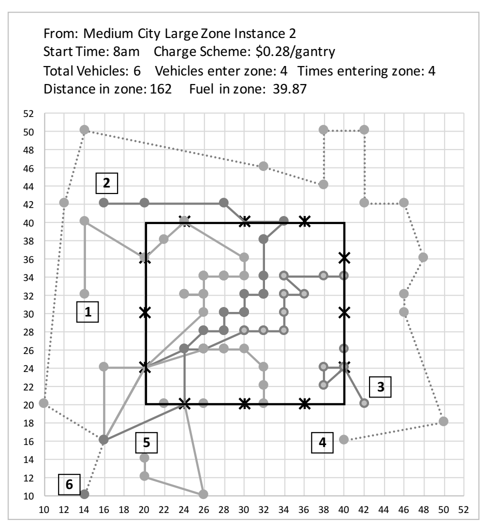
(c) t-d entry



(d) fixed min



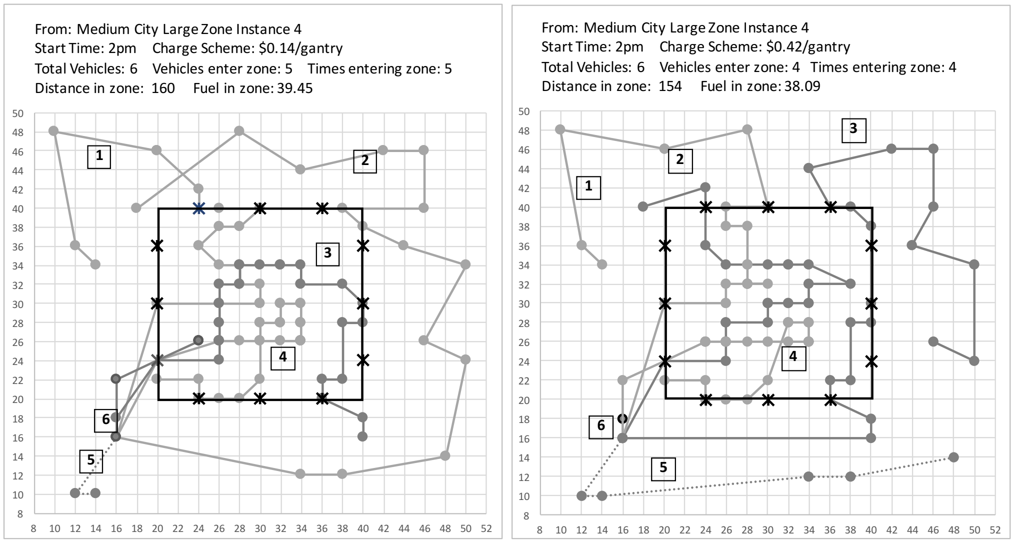
(e) t-d min



(f) gantry

Figure 3: Route plans for Different Charge Schemes for Sample Medium Sized City, Large Congestion Zone Instance

Figure 4: Low Charge vs. High Charge Based on a Medium Sized City Large Congestion Zone Instance



(a) low charge (b) high charge

routes within the congestion zone are quite different for daily and gantry schemes, for example, it is hard to characterize the nature of the differences. This indicates that it is important to use optimization tools and algorithms, such as used in this paper, when congestion schemes are employed.

To develop a better understanding of the per gantry charge schemes, we compare two solutions based on high ($0.42) and low ($0.14) fees for an instance with the medium sized city with a large congestion zone in Figure 4. The graphs (a) and (b) correspond to the low and high fee of the per gantry scheme, respectively. We consider the start time of 2pm for these routes. From the figure, we can see that there are more vehicles entering the congestion charge zone when the fee is lower. Also, customers are assigned to vehicles in a very different way, both in and outside the congestion zone. When the congestion charge changes from $0.14 per gantry to $0.42 per gantry, the distance travelled in zone is reduced from 160 kilometers to 154 kilometers, while the overall distance is increased from 508 kilometers to 524 kilometers. This example demonstrates the effectiveness of a higher fee in reducing the emissions in zone, while the overall emissions are increased.

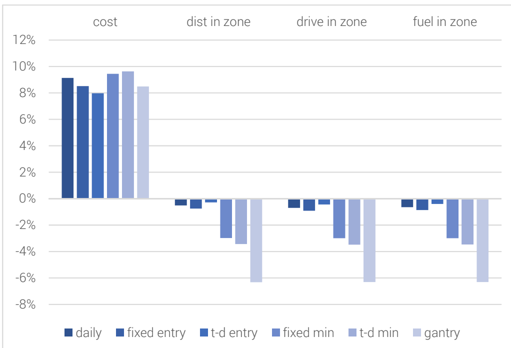
6.3 Varying the Size of the Congestion Zone

Next, we compare what happens with a smaller congestion zone size in Table 10. We compare the results from both the large and small zone sizes graphically with medium fees in Figure 5, to build an initial understanding of how they compare. In Figure 5, we see larger percentage increases in total cost with the large congestion zone. Similarly, we also see larger percentage reductions in our core metrics (distance in zone, drive in zone, fuel in zone) occurring with the large congestion zone. This makes sense since congestion zone customers make up a larger portion of the metrics with the larger congestion zone. This indicates that congestion schemes will have more impact on these metrics with larger congestion zones than with smaller ones. With the smaller congestion zone, we see that the gantry scheme still tends to perform well in terms of our key metrics. We note, though, that the performance of the gantry scheme is now closely followed by the time-dependent entry fee scheme.

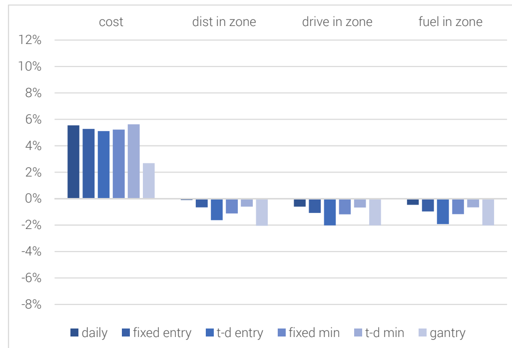
We examine the experiments with all fee levels in Table 10. For all experiments with the small congestion zone, the average number of vehicles required is 5.00, where 20 customers are visited by each vehicle on average. With high fees, the gantry scheme leads to the largest savings in *fuel in zone*, with a reduction of 2% more than than other schemes (-3.61% vs -1.11%). With low fees, though, gantry based schemes do not create the largest improvements. Instead, the biggest differences in *drive in zone*, *fuel in zone*, and *dist in zone* come from the time-dependent per minute scheme. Yet the largest reduction in fuel in zone for any scheme is only -1.25%. This indicates that small congestion zones with low fees are not likely to lead to big changes in *dist in zone*, *drive in zone*, or *fuel in zone*. For small congestion zones, though, the schemes do change how vehicles are used. This is seen by the changes in the values for *veh enter* and *times enter*. For daily and entry based schemes, reductions still are often close to 20%. However, these changes do not translate to large changes in time or fuel.

Next, we present an example of routes with a small congestion zone. In Figure 6, we compare the routes with a low daily charge to no congestion charge for an instance with the medium sized city and small congestion zone. The start time for this instance is 4pm. Both solutions require five vehicles. However, when there is no congestion charge, there are four vehicles entering the congestion zone, while there are only two when a daily charge of $12 is applied. With the daily charge scheme, the fuel within the congestion zone is reduced by around 9% compared with the no charge scheme, but the total costs are increased by around 6%. Here, vehicle 1 picks up many of the customers on the top half of the graph and does not enter the congestion zone. Similarly, vehicle 3 picks up many of the customers in the bottom right of the city and

Figure 5: Relative Results for Different Zone Sizes for Medium Sized City with Medium Fees



(a) large zone

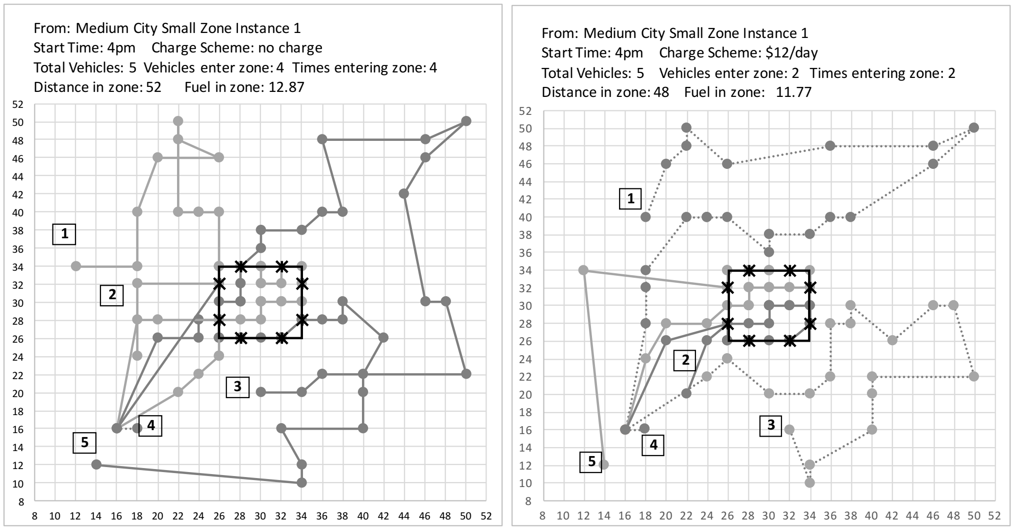


(b) small zone

Table 10: Average Metrics for Medium Sized City, Small Congestion Zone

fee	scheme	cost	dist in zone	drive	drive in zone	fuel	fuel in zone	veh enter	times enter
no	no	470.54	48.64	15.41	2.50	86.80	11.99	2.66	2.78
18	daily	8.12%	-0.09%	0.91%	-0.55%	0.53%	-0.42%	-19.67%	-16.33%
17	fixed entry	7.85%	-0.01%	1.14%	-0.45%	0.83%	-0.33%	-19.67%	-23.00%
17	t-d entry	8.02%	-0.31%	1.11%	-0.78%	0.82%	-0.66%	-19.67%	-23.00%
0.06	fixed min	8.30%	-0.75%	0.05%	-0.92%	-0.01%	-0.87%	0.33%	2.83%
0.06	t-d min	8.30%	-1.11%	-0.18%	-1.11%	-0.24%	-1.11%	4.50%	6.17%
0.42	gantry	4.10%	-3.61%	-0.14%	-3.62%	-0.12%	-3.61%	-3.17%	-0.67%
12	daily	5.56%	-0.09%	0.89%	-0.59%	0.53%	-0.46%	-19.67%	-13.50%
11	fixed entry	5.28%	-0.65%	1.03%	-1.07%	0.74%	-0.96%	-18.67%	-22.33%
11	t-d entry	5.11%	-1.62%	0.64%	-2.03%	0.32%	-1.92%	-19.67%	-23.00%
0.04	fixed min	5.23%	-1.12%	-0.44%	-1.18%	-0.55%	-1.16%	-2.83%	-0.83%
0.04	t-d min	5.64%	-0.61%	0.02%	-0.66%	0.00%	-0.65%	-1.00%	3.50%
0.28	gantry	2.69%	-2.04%	-0.24%	-2.02%	-0.21%	-2.02%	0.33%	-1.83%
6	daily	3.05%	0.22%	0.87%	-0.22%	0.49%	-0.10%	-17.00%	-13.67%
6	fixed entry	2.99%	-0.45%	0.73%	-0.91%	0.42%	-0.79%	-17.33%	-21.00%
6	t-d entry	2.98%	-0.83%	0.55%	-1.22%	0.21%	-1.12%	-16.67%	-20.17%
0.02	fixed min	2.69%	1.22%	-0.08%	1.18%	-0.22%	1.19%	5.00%	8.83%
0.02	t-d min	2.64%	-1.19%	-0.24%	-1.27%	-0.37%	-1.25%	0.17%	5.67%
0.14	gantry	1.47%	-0.12%	0.02%	-0.12%	0.08%	-0.12%	6.00%	6.17%
							average number of vehicles: 5.00		

Figure 6: No Charge vs. Daily Charge Based on a Medium Sized City Small Congestion Zone Instance



(a) no charge (b) daily charge

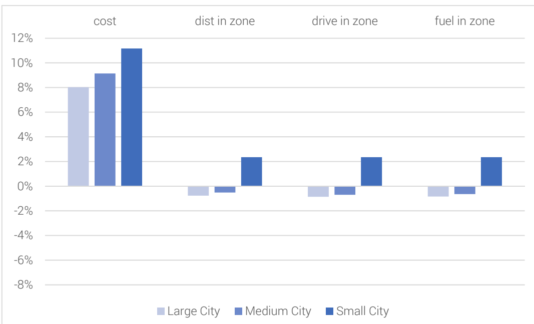
does not enter.

6.4 Varying the City Size

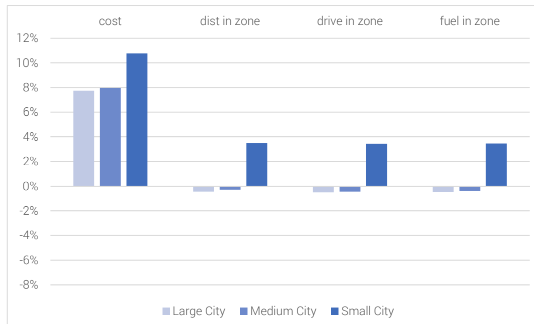
Next, we present the results for small and large city sizes with the large congestion zone. In Figure 7, we break out the results for all city sizes with medium sized fees graphically by congestion pricing scheme. In (a), we see that daily fees lead to savings in *distance in zone*, *drive in zone*, and *fuel in zone* for large and medium cities, but not small cities. This would imply that daily entry fees are a particularly bad choice for small cities, where they seem to be negligible in terms of routing. The same is true for time-dependent per entry fees. We only get reductions for all of these metrics through gantry charging schemes. This indicates that gantries are useful for all city sizes with large congestion zones.

Looking at the detailed results for the small and large sized cities with large congestion zones in Table 11 and Table 12, respectively, the improvements in key metrics for small cities are approximately half as with large cities. For example, the savings in *fuel in zone* from gantry schemes with high fees shift from -7.65% to -3.46%. For the small city instances with a large congestion zone, an average of 4 vehicles is needed per day, each serving 25 customers on average. For the large city instances with a large congestion zone, 8.2 vehicles are needed, each serving around 12 customers on average. Compared with the medium and large sized cities where the the values of key metrics are reduced by most congestion charges, for the small sized

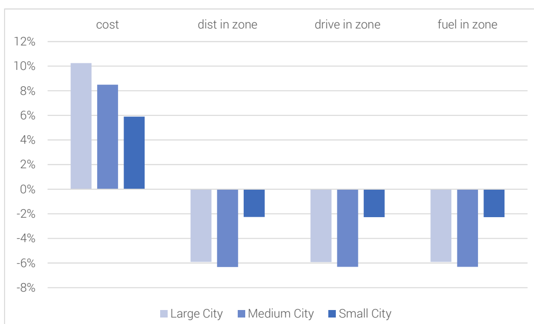
Figure 7: Relative Results for Different Charging Schemes for Large Congestion Zones



(a) daily fees



(b) t-d entry



(c) gantries

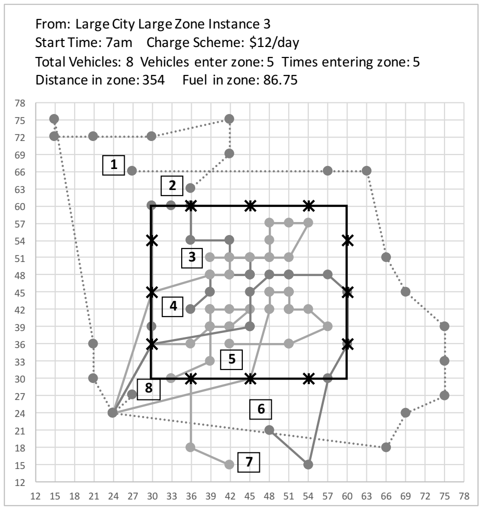
city with large congestion zone, the daily and entry based schemes increase the *distance in zone*, *drive in zone*, and *fuel in zone* by up to 3.46% from the no charge scheme. Further, the increase in the total costs by introducing congestion charges for the small sized city with large congestion zone is greater in general than that for the large sized city.

Table 11: Average Metrics for Small Sized City, Large Congestion Zone

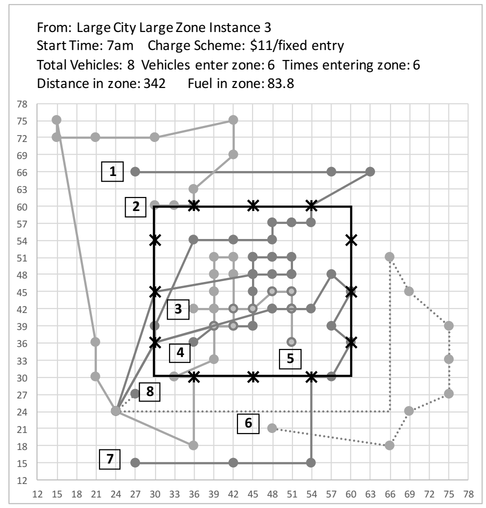
fee	scheme	cost	dist in zone	drive	drive in zone	fuel	fuel in zone	veh enter	times enter
no	no	331.65	72.78	7.89	3.74	42.43	17.93	3.12	3.48
18	daily	16.86%	3.36%	1.35%	3.26%	1.23%	3.28%	-3.00%	-4.10%
17	fixed entry	15.86%	3.30%	1.16%	3.16%	0.92%	3.20%	-3.00%	-11.40%
17	t-d entry	16.20%	2.67%	0.82%	2.63%	0.71%	2.64%	-3.00%	-11.40%
0.06	fixed min	17.56%	-1.28%	-0.10%	-1.30%	0.01%	-1.30%	1.83%	1.07%
0.06	t-d min	17.93%	-0.42%	-0.05%	-0.47%	0.03%	-0.46%	0.50%	-0.60%
0.42	gantry	8.91%	-3.45%	-0.04%	-3.46%	0.18%	-3.46%	1.67%	3.13%
12	daily	11.17%	2.35%	0.74%	2.36%	0.64%	2.36%	-3.00%	-1.43%
11	fixed entry	10.40%	2.96%	1.07%	2.90%	0.95%	2.92%	-3.00%	-11.40%
11	t-d entry	10.76%	3.51%	1.19%	3.45%	1.08%	3.46%	-3.00%	-11.40%
0.04	fixed min	11.79%	-0.74%	0.09%	-0.78%	0.15%	-0.77%	0.33%	1.23%
0.04	t-d min	12.10%	-0.29%	0.29%	-0.31%	0.37%	-0.30%	0.00%	3.30%
0.28	gantry	5.91%	-2.25%	-0.28%	-2.26%	-0.09%	-2.26%	1.17%	1.23%
6	daily	5.70%	2.77%	0.66%	2.71%	0.54%	2.72%	-3.00%	-1.57%
6	fixed entry	5.75%	2.15%	0.75%	2.04%	0.72%	2.07%	-3.00%	-11.40%
6	t-d entry	5.90%	2.53%	0.68%	2.52%	0.69%	2.52%	-3.00%	-11.40%
0.02	fixed min	5.89%	-0.11%	0.03%	-0.12%	0.07%	-0.12%	-1.17%	-0.27%
0.02	t-d min	6.08%	0.01%	0.23%	-0.04%	0.21%	-0.03%	1.17%	0.73%
0.14	gantry	3.03%	-0.89%	-0.02%	-0.95%	-0.03%	-0.93%	0.33%	3.20%
									average number of vehicles: 4.00

In Figure 8, we compare routing solutions from the medium pricing scheme for an instance with a large sized city and large congestion zone. The start time is 7am for the solutions. As shown in the figure, while all solutions use eight vehicles, the number of vehicles entering the zone varies from five to seven. We note that although there are only five vehicles entering the zone with the daily charge scheme, the travel distance and fuel consumption within the congestion zone are the highest from this scheme compared with the other five schemes. The time-dependent per minute scheme uses the least fuel within the congestion zone, even though it makes vehicles enter the zone for seven times. Comparing (c) with five vehicles in zone and (e) with seven, we find out that the routes in the zone have less crossing with latter. That is, when using fewer vehicles, the routes within the zone may not be very efficient.

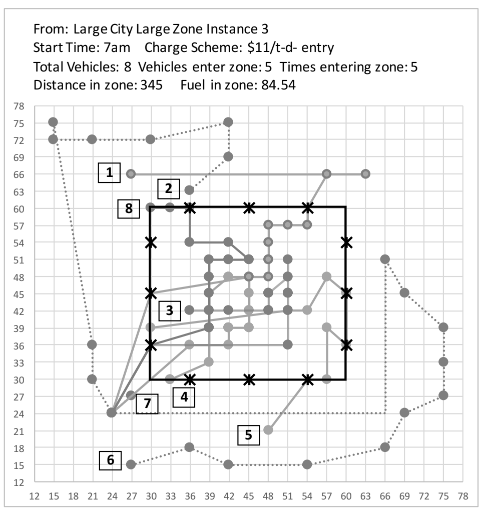
Figure 8: Different Charge Schemes Based on a Large Sized City Large Zone Instance



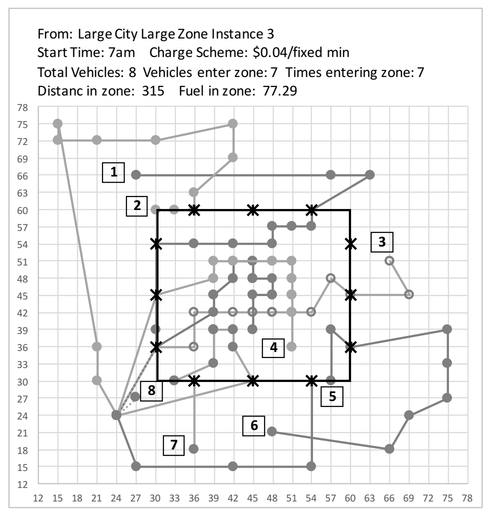
(a) daily



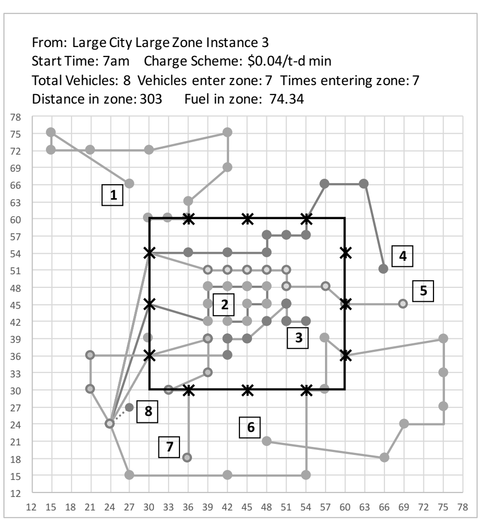
(b) fixed entry



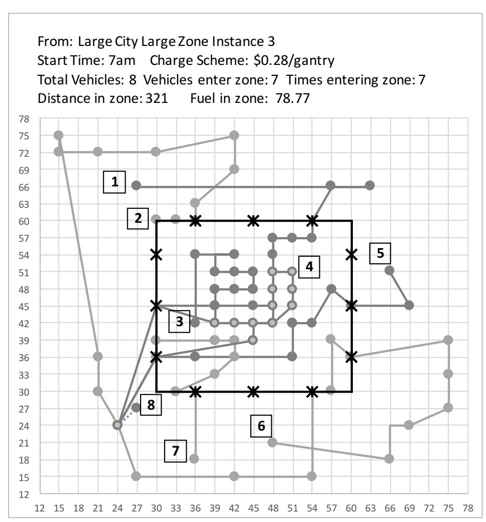
(c) t-d entry



(d) fixed min



(e) t-d min



(f) gantry

Table 12: Average Metrics for Large Sized City, Large Congestion Zone

fee	scheme	cost	dist in zone	drive	drive in zone	fuel	fuel in zone	veh enter	times enter
no	no	833.89	311.46	36.05	16.01	193.61	76.70	5.90	5.90
18	daily	11.84%	-1.13%	0.50%	-1.25%	0.58%	-1.22%	-9.93%	-9.93%
17	fixed entry	11.32%	-0.50%	0.81%	-0.61%	0.82%	-0.58%	-11.00%	-11.00%
17	t-d entry	11.93%	0.68%	1.20%	0.50%	1.15%	0.55%	-10.95%	-10.95%
0.06	fixed min	12.07%	-4.69%	-0.02%	-4.72%	0.32%	-4.71%	-1.77%	-1.77%
0.06	t-d min	11.96%	-5.97%	-0.40%	-6.00%	0.07%	-5.99%	-0.92%	-0.59%
0.42	gantry	14.95%	-7.64%	0.44%	-7.65%	0.97%	-7.65%	-1.50%	-1.50%
12	daily	8.03%	-0.77%	0.41%	-0.86%	0.43%	-0.84%	-9.00%	-9.00%
11	fixed entry	7.66%	-0.57%	0.57%	-0.65%	0.51%	-0.63%	-7.10%	-7.10%
11	t-d entry	7.75%	-0.43%	0.40%	-0.50%	0.43%	-0.48%	-7.33%	-7.33%
0.04	fixed min	7.91%	-4.27%	-0.26%	-4.27%	0.06%	-4.27%	-1.61%	-1.61%
0.04	t-d min	7.78%	-4.34%	-0.60%	-4.36%	-0.36%	-4.36%	-3.06%	-2.66%
0.28	gantry	10.25%	-5.90%	0.39%	-5.91%	0.85%	-5.91%	0.92%	1.32%
6	daily	3.88%	-0.79%	-0.23%	-0.85%	-0.23%	-0.83%	-4.23%	-4.23%
6	fixed entry	4.19%	0.05%	0.12%	0.00%	0.06%	0.01%	-3.08%	-3.08%
6	t-d entry	4.13%	-0.21%	-0.05%	-0.28%	-0.13%	-0.26%	-4.43%	-4.43%
0.02	fixed min	3.91%	-1.79%	-0.20%	-1.86%	-0.20%	-1.84%	-0.42%	-0.42%
0.02	t-d min	3.97%	-2.31%	-0.28%	-2.33%	-0.10%	-2.33%	0.43%	0.43%
0.14	gantry	5.01%	-2.96%	-0.14%	-2.96%	0.05%	-2.96%	-0.52%	0.54%
									average number of vehicles: 8.20

6.5 Varying the Departure Time

We next analyze the impact of congestion charges by comparing results for different departure times. In Table 13, we show our metrics for the large sized city with large congestion zone for 6am, 2pm and 5pm departure times and no congestion fees. We then present the results at 6am, 2pm and 5pm for the different congestion charge schemes in Table 14, Table 15, and Table 16, respectively.

Table 13: Early vs. Late Departure Time for Large Sized City, Large Congestion Zone, Medium Fees

scheme	start	cost	dist in zone	drive	drive in zone	fuel	fuel in zone	veh enter	times enter
no	6am	791.56	287.40	33.34	14.61	184.10	70.22	5.6	5.6
no	2pm	810.90	303.60	34.54	15.71	188.82	75.13	6.2	6.2
no	5pm	740.44	294.00	30.12	15.02	172.12	72.06	5.8	5.8

Table 14: Early Morning Departure Time for Large Sized City, Large Congestion Zone, Medium Fees

scheme	start	cost	dist in zone	drive	drive in zone	fuel	fuel in zone	veh enter	times enter
no	6am	791.56	287.40	33.34	14.61	184.10	70.22	5.60	5.60
daily	6am	7.91%	-3.94%	0.28%	-3.85%	0.70%	-3.88%	-9.05%	-9.05%
fixed entry	6am	6.36%	-1.04%	-1.12%	-1.07%	-1.20%	-1.06%	-6.19%	-6.19%
t-d entry	6am	6.49%	-4.82%	-0.74%	-4.73%	-0.50%	-4.76%	-9.05%	-9.05%
fixed min	6am	7.25%	-4.07%	-1.07%	-4.02%	-0.93%	-4.03%	-6.19%	-6.19%
t-d min	6am	6.69%	-2.76%	-2.06%	-2.82%	-2.06%	-2.81%	-9.05%	-5.05%
gantry	6am	10.48%	-5.81%	1.04%	-5.73%	1.69%	-5.75%	1.81%	1.81%
									The total number of vehicles is 7.60 for all 6am departures.

Analyzing the results of Table 13, the cost for the 2pm departure is about 2.5% greater than that for

Table 15: Early Afternoon Departure Time for Large Sized City, Large Congestion Zone, Medium Fees

scheme	start	cost	dist in zone	drive	drive in zone	fuel	fuel in zone	veh enter	times enter
no	2pm	810.90	303.60	34.54	15.71	188.82	75.13	6.20	6.20
daily	2pm	7.21%	-5.09%	-0.30%	-5.15%	-0.15%	-5.13%	-19.05%	-19.05%
fixed entry	2pm	7.86%	-0.88%	1.24%	-0.99%	0.69%	-0.96%	-16.19%	-16.19%
t-d entry	2pm	6.85%	0.35%	0.10%	0.12%	-0.37%	0.18%	-19.05%	-19.05%
fixed min	2pm	7.79%	-2.63%	-0.61%	-2.62%	-0.48%	-2.63%	-12.86%	-12.86%
t-d min	2pm	6.16%	-9.08%	-2.67%	-8.89%	-1.77%	-8.94%	-16.19%	-16.19%
gantry	2pm	10.15%	-7.87%	0.50%	-7.66%	0.92%	-7.71%	-2.86%	-2.86%

The total number of vehicles is 8.00 for all 2pm departures.

Table 16: Late Afternoon Departure Time for Large Sized City, Large Congestion Zone, Medium Fees

scheme	start	cost	dist in zone	drive	drive in zone	fuel	fuel in zone	veh enter	times enter
no	5pm	740.44	294	30.12	15.02	172.12	72.06	5.80	5.80
daily	5pm	8.15%	-2.86%	0.17%	-3.12%	-0.11%	-3.05%	-13.79%	-13.79%
fixed entry	5pm	7.80%	-2.45%	0.19%	-2.82%	-0.06%	-2.72%	-10.34%	-10.34%
t-d entry	5pm	8.86%	-3.88%	0.71%	-4.34%	0.89%	-4.22%	-10.34%	-10.34%
fixed min	5pm	8.35%	-3.06%	-0.63%	-3.07%	-0.44%	-3.07%	0.00%	0.00%
t-d min	5pm	7.84%	-7.35%	-0.78%	-7.77%	-0.76%	-7.65%	-10.34%	-10.34%
gantry	5pm	10.97%	-2.45%	0.20%	-2.70%	0.10%	-2.63%	-3.45%	-3.45%

The total number of vehicles is 7.40 for all 5pm departures.

the 6am departure and is about 9.5% greater than the 5pm departure. This is due to the slower speeds on the roads in the afternoon rush hour which occurs during the 2pm routes. For routes beginning at 5pm, most of the 8 hours is after the peak drive times. Based on Table 7, during the eight-hour working time, the average speed of vehicles for the 2pm start time are slower than that for the 6am and 5pm start times. This slow down in speed translates to increases of *drive in zone* and *fuel in zone*. Thus, afternoon rush hours create higher values for our key metrics than the off-peak times. The tables of results for different congestion schemes will help us understand whether different times are more impacted by different congestion schemes.

Looking at the results for 6am departures in Table 14, gantries are very effective in reducing the *fuel in zone* values (-5.75%). This comes at the cost of total fuel consumption, though, yielding an increase in total fuel of 1.69%. Looking at the results with 2pm departure in Table 15, the relative cost picture is similar to that from the early morning departures. However, the most effective scheme seems to be the time-dependent per minute scheme now, since this decreases *drive in zone* and *fuel in zone* as well as the vehicles entering the zone the most. Gantries are a close second indicating that they are a fairly stable solution. Looking at the results for 5pm departure results in Table 16, the most effective charging scheme is also the time-dependent per minute scheme. With congestion charges, the average numbers of vehicles used for 6am, 2pm, and 5pm departure times are 7.6, 8, and 7.4, respectively. With slower speeds, more vehicles are needed to finish the tasks.

6.6 Considering Time Windows

In many cases, carriers are hired by customers who want deliveries at specific times. The customers also do not care about choosing these time windows in a way that is beneficial for the carriers in terms of the metrics considered here. Thus, we next address how delivery time windows impact the routing of different congestion pricing schemes. As in §6.4, we look at the results for different start times to evaluate the sensitivity across the different times of day.

For each start time, we consider six different time windows. We present the time windows for different start times in Table 17. We randomly divide the 100 customers from each instance into six groups. The customers within a group have the same time window. Specifically, we assign 17 customers to each of the four earlier time windows (e.g., [6am, 8am], [7am, 9am], [8am, 10am], [9am, 11am] for start time 6am), and 16 customers to each of the last two time windows.

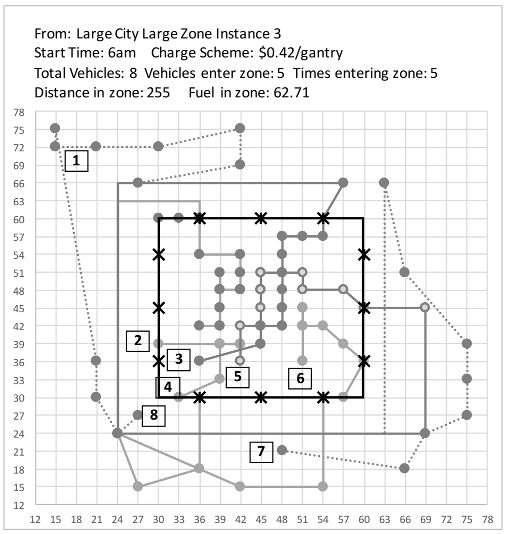
Table 17: Time Windows for Experiments with Different Start Times

start time	time windows
6am	[6am, 8am], [7am, 9am], [8am, 10am], [9am, 11am], [10am, 12pm], [11am, 1pm]
2pm	[2pm, 4pm], [3pm, 5pm], [4pm, 6pm], [5pm, 7pm], [6pm, 8pm], [7pm, 9pm]
5pm	[5pm, 7pm], [6pm, 8pm], [7pm, 9pm], [8pm, 10pm], [9pm, 11pm], [10pm, 12am]

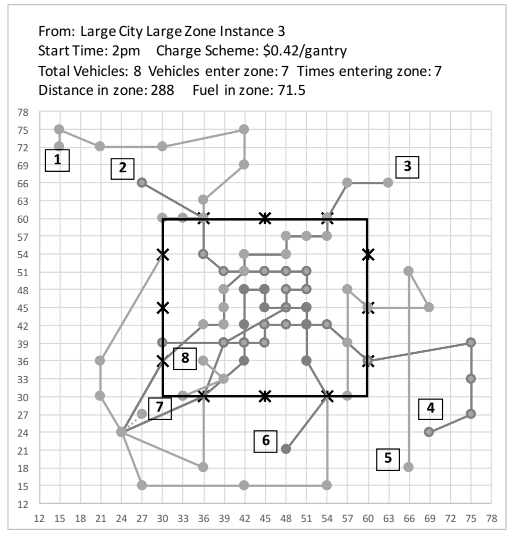
In Tables 18 through 20, we present our results for the experiments with time windows. With time windows, the gantry charge scheme still performs best on average in reducing the emissions in the congestion zone. Out of the nine scenarios (three start times and three charge levels for each start time), the gantry charge wins eight times. Meanwhile, as shown by the last columns in these tables, fewer vehicles entering the congestion zone may lead to more emissions in the zone. This observation is also consistent with that made when there are no customer time windows.

Although adding time windows does not affect the relative performance of congestion charge schemes in reducing emissions, the variations in operational costs among different charge schemes decrease slightly compared to those in the experimental results with time windows. In Tables 18 through 20, for the medium charge level in a large city with a large congestion zone, when there are time windows at customers, the gaps between the greatest and least increases in objective with congestion charges are 2.27%, 3.85%, and 2.84%

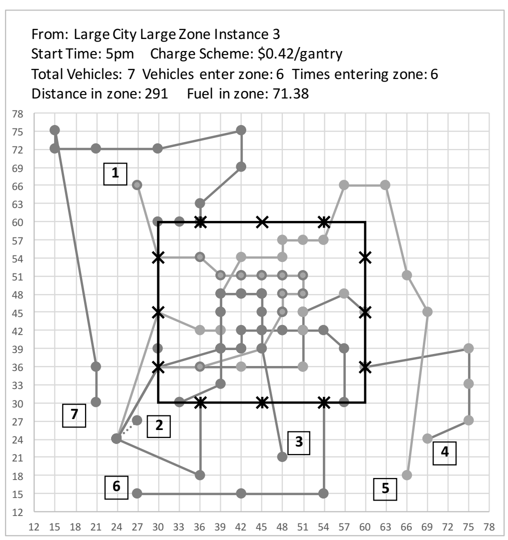
Figure 9: Early vs. Late Departure Time Based on a Large Sized City Large Zone Instance



(a) 6 am



(b) 2 pm



(c) 5 pm

Table 18: Early Morning Departure Time for Large Sized City, Large Congestion Zone with Time Windows

scheme	fee	start	cost	dist in zone	drive	drive in zone	fuel	fuel in zone	veh enter	times enter
no	n/a	6am	960.98	378.00	40.93	19.16	222.91	92.14	7.00	7.20
daily	18	6am	11.75%	-1.31%	0.79%	-1.33%	0.96%	-1.32%	-19.29%	-20.95%
fix entry	17	6am	12.17%	1.79%	1.65%	1.82%	1.72%	1.81%	-16.43%	-18.10%
t-d entry	17	6am	11.05%	1.25%	-0.20%	1.22%	-0.29%	1.23%	-13.57%	-15.24%
fix minute	0.06	6am	11.80%	-4.35%	-0.33%	-4.27%	0.21%	-4.29%	-2.02%	3.33%
t-d minute	0.06	6am	12.22%	-4.91%	-1.20%	-4.74%	-0.94%	-4.79%	-8.21%	-7.94%
gantry	0.42	6am	15.33%	-12.01%	-0.78%	-11.79%	0.52%	-11.85%	-5.36%	-5.08%
daily	12	6am	7.38%	-1.80%	-0.41%	-1.88%	-0.29%	-1.86%	-13.57%	-10.79%
fix entry	11	6am	7.47%	-3.52%	-0.27%	-3.54%	0.00%	-3.53%	-13.57%	-15.24%
t-d entry	11	6am	8.15%	-2.27%	0.77%	-2.22%	1.08%	-2.23%	-13.57%	-15.24%
fix minute	0.04	6am	7.08%	-3.10%	-1.09%	-3.01%	-0.70%	-3.03%	0.00%	0.00%
t-d minute	0.04	6am	7.81%	-2.52%	0.27%	-2.48%	0.57%	-2.49%	-2.86%	0.00%
gantry	0.28	6am	9.35%	-5.27%	-2.20%	-5.11%	-1.77%	-5.16%	0.00%	0.00%
daily	6	6am	3.09%	-0.29%	-2.70%	-0.26%	-2.88%	-0.27%	-10.71%	-10.16%
fix entry	6	6am	4.12%	1.20%	0.48%	1.14%	0.48%	1.16%	-8.21%	-10.16%
t-d entry	6	6am	3.36%	1.38%	-0.57%	1.45%	-0.65%	1.43%	-10.71%	-10.16%
fix minute	0.02	6am	3.89%	0.98%	0.53%	1.01%	0.72%	1.00%	0.36%	0.63%
t-d minute	0.02	6am	3.83%	0.07%	-0.88%	0.09%	-0.92%	0.09%	-2.50%	-2.22%
gantry	0.14	6am	5.54%	-3.69%	-0.45%	-3.66%	0.00%	-3.67%	2.86%	2.86%

The total number of vehicles is 9.6 for all 6am departures.

Table 19: Early Afternoon Departure Time for Large Sized City, Large Congestion Zone with Time Windows

scheme	fee	start	cost	dist in zone	drive	drive in zone	fuel	fuel in zone	veh enter	times enter
no	n/a	2pm	964.45	377.40	41.85	19.44	224.03	93.07	6.60	6.60
daily	18	2pm	12.24%	2.50%	2.18%	2.49%	1.78%	2.49%	-14.76%	-11.90%
fix entry	17	2pm	11.28%	-0.79%	0.04%	-0.75%	0.01%	-0.76%	-14.76%	-14.76%
t-d entry	17	2pm	12.00%	1.46%	0.68%	1.51%	0.45%	1.50%	-11.90%	-11.90%
fix minute	0.06	2pm	12.59%	-4.61%	-0.15%	-4.62%	0.05%	-4.62%	0.48%	3.33%
t-d minute	0.06	2pm	12.88%	-5.27%	0.00%	-5.25%	0.08%	-5.25%	-2.86%	0.00%
gantry	0.42	2pm	15.86%	-10.34%	-1.22%	-10.25%	-0.42%	-10.27%	-2.86%	-2.86%
daily	12	2pm	9.25%	0.92%	2.47%	0.85%	2.11%	0.87%	-9.05%	-9.05%
fix entry	11	2pm	7.48%	0.47%	0.69%	0.48%	0.64%	0.48%	-9.52%	-9.52%
t-d entry	11	2pm	7.19%	3.81%	0.58%	3.84%	0.46%	3.84%	-11.90%	-11.90%
fix minute	0.04	2pm	8.39%	-5.14%	-0.72%	-5.01%	-0.50%	-5.05%	-2.86%	-2.86%
t-d minute	0.04	2pm	8.18%	-0.56%	-0.65%	-0.48%	-0.56%	-0.50%	0.48%	3.33%
gantry	0.28	2pm	11.04%	-10.59%	-0.05%	-10.62%	0.41%	-10.61%	0.48%	3.33%
daily	6	2pm	4.75%	1.36%	1.48%	1.46%	1.35%	1.43%	-9.05%	-9.05%
fix entry	6	2pm	4.99%	2.00%	-1.01%	1.98%	-0.88%	1.99%	-2.86%	-2.86%
t-d entry	6	2pm	4.67%	0.51%	0.35%	0.50%	0.24%	0.50%	-6.19%	-6.19%
fix minute	0.02	2pm	4.73%	-2.96%	0.03%	-2.96%	0.27%	-2.96%	0.00%	2.86%
t-d minute	0.02	2pm	4.62%	-3.65%	0.42%	-3.69%	0.49%	-3.68%	3.33%	3.33%
gantry	0.14	2pm	6.29%	-0.45%	0.41%	-0.35%	0.37%	-0.38%	9.52%	12.38%

The total number of vehicles is 10 for all 2pm departures.

Table 20: Late Afternoon Departure Time for Large Sized City, Large Congestion Zone with Time Windows

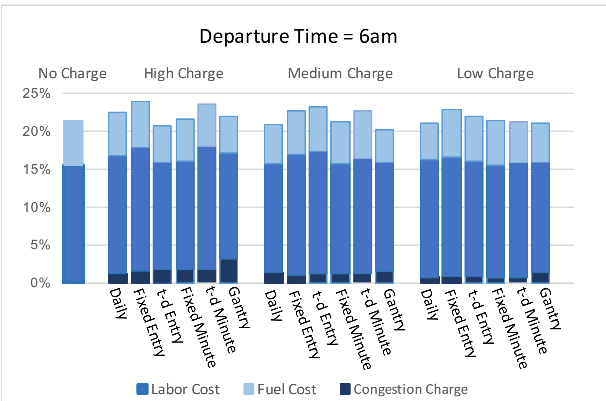
scheme	fee	start	cost	dist in zone	drive	drive in zone	fuel	fuel in zone	veh enter	times enter
no	n/a	5pm	759.87	318.00	32.25	16.23	177.79	77.90	5.83	5.83
daily	18	5pm	9.43%	-1.72%	0.74%	-2.14%	0.34%	-2.03%	-18.15%	-18.15%
fix entry	17	5pm	9.31%	-1.61%	-0.77%	-1.78%	-0.89%	-1.73%	-11.31%	-11.31%
t-d entry	17	5pm	9.45%	-3.53%	0.11%	-4.05%	-0.23%	-3.91%	-16.07%	-16.07%
fix minute	0.06	5pm	9.29%	-7.88%	-0.77%	-8.20%	-0.25%	-8.11%	0.30%	0.30%
t-d minute	0.06	5pm	9.21%	-5.75%	-1.35%	-5.93%	-0.95%	-5.88%	-6.55%	-6.55%
gantry	0.42	5pm	12.89%	-8.79%	-0.08%	-9.19%	0.52%	-9.08%	0.60%	2.98%
daily	12	5pm	6.67%	-0.37%	0.19%	-0.70%	-0.32%	-0.61%	-16.47%	-14.09%
fix entry	11	5pm	6.72%	0.06%	0.04%	-0.08%	-0.16%	-0.05%	-11.61%	-11.61%
t-d entry	11	5pm	7.10%	0.20%	-0.59%	-0.10%	-0.96%	-0.02%	-13.69%	-13.69%
fix minute	0.04	5pm	6.57%	-6.01%	-1.68%	-6.32%	-1.31%	-6.24%	-2.08%	-2.08%
t-d minute	0.04	5pm	6.30%	-5.30%	-1.67%	-5.51%	-1.32%	-5.45%	-2.08%	2.38%
gantry	0.28	5pm	9.14%	-7.67%	-0.26%	-7.82%	0.44%	-7.78%	-1.79%	0.30%
daily	6	5pm	3.78%	-0.20%	-0.09%	-0.34%	-0.21%	-0.31%	-4.46%	-2.08%
fix entry	6	5pm	3.84%	0.40%	-0.03%	0.36%	-0.23%	0.37%	-4.46%	-4.46%
t-d entry	6	5pm	3.89%	-0.82%	-0.44%	-0.99%	-0.66%	-0.94%	-8.93%	-8.93%
fix minute	0.02	5pm	3.40%	-3.43%	-0.93%	-3.48%	-0.60%	-3.47%	0.30%	0.30%
t-d minute	0.02	5pm	3.52%	0.17%	-0.34%	0.23%	-0.35%	0.22%	2.68%	5.06%
gantry	0.14	5pm	4.82%	-4.20%	-0.53%	-4.18%	-0.14%	-4.18%	0.30%	3.08%

The total number of vehicles is 7.83 for all 5pm departures.

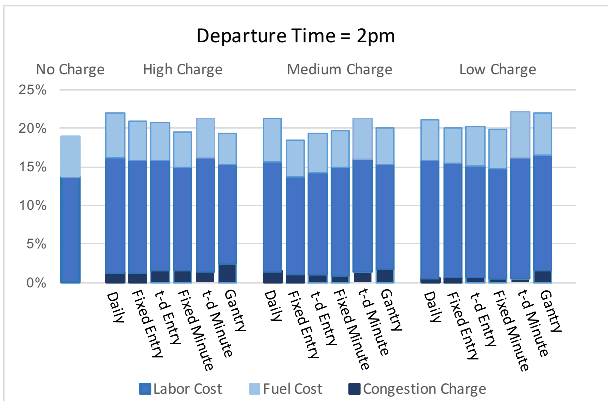
for the start time of 6am, 2pm, and 5pm, respectively. When there are no time windows, these gaps are 4.12%, 3.99%, and 3.13% for the three start times, respectively, as shown in the third columns in Tables 14 through 16. The lower variations in total cost is due to the fact that without time windows the vehicles have more flexibility in minimizing the total costs of operation.

In Figure 10, we present the differences between objectives from experiments with time windows and those without time windows to better understand the impact of the time windows. The isolated bar on the left side of each graph represents the objective increase due to time windows. The three groups of bars, from left to right, corresponds to the high, medium, and low charge levels, respectively. Within each group, there are six bars, which, from left to right, correspond to the increase in objectives for the daily, fixed per entry, time dependent per entry, fixed per minute, time dependent per minute and gantry charges, respectively. We demonstrate the contributions that each type of costs make to the total increase by different colors. For instance, for the start time of 6am and with an $18 daily charge, compared to no time window results, the time windows introduce 22.53% increase in objective in total, where 1.23% of it comes from the increase in congestion charge, 15.6% contributed by labor costs, and 5.7% by the fuel costs. In general, the average objective increases compared to no time window experiments are 21.9%, 20.44%, and 22.67% for the start times of 6am, 2pm, and 5pm, respectively. With time windows, the number of times vehicles entering the

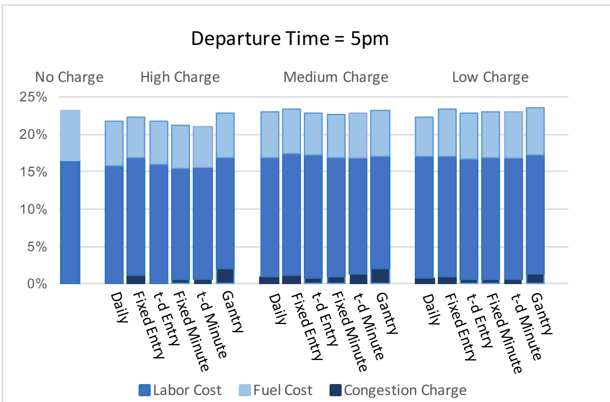
Figure 10: Increase in Total Costs with Time Windows



(a) total cost increase for the start time of 6am



(b) total cost increase for the start time of 2pm



(c) total cost increase for the start time of 5pm congestion zone increases only slightly, but the vehicles drive for much longer distance in and outside the zone to meet service requests. Therefore, there are more increases in labor and fuel costs than in congestion charges. Further, we note that on average the value of the labor costs are about two times more expensive than the fuel costs.

7 Conclusion and Outlook

In this study, we investigate the impact of different congestion charge schemes on the routing of commercial fleets and on the environment. Congestion charges generally increase operational costs of commercial fleet operators, and considering congestion schemes in vehicle routing procedures allows them to find alternative routes that are almost as time-efficient as the no fee options. We test our modeling and solution approach with several instances. The observations illustrated by our computational experiments are summarized as below. First, the congestion pricing schemes can impact routing of commercial fleets significantly. For instance, with a congestion charge, the vehicles may travel less in the congestion zone than with no charge. Surprisingly, the daily congestion charge does not always lead to more environmental-friendly solutions, i.e., with a daily fee, the vehicles may even travel more in the congestion zone. Second, larger congestion fees usually have more impact than smaller fees and the gantry charging schemes are surprisingly effective for most city and congestion zone sizes. Third, having fewer vehicles or entrances to the zone can translate to less efficient use of the vehicles in the zone when compared with letting more vehicles enter the zone for short periods. Fourth, the congestion charging schemes investigated in this paper usually have more impact on the key metrics (i.e., *distance in zone*, *drive in zone* and *fuel in zone*) for larger city and congestion zones than for smaller sizes. When the city and congestion zones are small, smaller distances are travelled, then less impact will be felt. This implies that the daily entry fees are a particularly bad choice for small cities. Fifth, the gantry based charging schemes are useful for all city sizes with relatively large congestion zones. Further, the departure times of the vehicles will impact the key metrics of routing and the number of vehicles required overall and to enter the congestion zone. Last, the introduction of time windows does not change the effectiveness of congestion charges, although it will increase the total cost values by over 20% on average, which is mostly contributed by the labor and fuel costs.

One future research direction is to consider alternative tolling methods and investigate their impact on the routing of urban fleets. Second, it would be interesting to evaluate the impact of travel speeds and route durations on our results. Third, we would like to analyze fleets consisting of more than one type of vehicle, where the congestion tolling scheme depends on the vehicle types. Fourth, it would be interesting to model the impact of the congestion charges on multiple players besides the commercial fleets, investigating how different charging schemes will affect the traffic on certain roads.

Acknowledgement

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