Evaluation of Urban Freight Deliveries using Microsimulation and Surrogate Safety Measures

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Abstract

Freight deliveries on signalized urban streets are known to cause lane blockages during deliveries. When delivery vehicles block lanes of traffic near signalized intersections, the capacity of the intersection is affected. Current practice is for traffic signals to be timed assuming that each approach can serve vehicles at the unobstructed saturation flow. There are three goals of this research: 1) to develop models to quantify the capacity and delay effects of a lane-blocking freight delivery on a signalized urban street, 2) to develop a model for adapting the traffic signal timing in real time for signal cycles during which a delivery blocks a link upstream of the intersection, and 3) to quantify the safety impacts of freight deliveries. The results of the queueing model show that accounting for the dynamics of queuing provides closed-form analytical formulas for delay and capacity that can account for varying locations of deliveries and different impacts on different lane groups. The signal control algorithm requires real-time information about the location of the double-parked delivery vehicle, which is assumed to be available from connected vehicle data from urban freight vehicles or from another detection system. The results show that for low levels of traffic demand, the signal control method reduces intersection delay compared to a signal that is timed for unblocked traffic. The algorithm also keeps the intersection approach undersaturated for higher levels of demand, which is important because deliveries can last for many signal cycles. For the safety analysis, the number of conflicts follows a similar pattern as delay with a decrease in number as freight stops move away from the intersection. The crash severity does not appear to change significantly. This study suggests that any measures that can be taken to encourage delivery stops to be made near the middle of the block would be effective for improving traffic flow and safety. Managing freight deliveries in this way is likely to be more feasible than attempting to ban double parking altogether.

1 Introduction

Freight deliveries are known to disrupt traffic on urban arterials. Traffic congestion associated with urban freight deliveries has gained increasing attention in recent years as traffic engineers and planners are tasked with finding solutions to manage increasing demand in a more sustainable way with limited road capacity. Although trucks make up only a small percentage of vehicular traffic (6% of vehicles on urban freeways), they incur a greater proportion of the total cost of delays (26% of total cost) [1]. In the U.S., approximately 7% of urban traffic is made up of trucks [2], but the deliveries are increasing dramatically as a result of e-commerce. Emerging discussion of policies to shift deliveries to off-hours are intended to mitigate the impacts on traffic congestion.

This study presents an analysis using traffic flow theory and microsimulation to quantify the effect of urban freight deliveries on traffic delay and safety on signalized arterials. Although there is an increasing body of literature related to policies and operational issues associated with urban freight movements, there is a need for systematic analysis of the localized impact of individual deliveries on traffic.

1.1 Literature Review

The effects of truck deliveries in urban networks can be generally separated into two categories: 1) the effect of heavy vehicles in the traffic stream on the flow of vehicles, and 2) the effect of truck delivery stops on traffic flow when lane blocking occurs. The first category of effects has been analyzed more extensively in the literature. Some studies have made use of traffic simulations to account for the effect of trucks in the traffic stream [3, 4]. Other studies have made use of empirical field measurements along with calibrated traffic simulations [5]. A significant synthesis of the effects of heavy vehicles in the traffic stream was published in NCFRP Report 31 [6]. The report summarizes the effect of trucks on mid-block arterial speeds and presents improved methods for calculating truck passenger car equivalent factors for capacity analysis of signalized intersections. These methods do not account for blockages caused by parked trucks.

The effect of freight delivery stops that block lanes of traffic on arterial capacity and intersection delays has received less attention in the literature. Han et al. [7] conducted a GIS-based investigation of the extent and order of magnitude of double-parking disruptions for pickups and deliveries nationwide in the U.S. Other recent studies have considered the problem of truck parking for deliveries from the perspective of the carrier [8–10]. Others have identified many of the characteristics of delivery patterns and businesses on urban streets [11, 12]. Very few investigations of the effect of parked trucks on intersection capacity have been conducted, and they have not provided a comprehensive analytical approach for estimating capacity and delay [13].

Although a few studies have identified safety implications as an important consequence of urban freight deliveries, the magnitude of these effects have not been systematically quantified [14, 15]. The studies that have sought to use surrogate safety assessment tools with microsimulation to investigate the effect of trucks in urban locations have focused on urban freeways [16, 17]. These studies focus on the interactions between trucks and other vehicles when the trucks are moving in traffic. This leaves a gap in the literature to investigate the safety effects of stopped freight vehicles that make deliveries on urban streets.

A growing body of research has investigated policies to encourage the schedule of deliveries in urban areas during off-peak hours [18–21]. Although a major motivation for off-hour delivery programs is to reduce traffic congestion, most of the analysis focuses on the experience from the perspective of agencies or the delivery drivers, who are able to travel at greater speeds during lower traffic periods [22–24]. The challenge is to convince receivers to schedule off-hour deliveries, which in many cases requires paying an employee of a store to stay after normal business hours or make special arrangements for the delivery to be made in the absence of someone to receive the delivery [25]. Programs to reduce traffic congestion by managing urban freight are limited [26, 27]. A trial off-peak delivery program in New York City paid businesses approximately $2000 to receive shipments during off-hours rather than normal business hours for a month; carriers were paid $300 to participate in the trial [28]. Evaluations of the congestion and reliability effects of the off-hour delivery program in New York required extensive simulation analysis but did not include the impact of lane blocking during delivery [4, 29]. Being able to quantify the effects of urban freight deliveries on the performance of signalized streets in terms of delays and safety would be useful for evaluating urban freight delivery policies that may attempt to reduce, relocate, or reschedule urban freight deliveries.

A related problem is timing traffic signals for real-time transit operations. Studies have evaluated the effect of bus stops near intersections on intersection capacity [30-32] and real-time signal control strategies to minimize person delay [33, 34]. This literature investigates the effect of transit vehicles stopping at fixed stop locations, which typically have an effect for a short duration for loading and unloading passengers. Signal control algorithms are often designed to provide some priority to transit in order to reduce delays that passengers experience at signalized intersections. Currently, delivery vehicles do not communicate that they are double-parking because it is usually considered a traffic violation for which operators can be fined. If the locations of urban deliveries could be detected (e.g., with data from connected vehicle communications), there is an opportunity to adjust signal timings to account for the presence of double-parked delivery vehicles. The benefit of such a system would be to reduce delays by timing signals to sustain undersaturated conditions during deliveries for the widest range of traffic demands, thereby reducing the occurrence of queue spillbacks and gridlock congestion.

1.2 Study Contribution

This study makes three contributions to the literature. First, models are developed to quantify the effect of freight deliveries on capacity and vehicle delay on a signalized urban street consistent with kinematic wave theory [35, 36]. The 2010 Highway Capacity Manual [37] does not provide any guidance for urban freight deliveries, but double-parked delivery vehicles may have a similar effect as two types of lane blockages: buses stopping to board and alight passengers, and vehicles making parallel parking maneuvers. Second, an algorithm is presented for adapting traffic signal timing in real time for signal cycles during which a delivery blocks a link upstream of the intersection. Third, a Surrogate Safety Assessment Model (SSAM) is used with microsimulation to quantify the effect of freight deliveries on vehicle interactions as an indication of safety risk. Specifically, the study focuses on quantifying the relationship between the location of the freight delivery along the block and the impact on traffic.

This report is organized as follows. First, a simple method for calculating capacity and delays based on the HCM2010 methodology for accounting for stopping buses is presented. A model is presented for arterial capacity that is consistent with queueing dynamics on a link, followed by a procedure for calculating intersection delay based on the dynamics of queuing when a delivery vehicle blocks part of the street upstream of a signalized intersection. A comparison of the two methods reveals that the HCM2010 methodology provides only a coarse indication of the effect of a freight delivery on capacity and delays. A signal optimization is proposed to minimize total intersection delay when undersaturated conditions can be achieved. Then, a microsimulation analysis is conducted to demonstrate that the effect of freight delivery location on traffic delays is consistent with a simulated environment. This microsimulation model also provides outputs that are evaluated with SSAM as a measure of safety.

2 Observations from the Field

The effect of blocked lanes due to stopped delivery vehicles has also been observed in field observations, and microsimulation confirms the relationship between the location of the blockage and the effect on capacity and delay. Live video feeds from the New York City Department of Transportation's Transportation Management Center are available for streets all over Manhattan.[1] Six hours of continuous video recording from the vantage point of a cantilever-mounted traffic signal over 8th Avenue between 36th and 37th streets was recorded by NYCDOT and shared with the authors. A frame of this video is shown in Figure 2.1. Between 10 a.m. and 4 p.m. on Tuesday, August 11, 2015, there were 14 observed on-street deliveries lasting an average of 12.4 minutes.

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[1] www.nytmc.org

Figure 2.1 – Northward view of 8th Avenue at 36th Street, New York City

A number of qualitative observations were made of the urban freight deliveries in New York City, which are general characteristics of freight deliveries that apply to all cities:

1. Freight vehicles stop to make deliveries at locations that are randomly distributed along the length of the block or street segment.
2. The duration of deliveries is typically longer than a signal cycle and often lasts for many signal cycles.
3. The blocked lane has different effects on traffic moving in different lane groups; e.g., turning vehicles must merge with through lanes to get around delivery vehicles before returning to their desired lane.
4. Drivers appear to have different propensities for using the open street space in front of a delivery vehicle depending on the location and road conditions.

For these reasons, urban freight deliveries are different from other types of lane blockages, such as buses stopping for passengers or vehicles stopping to park. These specific characteristics are reasons that the existing HCM2010 methodology is not sufficient to model the capacity and delays for urban freight deliveries, and the proposed detailed model addresses these shortcomings.

3 Methodology

This research study begins with the development of analytical models based on traffic flow theory to quantify the intersection capacity and delay as a function of the freight delivery and traffic characteristics. The analytical models produce formulas that can be compared with models that are currently published in the HCM2010. These formulas can also be used to develop an objective function for an optimization algorithm to retime signals so that delays are minimized even when freight deliveries are being made. The benefit of analytical models is that when based on the traffic flow theory, they are consistent with traffic dynamics on links in a network; however, these models are based on the assumption that all vehicle arrivals are deterministic and drivers are identical.

In order to account for more realistic conditions, such as platooned arrivals of vehicles from upstream intersections and distributions of driver behaviors, a more detailed method is needed. Although observations of real traffic on city streets would provide the most convincing validation of models, it is difficult to observe enough different traffic conditions to make systematic conclusions about the relationships between freight deliveries and the effect on delay and safety. A microsimulation model provides a useful controlled test environment in which to compare traffic operations in different scenarios. Using Aimsun, a full-featured, commercial microsimulation software, a simple network is constructed that represents a couple of blocks of 8th Avenue in New York City, where urban freight deliveries are known to be a problem. This microsimulation model is then used to compare the effect of freight deliveries at different locations along the block on traffic operations. From the microsimulation, every vehicle is tracked so that delays can be directly observed and vehicle trajectories can be analyzed for conflicts using SSAM.

4 Analytical Models of Delay and Capacity

First, the conventional expression for uniform delay at an unblocked intersection approach is presented. Then, two methods are presented to quantify the delay on an approach that is affected by the blockage of a parked delivery vehicle: a conventional procedure based on the HCM2010 methods for a transit bus stopping for passengers, and a revised method that accounts for the dynamics of queuing to make a more refined prediction.

4.1 Unblocked Intersection Approach

For a uniform rate of vehicle arrivals on approach i, q_i, when there is no truck blocking traffic for a freight delivery, the traffic situation would appear as illustrated in Figure 4.1. Figure 4.2 shows the queuing delay, d_i, resulting from a signal with cycle length C, green time g_i, and saturation discharge rate s_i. The uniform control delay per signal cycle for an unblocked approach is given by Webster's well-known equation with subscript i indicating the specific intersection approach:

$$d_i = \frac{q_i(C - g_i)^2}{2(1 - q_i/s_i)} \tag{4.1}$$

This expression applies for undersaturated conditions, meaning that g_i is longer than the minimum green time required to clear the queue, $g_{min,i}$, which is given by

$$g_{min,i} = q_i C/s_i \tag{4.2}$$

The average delay per vehicle can always be calculated by dividing the total approach delay by the total number of vehicle arriving per signal cycle, $q_i C$.

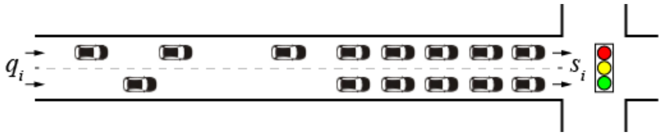


Figure 4.1 – Saturation flow associated with an unblocked intersection approach

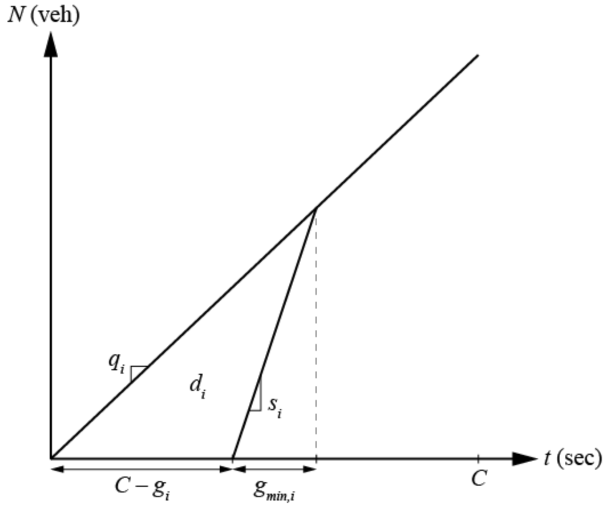


Figure 4.2 – Queuing diagram showing delay for an unblocked approach

4.2 Blocked Approach: Coarse Model

When a double-parked vehicle blocks the flow of traffic along a street, there is not an established procedure in the HCM2010 to account for the impact on delays. The nearest example is to treat the freight delivery like a transit stop. According the HCM2010 [37], a blockage is considered to have no effect on intersection capacity if the distance of the blockage from the intersection, x, is greater than 250 feet. In that case, the delay calculation and minimum green time would be given as in Equations 4.1 and 4.2.

If the location of a freight vehicle is less than 76.3 m (250 feet) from an intersection, as shown in Figure 4.3, then the capacity of the approach is assumed to be reduced to the saturation rate of the remaining lanes at the blockage, $s_{b,i}$. The resulting calculation of delay and minimum green time is therefore given by conditional expressions:

$$d_i = \begin{cases} \dfrac{q_i(C-g_i)^2}{2\left(1-q_i/s_{b,i}\right)}, x < 76.3 \\ \dfrac{q_i(C-g_i)^2}{2(1-q_i/s_i)}, x \geq 76.3 \end{cases} \tag{4.3}$$

$$g_{min,i} = \begin{cases} q_i C/s_{b,i}, x < 76.3 \\ q_i C/s_i, x \geq 76.3 \end{cases} \tag{4.4}$$

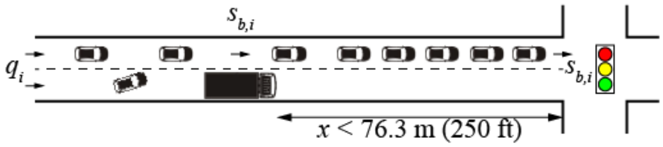


Figure 4.3 – Saturation flow associated with a delivery truck blockage in the simplified model based on HCM2010

4.3 Blocked Approach: Detailed Approach

Double-parked delivery vehicles affect the capacity of signalized intersections by blocking the flow of traffic along the street. Figure 4.4 provides an illustration a delivery vehicle blocking one lane of traffic on an intersection approach. The distance for a stopped delivery vehicle to an intersection, x, affects the number of vehicles that can be served at the unblocked saturation rate, s, and the restricted flow, s_b, that results when queued vehicles must pass around the stopped vehicle.

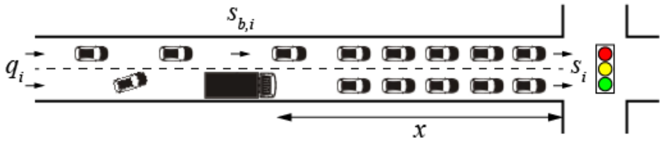


Figure 4.4 – Saturation flow associated with a delivery truck blockage in the detailed model consistent with queueing dynamics

If the delivery location is far enough away from the intersection that it does not interfere with the queue of vehicles that develops during the red phase, the signal delay is given by Equation 4.1. The minimum critical distance for this case is given by:

$$x_{crit} = \frac{sq_i(C - g_i)}{k_i(s_i - q_i)} \tag{4.5}$$

where k_i is the jam density of vehicles on approach i.

For deliveries that are closer to the intersection, the delay must be calculated as shown in Figure 4.5 for undersaturated conditions. Following from the geometry, the total approach delay per cycle is:

$$\begin{aligned} d_{b,i} = \tfrac{1}{2}(C - g_i + \tau_1 + \tau_2)^2 q_i - \tfrac{1}{2}\tau_1^2 s_i \\ - \tfrac{1}{2}\big(xk_i + q_i(C - g_i + \tau_1 + \tau_2)\big)\tau_2 \end{aligned} \tag{4.6}$$

where

$$\tau_1 = xk_i/s_i \tag{4.7}$$

$$\tau_2 = \frac{1}{s_{b,i} - q_i}\left(q_i\left(C - g_i + \frac{xk_i}{s_i}\right) - xk_i\right) \tag{4.8}$$

The minimum green time required for undersaturated conditions when a delivery vehicle blocks part of the queue is given by

$$g_{b,min,i} = \tau_1 + \tau_2 \tag{4.9}$$

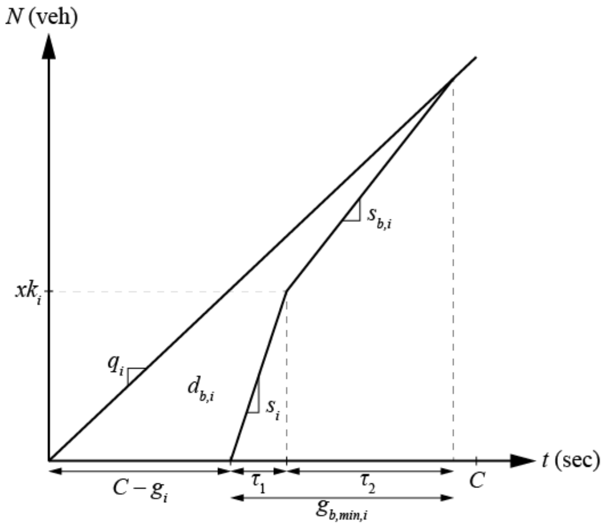


Figure 4.5 – Queuing diagram showing delay for an approach blocked by a freight delivery

4.4 Comparison of Analytical Models

A numerical example is used to provide a comparison between the delays estimated using the two methods. The input parameters for the numerical example are summarized in Table 4.1. The example used the same two-lane street presented in Figures 4.1, 4.3, and 4.4. When there is no delivery on the link, the average vehicle delay is 20 seconds per vehicle at the intersection based on Equation 4.1. This is the baseline delay against which additional delays associated with freight deliveries are compared.

Looking at a single signal cycle while a delivery is occurring, Figure 4.6 shows how delay per vehicle relates to the location of the stopped delivery vehicle for the coarse model expressed by Equation 4.3 and the detailed analytical model expressed by Equation 4.6. The models are only in agreement when the delivery vehicle is at the intersection or further upstream than x_{crit}. The thick blue curve shows how delays diminish as the distance from the intersection to the delivery vehicle, x, increases. The thin green curve, by contrast, shows how the coarse model may overestimate or underestimate the effect of the blockage depending on the location of the delivery.

Table 4.1 – Parameter values for numerical example for delay calculation

Parameter	Value	Units
Cycle Length, C	120	sec
Effective Green, g	60	sec
Arriving Demand, q	450	veh/hr
Unblocked Saturation Flow, s	1800	veh/hr
Saturation Flow at Blockage s_b	900	veh/hr
Jam Density, k	100	veh/km
Minimum Critical Distance, x_{crit}	100	m

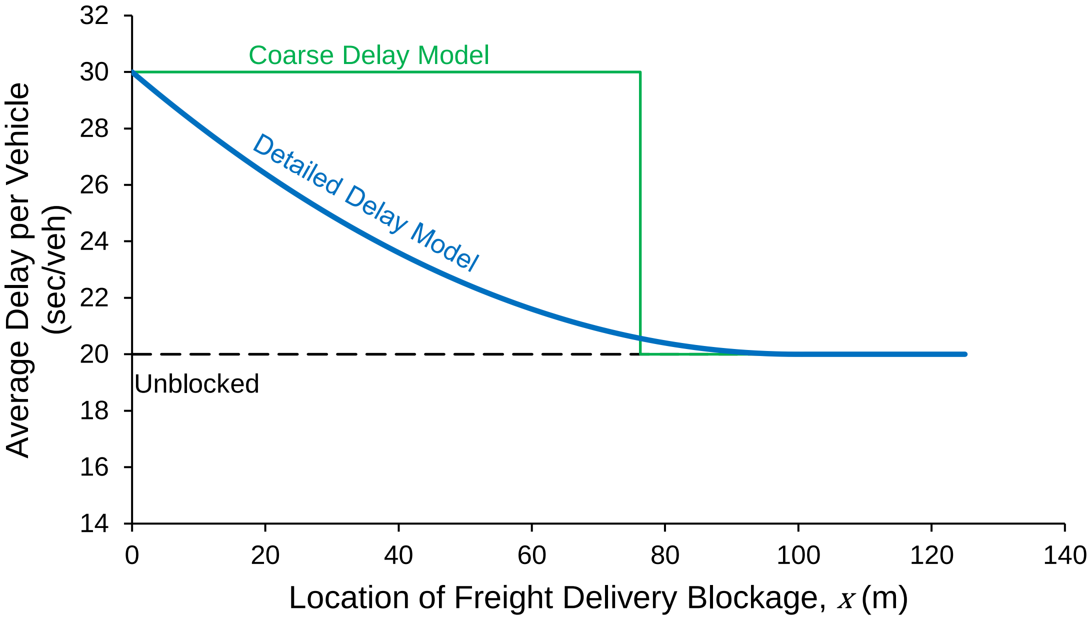


Figure 4.6 – Effect of freight delivery blockage location on average intersection delay per vehicle

5 Optimizing Traffic Signals for Freight Delivery Blockages

Using the models of delay for unblocked and blocked intersection approaches, signal timings can be optimized in order to minimize the total delay per cycle. A simple mathematical program is presented to optimize signal timings for the arriving demand on each approach when there is no blockage. Then, a mathematical program is proposed to re-optimized signal timings based on the location and severity of a freight delivery blockage.

5.1 Unblocked Approach

We suppose that in an urban environment, traffic signals operate on a fixed signal cycle C. For simplicity, we consider two lane groups (representing two intersection approaches) served by two signal phases. There is a total loss time L associated with switching phases. The decision variables for optimizing the traffic signal in a signal cycle are g_1 for the primary approach and g_2 for the secondary approach.

$$\min_{g_1,g_2} d_1(g_1) + d_2(g_2) \tag{5.1}$$

$$\text{s.t. } g_i \geq g_{min,i}\ \forall i \tag{5.2}$$

$$g_i \geq g_{p,i}\ \forall i \tag{5.3}$$

$$g_1 + g_2 + L = C \tag{5.4}$$

Constraint 5.2 ensures that the intersection operates in undersaturated conditions, with minimum green times defined by Equation 4.2. Constraint 5.3 ensures that the green interval exceeds the minimum time required for pedestrians to cross the intersection, $g_{p,i}$. The delay terms are convex functions of g_1 and g_2, respectively. This is a convex optimization with linear constraints, which can be solved quickly for global optimality.

5.2 Blocked Approach

When a freight delivery creates a blockage on the primary approach, the mathematical program is modified to allow for the cases when the blockage interacts with the queue of vehicles. Depending on the location of the delivery, the delay may be given by the unblocked Equation 4.1 or the blocked Equation 4.6. An integer variable, y, is introduced to select the appropriate case, and a sufficiently large M activates the corresponding constraints.

$$\min_{g_1,g_2} (1-y)d_1(g_1) + yd_{b,1}(g_1) + d_2(g_2) \tag{5.5}$$

$$\text{s.t. } g_1 + My \geq g_{min,1} \tag{5.6}$$

$$g_1 + My \geq g_{crit,1} \tag{5.7}$$

$$g_1 - My \geq g_{b,min,1} - M \tag{5.8}$$

$$g_1 + My \leq g_{crit,i} + M \tag{5.9}$$

$$g_2 \geq g_{min,2} \tag{5.10}$$

$$g_i \geq g_{p,i}\ \forall i \tag{5.11}$$

$$g_1 + g_2 + L = C \tag{5.12}$$

$$y \in \{0,1\} \tag{5.13}$$

The value of M must be at least big enough to satisfy constraints 5.6 and 5.7 when $y = 1$ and constraints 5.8 and 5.9 when $y = 0$.

$$M \geq \max\{g_{min,i}, g_{crit,1}, g_{b,min,1}, C - g_{crit,1}\} \tag{5.14}$$

In practice, $M = C$ will always suffice.

The critical value of green time that distinguishes between the unblocked and blocked cases results from solving Equation 4.5 for g_i:

$$g_{crit,i} = C - \frac{xk_i(s_i - q_i)}{s_i q_i} \tag{5.15}$$

A green interval that is longer that $g_{crit,i}$ results in a red interval that is short enough that the queue never reaches the parked delivery vehicle at x.

The optimization problem is now a mixed-integer non-linear program (MINLP). The characteristics of the mathematical program can be improved by substituting $R_1 = (C - g_1)$ and eliminating bilinearities by substituting $w_1 = yR_1$, and $w_2 = yR_1^2$ into the objective function and constraints above. Eliminating the bilinearities in this way requires the addition of constraints as detailed in the literature [38]. The result is a convex integer program with linear constraints, which is equivalent to the MINLP presented above but can be solved more efficiently.

5.3 Evaluation of Real-time Signal Control

The proposed real-time signal control has been tested at a generic intersection under a variety of traffic demands and delivery locations. Table 5.1 shows the general characteristics of the intersection that is considered for the numerical results presented in this section. The primary approach ($i = 1$) is the approach that is affected by the occurrence of a freight delivery, and the secondary approach ($i = 2$) is assumed to operate in the unblocked condition. The following sections present numerical results for this hypothetical intersection to illustrate the effect of re-optimizing the traffic signal on intersection delay and whether or not the intersection operates in undersaturated conditions.

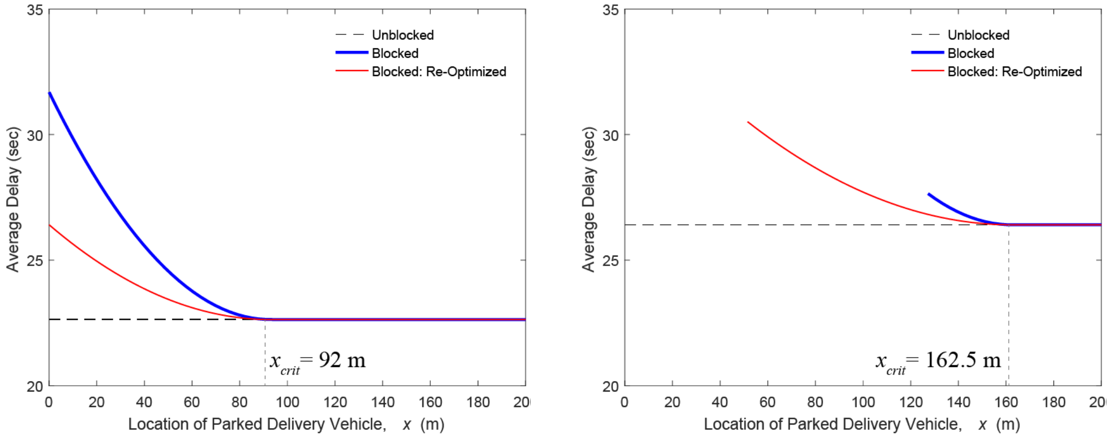
Table 5.1 – Parameter values for numerical example for signal control

Parameter	Value	Units
Cycle Length, C	120	sec
Loss Time, L	10	sec
Min Time for Peds on Approach 1, $g_{p,1}$	12	sec
Min Time for Peds on Approach 2, $g_{p,2}$	12	sec
Unblocked Saturation Flow on Approach 1, s_1	1800	veh/hr
Unblocked Saturation Flow on Approach 2, s_2	1800	veh/hr
Saturation Flow at Blockage $s_{b,1}$	900	veh/hr

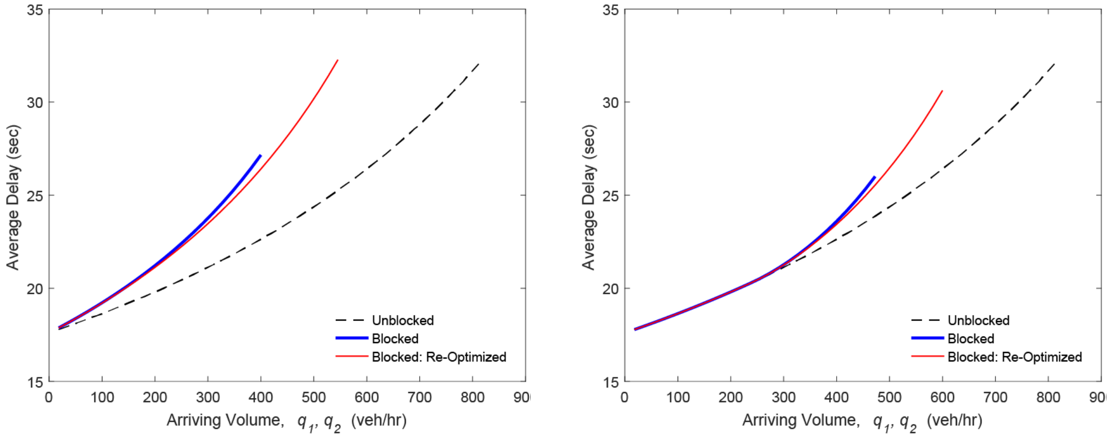
Jam Density on Approach 1, k_1	100	veh/km

5.3.1 *Effect of Delivery Location*

The impact of a freight delivery on delays depends on the distance from the vehicle to the intersection. Figures 5.1a and 5.1b show how the average vehicle delay at the intersection is affected by the location of the delivery when arriving demands are balanced. The dashed black line indicates the average delay under unblocked conditions, the thick blue curve shows the delay that results from a double-parked delivery vehicle when signal timings are not changed, and the thin red curve shows the delay that results from re-optimizing the signal timings for the specific values of q_1, q_2, and x.



(a) $q_1, q_2 = 400$ veh/hr (b) $q_1, q_2 = 600$ veh/hr



(c) $x = 0$ m (d) $x = 50$ m

Figure 5.1 – Effect of freight delivery location and arriving demand on intersection delay without changing signals (thick blue) and re-optimized signals (thin red).

Both plots illustrate a clear relationship between x and vehicle delay. These delays are greatest when the delivery is near the intersection, because this results in the smallest space to store a queue that can discharge at the full saturation rate, s_1. The critical distance, x_{crit}, beyond which the delivery has no effect on delay, increases with increasing arrival rate.

The blocked delay curves in Figure 5.1a are defined for all values of x, because the intersection operates in undersaturated conditions for both timings when the arrival rate is $q_1, q_2 = 400$ veh/hr. For this low demand, the effect of re-optimizing the signal is simply to reduce the delay experienced at the intersection. The blocked delay curves in Figure 5.1b are not defined for low values of x, because the intersection becomes oversaturated, and the actual delay would increase for each subsequent cycle. Note that for $q_1, q_2 = 600$ veh/hr, the blockage causes oversaturated conditions for any x less than 125 m under the initial signal timings. Re-optimizing the signal can achieve undersaturated conditions when x is as low as 50 m. Maintaining undersaturated conditions is particularly important in the context of freight deliveries, because the blockage is likely to last for many signal cycles.

5.3.2 Effect of Arriving Demand

The average intersection delay associated with a freight delivery is also affected by the traffic demand. Figure 5.1c and 5.1d show the average intersection delay as the arriving demand increases on both intersection approaches. In both cases, the arriving volumes are assumed to be the same on both approaches; i.e., $q_1 = q_2$. Clearly, delays increase with demand, because it takes longer to clear the queue.

When a delivery vehicle stops right at the intersection ($x = 0$ m), the saturation rate is reduced to $s_{b,1}$ from the first queued vehicle. The result, shown in Figure 5.1c, is increased intersection delay for all levels of demand. As the location of the delivery moves away from the intersection, an increasing range of low demands can be served with the same delay as in the unblocked case. This is because the entire queue can be stored in front of the parked delivery vehicle (i.e., within x), and these vehicles discharge at the original saturation rate, s_1, during the green interval. Like the results in Figure 5.1a and 5.1b, the effect of re-optimizing traffic signals in reducing intersection delay is small when the intersection remains undersaturated even with the original signal timings. The more important effect is that re-optimizing the signal allows for undersaturated conditions to be sustained for a greater range of arriving demands.

A more comprehensive way to look at the effect of re-optimizing traffic signals is to systematically evaluate the delay associated with every combination of arrival rates. As a basis for comparison, Figure 5.2 shows the average delays associated with every combination of q_1 and q_2 when there is no delivery and the signal is optimized for unblocked conditions as in the optimization defined by Equations 5.1 through 5.4. The delay contours are symmetric because the approaches are symmetric for our example. The areas in white indicate combinations of vehicle arrival rates that cannot be served in undersaturated conditions.

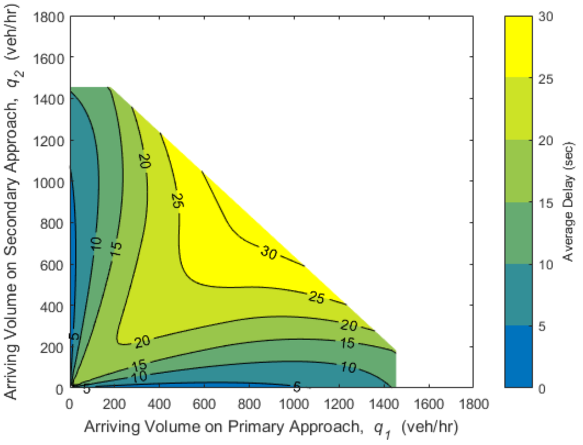
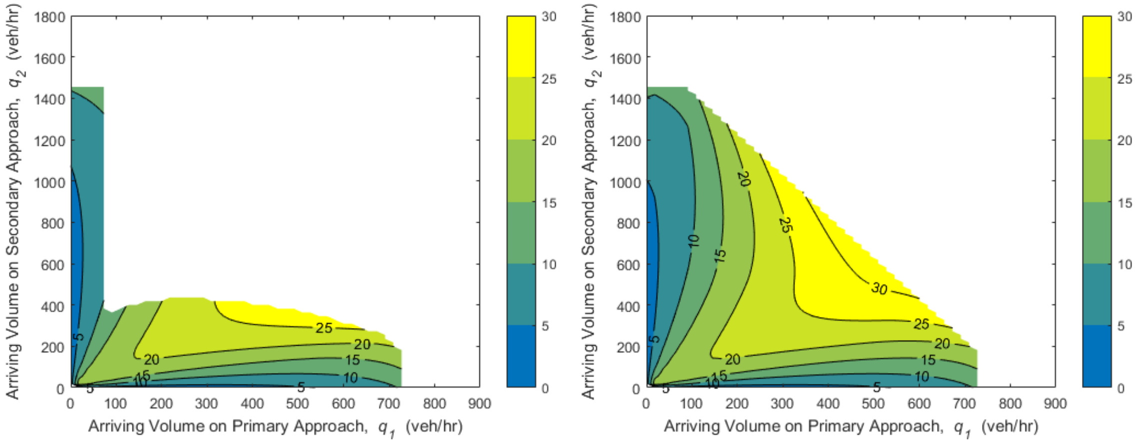


Figure 5.2 – Average intersection delay for all combinations of arriving demand at an unblocked intersection

When a delivery vehicle blocks the intersection approach at location $x = 0$ m, Figure 5.3a shows the delays that are associated with intersection, assuming that the same signal timings are implemented as for Figure 5.2. Note that the horizontal axis has been rescaled because the blocked saturation rate ($s_{b,1} = 900$ veh/hr) reduces the maximum arrival rate that can be served on approach 1 by half compared to the unblocked saturation rate ($s_1 = 1800$ veh/hr). The intersection becomes oversaturated for a wide variety of traffic volumes that were undersaturated in Figure 5.2. The vertical strip on the left side of Figure 6b is the result of the minimum green time required for pedestrians, which ensures that for the lowest values of q_1 there is always a minimum of $g_{p,1} = 12$ sec. This minimum green allows a buffer against the increased time required to clear the queue of vehicles when a delivery vehicle restricts capacity so that the intersection remains undersaturated. When q_2 is relatively larger than q_1, the unblocked signal optimization allocates more time to g_2 and less time to g_1, and the blockage caused by a parked delivery vehicle is more likely to make the intersection oversaturated.



(a) Blocked Intersection (b) Re-optimized Signals

Figure 5.3 – Average intersection delay for all combinations of arriving demand when a) fixed signal timing is applied to a blocked intersection and b) signals are re-optimized

The impact of re-optimizing the traffic signal to account for the presence of a parked delivery vehicle is clearly shown in Figure 5.3b. By re-timing the signal based on the location and severity of the blockage in addition to the arriving demands, the re-optimized signal timing keeps the intersection undersaturated for a wide range of arriving demands that could not be accommodated before. This is especially true for cases in which q_2 is relatively larger than q_1. The case that is illustrated is for a freight delivery at $x = 0$ m, so delays are reduced compared to all undersaturated points in Figure 5.3, but the magnitudes of these savings are small.

6 Simulation Analysis

Data from the observations in New York City (Section 2) was used to build a microsimulation model of the arterial in Aimsun as shown in Figure 6.1. At this location, 8th Avenue has 4 through lanes heading in the northbound direction (toward the right of the figure). An auxiliary left turn lane exists at the intersection with 37th Street, which runs one-way in the westbound direction. The signal timing in the corridor is an 84 second cycle with 45 seconds of effective green time. Simulations were run for a baseline case in which no blockages occurred. Then, a series of simulations were run to evaluate the effect of a blocked lane associated with a stopped delivery vehicle at distances from 0 to 175 feet from the intersection stop line.

Figure 6.1 – Aimsun microsimulation of 8th Avenue between 36th and 38th Streets in New York City

6.1 Effect of Freight Delivery on Intersection Approach Delay

The simulated network illustrated in Figure 6.1 was run with 5 replications for a base case condition with no blockage and then for cases in which a truck stopped at 0, 25, 50, 75, 100, 125, 150, and 175 feet from the intersection stop bar. Figure 6.2 shows the same relationship between delay and delivery blockage location as predicted by the detailed analytical model. When the delivery location is at the intersection stop bar, the effect on delay is a statistically significant increase. As the delivery location moves upstream from the intersection, the delay diminishes because vehicles are able to form a queue in all lanes in front of the delivery vehicle. When the delivery location is far enough from the intersection, the effect on delay diminishes until the difference is no longer statistically significant. This supports the analytical model and the conclusion that moving deliveries away from intersections reduces their impact on traffic delays and congestion.

6.2 Effect of Freight Delivery on Traffic Safety

Although it is commonly noted in the literature that freight deliveries have a negative impact on traffic safety, the magnitude has not been systematically quantified. In a microsimulation environment, car-following and lane-changing rules prevent simulated vehicles from ever crashing. However, safety can be estimated by surrogate measures of safety. Notably, FHWA’s Surrogate Safety Assessment Model (SSAM) is designed to analyze simulated vehicle trajectories in order to quantify conflicts that are surrogate measures of safety. There are two notable conflict types associated with freight deliveries: rear-end conflicts occur when a vehicle must brake in order to avoid hitting another vehicle from behind; lane-change conflicts occur when a lane-change maneuver poses a risk of collision between two vehicles.

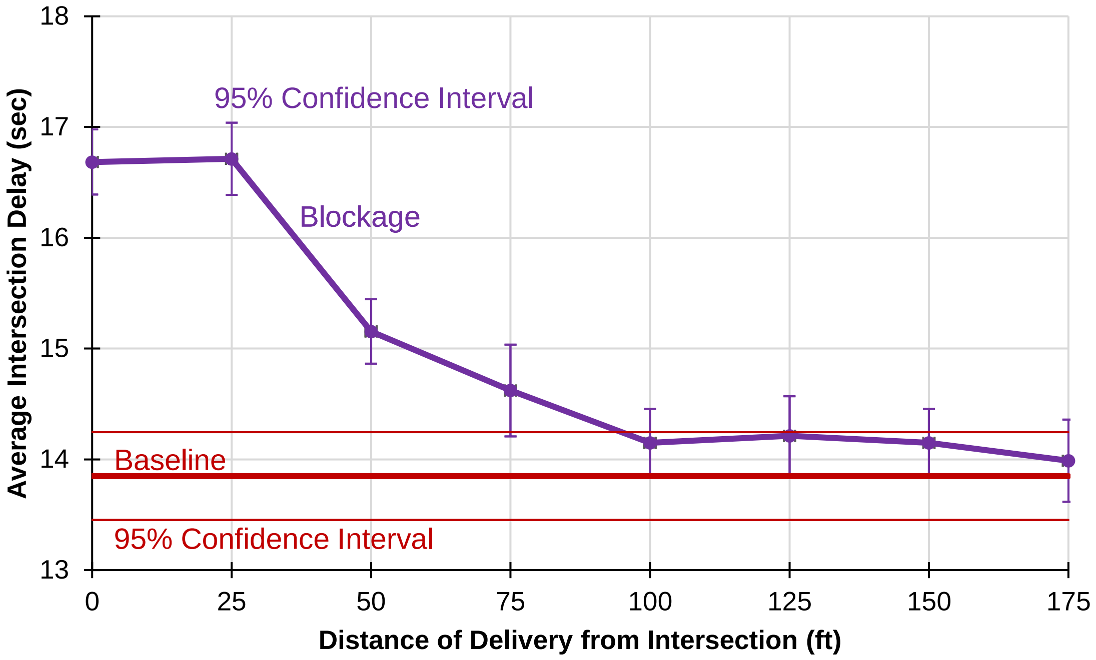


Figure 6.2 – Effect of delivery location on average intersection approach delay

An analysis of the trajectories from the base case and delivery locations at 0, 25, 50, 75, 100, 125, 150, and 175 feet from the intersection shows how the number of conflicts is affected by the presence and location of a freight delivery on the link. Figure 6.3 shows that the number of rear-end conflicts is significantly greater when the delivery is at the intersection. The relationship has the same shape as the effect on delay shown in Figure 6.2 with conflicts decreasing as the blockage moves away from the intersection until there is no statistically significant difference at approximately 100 feet from the intersection. This distance corresponds to the length of the queue. When the blockage does not interact with the queue of vehicles at the intersection, there appears to be no significant increase in rear-end conflicts. This analysis implies that rear-end crashes are more likely only when delivery vehicles are near the intersection.

The same simulation cases were also analyzed for lane-change conflicts. Since the freight delivery blocks a lane of traffic, any vehicles traveling in that lane must make a lane change-maneuver in order to proceed along the corridor. The relationship between the number of lane-change conflicts and the location of the freight delivery is shown in Figure 6.4. Again, there are more conflicts the closer the freight delivery is to the intersection. In this case, the conflicts decrease linearly with distance until about 100 feet, where the delays and rear-end conflicts had also been no different from the base case. When the delivery location is near the intersection, the lane changes from behind the delivery vehicle interact more with the queue of vehicles queued in the other lanes. The close proximity of the queued vehicles increases the number of conflicts.

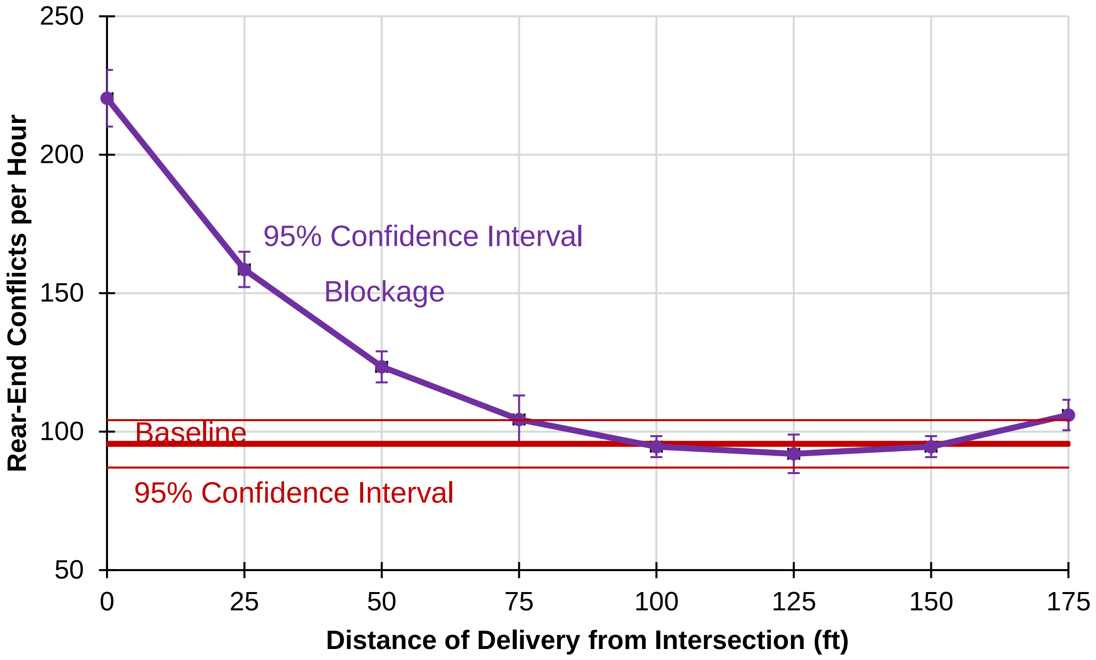


Figure 6.3 – Effect of delivery location on the number of rear-end conflicts

A final surrogate safety measure that is compared based on the trajectories is a value called *MaxDeltaV*, which represents the maximum difference of speeds between two vehicles involved in a conflict. This is a measure of severity. Whereas conflicts are counted whenever the time to collision (TTC) is within a threshold of 1.5 seconds or the post-encroachment time (PET) is within a threshold of 4.5 seconds, this measure only states that there is potential for two vehicles to crash. In order to say something about how severe the crash would be, we can consider the difference in speeds, which provides an indication of the forces that would be involved in a crash.

The average MaxDeltaV associated with each of the simulated scenarios is presented in Figure 6.5. Unlike the delay and number of conflicts, there is not a statistically significant difference in safety severity from the sample. If anything, it appears that the average crash severity is reduced for cases in which the delivery is near the intersection. This is likely due to the fact that the additional conflicts associated with freight deliveries near the intersection involve maneuvers in and adjacent to queued vehicles, which are moving slowly. This offsets some of the additional safety risk associated with the freight deliveries, because additional crashes are not likely to be severe even though more crashes are likely to occur.

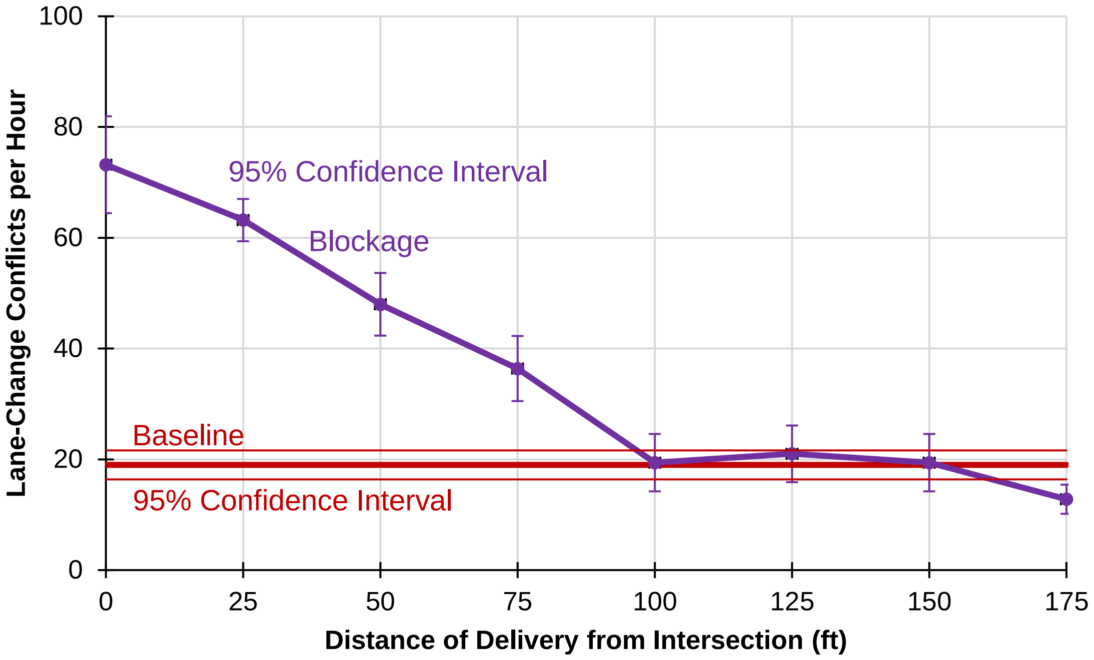


Figure 6.4 – Effect of delivery location on the number of lane-change conflicts

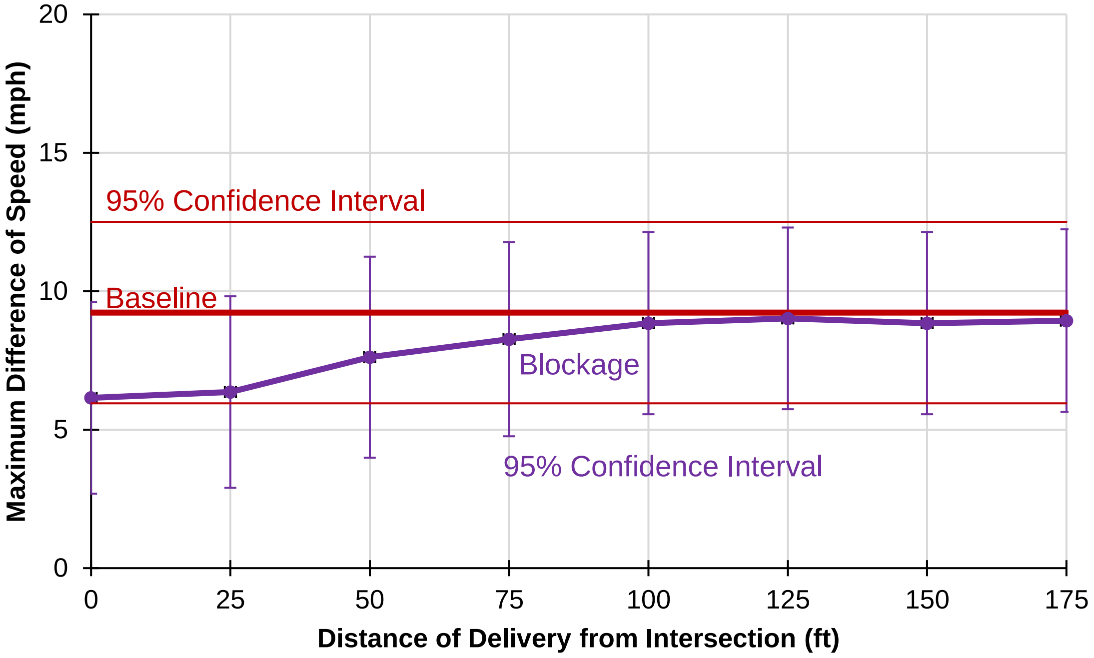


Figure 6.5 – Effect of delivery location on the average value of MaxDeltaV

7 Conclusion

Urban freight deliveries are a growing concern in cities around the world as increasing demand for good deliveries results in increased truck traffic and blockages caused by double-parked delivery vehicles. While much of the literature is focused on estimating and managing demand, this paper presents a technical approach to mitigating the congestion effects of delivery vehicles. By re-optimizing traffic signals to account for the reduced capacity of blocked intersection approaches to clear queues, delays can be reduced in light traffic conditions. More importantly, otherwise oversaturated intersections can be controlled in undersaturated conditions during signal cycles when a delivery vehicle blocks traffic flow.

The proposed method uses traffic flow theory to account for the effect of delivery vehicle location, severity of the blockage caused by the parked vehicle, and the arriving vehicle demand on intersection delays. As a result, re-optimized traffic signals contain queues by maintaining undersaturated traffic conditions. Unlike other types of temporary blockages on urban streets, such as stopping transit vehicles and cars making parallel parking maneuvers, the duration of a freight delivery tends to last multiple signal cycles. As a result, the benefit of maintaining undersaturated traffic conditions is large because queues are managed in order to prevent the spillbacks that cause cascading gridlock. Especially on busier street networks, this can be the difference between operating a network in efficient uncongested conditions or inefficient congestion.

Trucks do not currently broadcast the location and duration of double-parking activities because the practice is illegal. Current practice is for the carrier to simply pay parking tickets (and pass on the cost to consumers) as part of the cost of doing business. The contribution of this study is to show the value of real-time information on freight deliveries on signalized arterials, which could be available through connected vehicle technologies. One could imagine an intelligent transportation system in which carriers are incentivized to share information about the location of delivery stops or a detection system to estimate such information. Re-timing traffic signals in response to the actual traffic congestion and street capacity provides a technical solution to reducing urban traffic congestion.

For safety analysis, it is important to consider both the number of crashes and their severity in assessing the safety risks associated with freight deliveries that block lanes of traffic. From the microsimulation analysis conducted in this study, it appears that the increase in potential crashes is much greater than the reduction in average severity. The analysis only considered safety implications for vehicle-vehicle interactions. There are also safety risks to pedestrians and cyclists that are likely to be greatly increased when delivery vehicles obstruct visibility near crosswalks. All said, this study suggests that any measures that can be taken to encourage delivery stops to be made near the middle of the block would be effective for improving traffic flow and safety. Managing freight deliveries in this way is likely to be more feasible than attempting to ban double parking altogether.

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