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The effects of on-street parking on the service rate of nearby intersections

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SUMMARY

An on-street parking maneuver can often start a temporary bottleneck, leading to additional delay endured by the following vehicles. If the maneuver occurs near a signalized intersection, the service rate of the intersection might be reduced. In this paper, a model is built to analyze the effects of parking maneuvers on the intersection service rate. Based on the hydrodynamic theory of traffic flow, the perturbation caused by the parking maneuver is analyzed. Using dimensional analysis, we illustrate the relation between the background conditions, the distance from the parking area to the intersection, and the intersection service rate. Based on this relation, one can compute the service rate reduction caused by existing on-street parking areas. A minimum distance between the parking area and the intersection to avoid such reduction can be accordingly found. Numerical examples based on empirical data from the city of Zurich, Switzerland, are provided to illustrate the practical applications. Although the analysis is based on streets with a single lane per direction, the findings can provide some insights regarding different situations. We hope such findings can be used as a basis for developing on-street parking design guidelines. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: traffic flow; bottleneck; on-street parking maneuver; service rate; intersection; throughput

1. INTRODUCTION AND BACKGROUND

On-street parking maneuvers often start temporary bottlenecks, potentially affecting some following vehicles, which might have to endure an extra delay. When close to signalized intersections, such delay can sometimes linger over multiple cycles, affecting vehicles that arrive much later. In this paper, we provide a generalized methodology to identify and further prevent such problematic cases of traffic delay caused by parking maneuvers.

Several studies have already been carried out analyzing the influence of on-street parking on traffic performance. In the early stages, scholars [1] focused on the road space required by the parking lane, and the ensuing road capacity reduction [2]. With time, scholars changed the focus to better understand how on-street parking maneuvers disrupt traffic flow. For example, Yousif [3, 4] analyzed the differences in delay caused by parallel and angle parking maneuvers. Portilla *et al.* [5] analyzed the average link journey times under the influence of on-street parking maneuvers and badly parked vehicles using queueing theory. Ye [6] analyzed traffic delays caused by parking maneuvers depending on the cycle length of the nearby intersection; the results showed that the delay increases with a longer cycle. In that study, individual vehicle delay was found based on the physical process of a parking maneuver (e.g., friction delay and blockage delay) and later aggregated to obtain the total delay. Our study will analyze the delay using a different methodology (based on traditional traffic flow theory tools), to provide more general conclusions with the aid of dimensional analysis. More recently, using variables such as effective lane width and number of parking maneuvers, Guo [7] proposed a model to estimate travel time, taking into account the

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effects of on-street parking. Additionally, some studies have also focused on other externalities of on-street parking such as the impacts of cruising for parking [8], and the interactions between parking and traffic performance [9]. Similar studies on bus stop locations can be found in the work by Gu *et al.* [10, 11].

Overall, it is generally accepted that parking maneuvers can cause traffic delay. However, not much attention has been paid to it in the literature, because in most cases, the effects (e.g., delay) of on-street parking maneuvers are not problematic, as the scope of the influence (i.e., number of cars affected) is limited. That being said, if the parking area is near a signalized intersection, the delay caused by the parking maneuver can either affect vehicles during a single cycle or linger over multiple cycles. Evidently, the second case (which happens when the parking maneuver reduces the service rate at the intersection) is the most unfavorable, as the perturbation might spread across the network. Hence, instead of looking at random on-street parking locations within an urban network, in this paper, we focus on the parking locations near the network nodes (i.e., intersections) and their impact on the intersection service rate.

When a queue from a downstream parking location spills back into an intersection, the discharging rate of the intersection could be easily reduced. Therefore, the parking location can be considered as an essential parameter for calculating the negative effects of parking maneuvers on traffic.

In this study, we analyze the effects of the on-street parking maneuvers on traffic performance and its relation to, among others, the distance between the parking area and the intersection. Notice that the analysis is based on streets with a single lane per direction, where the parking areas do not occupy any driving lane. As no conclusion on this has been drawn yet, our study will fill the gap in the literature by providing general guidelines. Because the resulting delay is highly related to the service rate at the intersection, we use the latter as the indicator to measure the effects of parking on traffic performance. Through dimensional analysis, the relation between the reduction on intersection service rate and the distance from the parking area to the intersection is illustrated. Also, a generalized function to compute the minimum distance to avoid severe delays is provided.

Notice that the relation mentioned earlier also takes into account the duration of the parking maneuvers (i.e., the time they actually block traffic), the signal control settings, and the demand volume of arriving traffic. That means, our model can also guide the development of other traffic management schemes (e.g., signal control) to avoid lingering delays caused by parking maneuvers.

The remaining sections of this paper are organized as follows. Section 2 shows the analytical model illustrating the relations described in the preceding text. Section 3 shows two validation experiments with real data and demonstrates the applications of the proposed methodology with detailed examples. Section 4 summarizes the findings of this study.

2. ANALYTICAL MODEL

This section is divided into two parts. First, all the assumptions and variables used in the analysis are defined and/or derived. Second, the two output variables from our model (service rate reduction at the intersection and minimum distance required to avoid that reduction) are introduced.

2.1. Definitions and formulations

2.1.1. Basic definitions

Assume the parking maneuver is conducted by the car passing the intersection Δt time after the start of the green light. The maneuver happens at a distance l_d downstream of the intersection and blocks traffic (i.e., vehicles must stop) for a period of time p ($p \leq g$). Figure 1 depicts the situation. Note that we are not considering any other interruptions from downstream except the parking maneuvers. Notice that the parking areas do not occupy any driving lane; thus, parked vehicles do not affect the road capacity or the intersection service rate. However, the parking or

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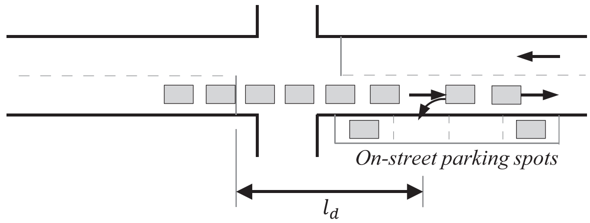

Figure 1. Illustration of l_d and the general situation.

unparking maneuvers, while taking place, do interrupt the proper usage of the driving lane and generate delay.

The length of the signal cycle is c, and the green time is g. Denote α as the ratio between p and g, $\alpha \in [0, 1]$.

$$\alpha = \frac{p}{g} \tag{1}$$

To model traffic conditions, the hydrodynamic theory of traffic flow is used [12, 13], with a triangular relationship between flow and density—triangular fundamental diagram (FD). Empirical evidence suggests that this is reasonable [14–17]. Figure 2(a) depicts an illustrative FD with the different traffic states observed in the scenarios described in the preceding text. State 1 represents the traffic flow arriving from upstream; state 2 represents the stopping traffic; and state 3 represents the traffic discharging from the queue. The shockwaves (i.e., interfaces) between those traffic states are indicated by the lines connecting each pair of points. Figure 2(b) shows an example of a possible time–space diagram; the numbers indicate the traffic states shown in the FD; the dark lines correspond to the shockwaves, and the dashed line shows a possible vehicle trajectory. The two diagrams assume that the geometry of the road is the same both upstream and downstream of the intersection, so the parking area does not occupy any space from the driving lanes. They also assume that the portion of right turning vehicles is small, so their effect is not considered.

As indicated in Figure 2(a), S is the saturation flow rate (i.e., maximum flow) during the effective green signal, q is the arrival flow rate (i.e., demand volume), and K_J is the jam density. The maximum number of vehicles that can pass within the green signal is $S \cdot g$. Denote β as the minimum space required to store those vehicles.

$$\beta = \frac{S \cdot g}{K_J} \tag{2}$$

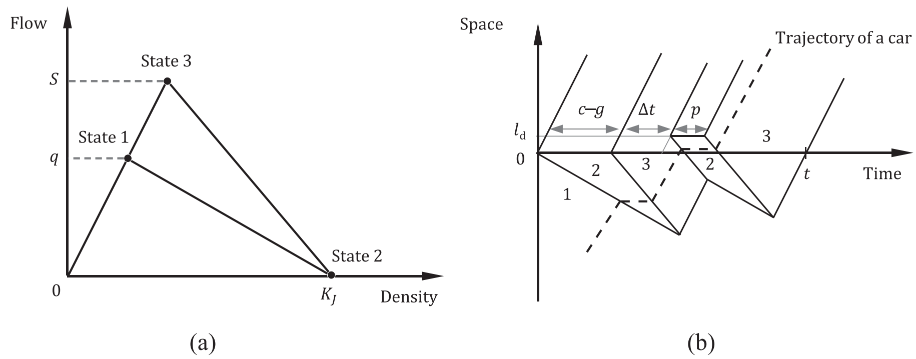

Figure 2. (a) Illustrative triangular fundamental diagram for the link. (b) Illustrative time–space diagram.

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The capacity of the intersection is $S{\cdot}\frac{g}{c}$, and the volume-to-capacity ratio, x, can be expressed as Equation (3) ($x \in [0, c/g]$).

$$x = \frac{q{\cdot}c}{S{\cdot}g} \tag{3}$$

In the absence of parking maneuvers, $x \in [0, 1]$ and $x \in (1, c/g]$ represent the undersaturated and oversaturated conditions of the intersection, respectively.

Note that $x\beta = \frac{q \cdot c}{K_J}$. It represents the minimum space required to store all the vehicles that have arrived in this cycle (i.e., $q \cdot c$).

As indicated in Figure 2(b), t is the theoretical time at which the last car affected (i.e., delayed) by this parking maneuver would pass the intersection.

$$t = \frac{c - (1 - \alpha)g}{c - xg} \cdot c \tag{4}$$

However, if the red light starts before this theoretical moment (i.e., $c < t$), then because of the blockage caused by the parking maneuver, some vehicles would have to wait until the next green signal to cross the intersection. In other words, when $c < t$, the intersection becomes oversaturated. This condition is equivalent to $x \in (1 - \alpha, c/g]$.

Hence, when a parking maneuver occurs, the intersection is oversaturated not only when $x \in (1, c/g]$ but also when $x \in (1 - \alpha, 1]$. Consider both situations with and without the parking maneuver; three possible scenarios arise depending on x:

Scenario 1: $x \in [0, 1 - \alpha]$ The intersection is undersaturated with or without a parking maneuver.
Scenario 2: $x \in (1 - \alpha, 1]$ The intersection becomes oversaturated with the parking maneuver (it is undersaturated in the absence of a parking maneuver).
Scenario 3: $x \in (1, c/g]$ The intersection is oversaturated with or without the parking maneuver.

The throughput of the intersection is the number of vehicles that are discharged in a cycle. Use μ to define the average throughput over the cycle, that is, the intersection service rate in the presence of a parking maneuver. The upper bound of it, $\overline{\mu}$, corresponds to the condition where no delay from downstream occurs, for example, no parking maneuver takes place. It is equal to the demand volume when the intersection is undersaturated, and the capacity otherwise.

$$\overline{\mu} = \begin{cases} q & \text{if } x \in [0, 1] \quad (5a) \\ S{\cdot}\dfrac{g}{c} & \text{if } x \in \left(1, \dfrac{c}{g}\right] \quad (5b) \end{cases}$$

Thus, $\overline{\mu} - \mu$ represents the reduction of the intersection service rate caused by the parking maneuvers; it further indicates the impact on the traffic performance. Hence, we can conclude the following;

- When $\overline{\mu} - \mu = 0$, the performance of the intersection is not affected by the parking maneuver at all, and the delay (if it exists) is concentrated into a single signal cycle; we define it as local delay.
- When $\overline{\mu} - \mu > 0$, the parking maneuver does affect the intersection, and the delay persists over multiple signal cycles; we define it as lingering delay. In the special case, when $\mu = 0$, the parking maneuver affects every vehicle going through the intersection in that cycle, making them wait at least until the next green signal.

2.1.2. Time variables

The intersection service rate is only affected (i.e., $\overline{\mu} - \mu > 0$) if the queue created by a parking maneuver spills back into the intersection and causes a blockage. In this part, we introduce two time variables demonstrating how the duration of the intersection blockage decreases with l_d.

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- t_b is the time when the back of the queue reaches the intersection.
- t_f is the time when the front of the queue reaches the intersection.

Thus, $t_f - t_b$ is the duration of the intersection blockage caused by the parking maneuver. The equations for t_b and t_f are given in the following. They are obtained through the time–space diagrams. The slopes of the shockwaves can be found based on an assumed FD diagram (Figure 2).

$$t_b = \begin{cases} c - g + \Delta t + g\cdot\dfrac{l_d}{\beta} & \text{if } l_d \le \dfrac{c-g}{c-xg}\cdot x\beta - \dfrac{\beta}{g}\cdot\Delta t \quad (6a) \\ \dfrac{c}{x}\cdot\left(\dfrac{l_d}{\beta} + \dfrac{\Delta t}{g}\right) & \text{if } l_d > \dfrac{c-g}{c-xg}\cdot x\beta - \dfrac{\beta}{g}\cdot\Delta t \quad (6b) \end{cases}$$

$$t_f = c - g + \Delta t + g\cdot\frac{l_d}{\beta} + p \tag{7}$$

In Figure 3, three time–space diagrams are given to illustrate t_b and t_f. Time zero corresponds to the start of the red signal for the current cycle, and time $c - g$ corresponds to the start of the green signal. l_d indicates the location of the parking maneuver. The solid lines represent the shockwaves between different traffic states; the dotted lines are auxiliary lines to indicate the values.

As seen in Figure 3 and Equation (6), a distance of $l_d = \frac{c-g}{c-xg}\cdot x\beta - \frac{\beta}{g}\cdot\Delta t$ is critical, because it is the furthest distance that causes the intersection to be blocked for time p.

- When l_d is smaller than this distance (Figure 3(a)), the back of the queue reaches the intersection before the upstream queue (because of the red signal) has fully dissipated, so the intersection is blocked for time p.
- When l_d is larger than this distance (Figure 3(c)), the back of the queue reaches the intersection after the upstream queue has dissipated, so the intersection is blocked for a period shorter than p.

2.1.3. Traffic throughput

Two new distance variables, l_1 and l_2, are defined based on t_f and t_b. The two variables are important in finding the throughput of the intersection (which leads to the service rate) when there is a parking maneuver. l_1 is the distance for which $t_f = c$. In other words, when $l_d = l_1$, the front of the queue reaches the

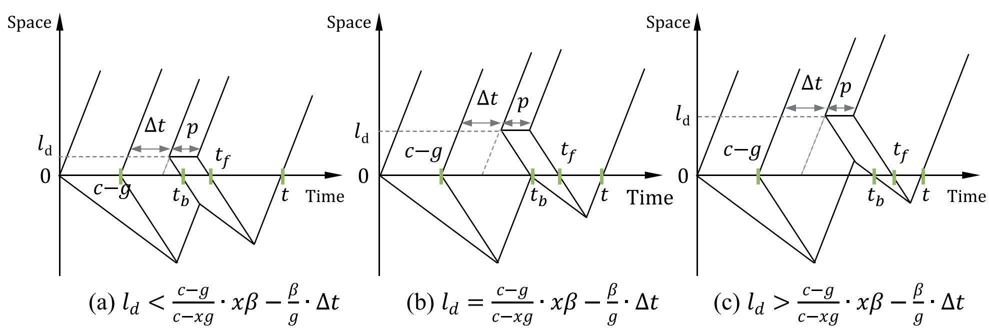

Figure 3. Time–space diagrams depicting time variables for different values of l_d. Variables: l_d represents the distance between the location of the parking maneuver and the stopping line; p represents the time the parking vehicle blocks traffic; x represents the volume-to-capacity ratio; c and g represent the cycle and green light time; the maximum number of vehicles that can pass within the green signal is $S\cdot g$; β represents the minimum space required to store those vehicles; and Δt represents the virtual time at which the parking vehicle would pass the intersection (after the start of the green light).

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intersection exactly at time c. Similarly, l_2 is the distance for which $t_b = c$. The formulas for l_1 and l_2 are given in Equations (8) and (9), respectively.

$$l_1 = \left(1 - \alpha - \frac{\Delta t}{g}\right) \cdot \beta \tag{8}$$

$$l_2 = \begin{cases} \left(x - \frac{\Delta t}{g}\right) \cdot \beta & \text{if } x \in (1 - \alpha, \ 1] \quad (9a) \\ \left(1 - \frac{\Delta t}{g}\right) \cdot \beta & \text{if } x \in \left(1, \ \frac{c}{g}\right] \quad (9b) \end{cases}$$

Recall that β is the minimum space required to store the maximum number of vehicles that can be discharged in a cycle; and $x\beta$ is the minimum space required to store all the vehicles arriving in the cycle.

Figure 4 shows three $t - x$ diagrams for different ranges of l_d; all correspond to situations where $x \in (1 - \alpha, c/g]$.

Three ranges of l_d are categorized and briefly explained in the following.

- $l_d \in [0, l_1]$ and $x \in (1 - \alpha, c/g]$, Figure 4(a): The front of the queue caused by the parking maneuver reaches the intersection before the end of the current cycle ($t_f \leq c$). The intersection is blocked for time p, and throughput equals $S \cdot (g - p)$.
- $l_d \in [l_1, l_2]$ and $x \in (1 - \alpha, c/g]$, Figure 4(b): The front of the queue caused by the parking maneuver reaches the intersection after the end of the current cycle ($t_f > c$). The intersection is blocked for a period shorter than p and does not only discharge at S but also at q for some time. The throughput equals $S \cdot [t_f - p - (c - g)]$, equivalent to $S \ (\Delta t + g \cdot \frac{l_d}{\beta})$ (based on Equation (7)).
- $l_d \in [l_2, \infty)$ and $x \in (1 - \alpha, c/g]$, Figure 4(c): The queue does not reach the intersection; therefore, no throughput reduction occurs.

As defined, μ is the average throughput over the cycle. It can be easily found based on our analysis shown until here. Results are given in the next section.

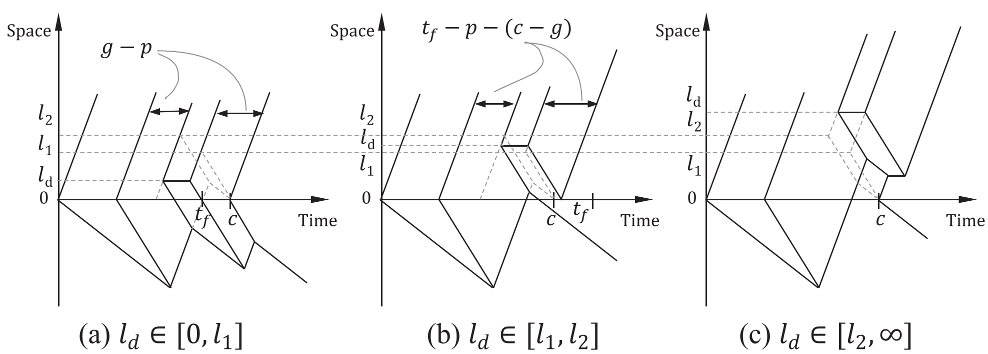

Figure 4. Intersection throughput based on different values of l_d when $x \in (1 - \alpha, c/g]$. Variables: l_d represents the distance between the location of the parking maneuver and the stopping line; p represents the time the parking vehicle blocks traffic; c and g represent the cycle and green light time; t_f represents the time when the front of the queue reaches the intersection; l_1 represents the distance between the parking maneuver and the intersection for which the front of the queue reaches the intersection at time c; and l_2 represents the distance between the parking maneuver and the intersection for which the back of the queue reaches the intersection at time c.

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2.2. Results

2.2.1. Formulations of the service rate reduction

Based on the analysis presented in the previous part, the service rate with a parking maneuver, μ, can be written as in the following:

$$\text{Scenario 1: if } x \in [0,\ 1-\alpha],\ \mu = q \tag{10a}$$

$$\text{Scenario 2: if } x \in (1-\alpha,\ 1],$$
$$\mu = \begin{cases} S \cdot \frac{g}{c} \cdot (1-\alpha) & \text{if } l_d \in [0,\ l_1] \\ S \cdot \left(\frac{\Delta t}{c} + \frac{g}{c} \cdot \frac{l_d}{\beta}\right) & \text{if } l_d \in [l_1,\ l_2] \\ q & \text{if } l_d \in [l_2,\ \infty) \end{cases},\ \text{where } l_2 = \left(x - \frac{\Delta t}{g}\right) \cdot \beta \tag{10b}$$

$$\text{Scenario 3: if } x \in \left(1,\ \frac{c}{g}\right],$$
$$\mu = \begin{cases} S \cdot \frac{g}{c} \cdot (1-\alpha) & \text{if } l_d \in [0,\ l_1] \\ S \cdot \left(\frac{\Delta t}{c} + \frac{g}{c} \cdot \frac{l_d}{\beta}\right) & \text{if } l_d \in [l_1,\ l_2],\ \text{where } l_2 = \left(1 - \frac{\Delta t}{g}\right) \cdot \beta \\ S \cdot \frac{g}{c} & \text{if } l_d \in [l_2,\ \infty) \end{cases} \tag{10c}$$

Therefore, based on Equations (5) and (10), we can obtain the formulation of $\overline{\mu} - \mu$, that is, the reduction of the service rate.

$$\text{Scenario 1: if } x \in [0,\ 1-\alpha],\ \overline{\mu} - \mu = 0 \tag{11a}$$

$$\text{Scenario 2: if } x \in (1-\alpha,\ 1],$$
$$\overline{\mu} - \mu = \begin{cases} q - S \cdot \frac{g}{c} \cdot (1-\alpha) & \text{if } l_d \in [0,\ l_1] \\ q - S \cdot \left(\frac{\Delta t}{c} + \frac{g}{c} \cdot \frac{l_d}{\beta}\right) & \text{if } l_d \in [l_1,\ l_2] \\ 0 & \text{if } l_d \in [l_2,\ \infty) \end{cases},\ \text{where } l_2 = \left(x - \frac{\Delta t}{g}\right) \cdot \beta \tag{11b}$$

$$\text{Scenario 3: if } x \in \left(1,\ \frac{c}{g}\right],$$
$$\overline{\mu} - \mu = \begin{cases} S \cdot \frac{g}{c} \cdot \alpha & \text{if } l_d \in [0,\ l_1] \\ S \cdot \left(\frac{g - \Delta t}{c} - \frac{g}{c} \cdot \frac{l_d}{\beta}\right) & \text{if } l_d \in [l_1,\ l_2] \\ 0 & \text{if } l_d \in [l_2,\ \infty) \end{cases},\ \text{where } l_2 = \left(1 - \frac{\Delta t}{g}\right) \cdot \beta \tag{11c}$$

Figure 5 illustrates $\overline{\mu} - \mu$, based on three scenarios of $x \in [0, 1-\alpha]$, $x \in (1-\alpha, 1]$, and $x \in (1, c/g]$. In each scenario, corresponding to the value of l_d, the reduction of the intersection service rate caused by the parking maneuver is shown.

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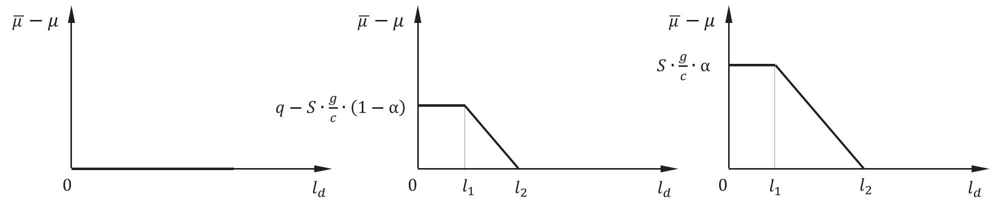

(a) Scenario 1: $x \in [0, 1-\alpha]$ (b) Scenario 2: $x \in (1-\alpha, 1]$ (c) Scenario 3: $l_d \in (1, \frac{c}{g}]$

Figure 5. Value of $\bar{\mu}-\mu$ as a function of l_d, based on different ranges of x.

We can see that no reduction is caused on the intersection service rate for scenario 1. For scenarios 2 and 3 where $x \in (1-\alpha, c/g]$, the following are seen:

- The service rate can be reduced. Such reduction is larger for scenario 3. As expected, for the same parking location, a parking maneuver is more problematic (i.e., has more negative effects) when the intersection is already oversaturated.
- The worst conditions arise when $l_d < l_1$. For any value of l_d smaller than l_1, the front of the queue always reaches the intersection before the end of the current cycle, affecting it for the maximum possible time period, p. Therefore, parking supply should be minimized (or avoided) within a distance $[0, l_1]$ downstream of the intersection (i.e., stopping line).
- For $l_d \in (l_1, l_2]$, $\bar{\mu}-\mu$ decreases with the value of l_d by the same rate/slope for the two scenarios. No service rate reduction is caused after l_d reaches l_2, because $\bar{\mu}-\mu=0$. However, l_2 has different values for scenarios 2 and 3. It means that, to totally avoid affecting the intersection with the parking maneuvers, a different distance limitation for parking should be applied based on the volume-to-capacity ratio (i.e., x). We define this distance limitation as the minimum distance. It is addressed in the next part.

2.2.2. Minimum distance formulations

As analyzed earlier, to completely avoid the throughput reduction, a minimum distance, L, can be applied.

$$L = \begin{cases} 0 & \text{if } x \in [0, 1-\alpha] \quad (12a) \\ \left(x - \dfrac{\Delta t}{g}\right)\cdot\beta & \text{if } x \in (1-\alpha, 1] \quad (12b) \\ \left(1 - \dfrac{\Delta t}{g}\right)\cdot\beta & \text{if } x \in \left(1, \dfrac{c}{g}\right] \quad (12c) \end{cases}$$

Figure 6 illustrates these conditions for the worst possible situation, $\Delta t = 0$ (i.e., the parking maneuver is performed by the first vehicle that passes the intersection on a given cycle).

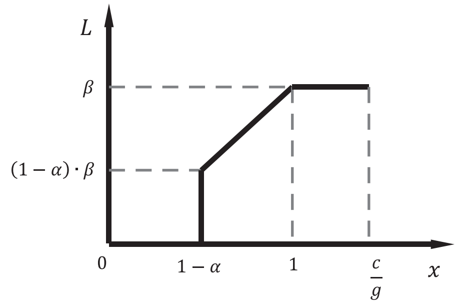

Figure 6. Value of L, when $\Delta t = 0$.

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The line in Figure 6 shows three distinct parts, corresponding to the three scenarios previously described:

Scenario 1: $x \in [0, 1 - \alpha]$. No lingering delay or throughput reduction will happen no matter how near the parking location is to the intersection ($L = 0$).

Scenario 2: $x \in (1 - \alpha, 1]$. The minimum l_d required to avoid a throughput reduction increases with the volume-to-capacity ratio ($L = x\beta$).

Scenario 3: $x \in (1, c/g]$. The minimum l_d required to avoid a throughput reduction corresponds to the space needed to store all vehicles that discharge from the intersection and is independent of the demand ($L = \beta$).

Note that there are two cases not considered in the explanation of Figure 6.

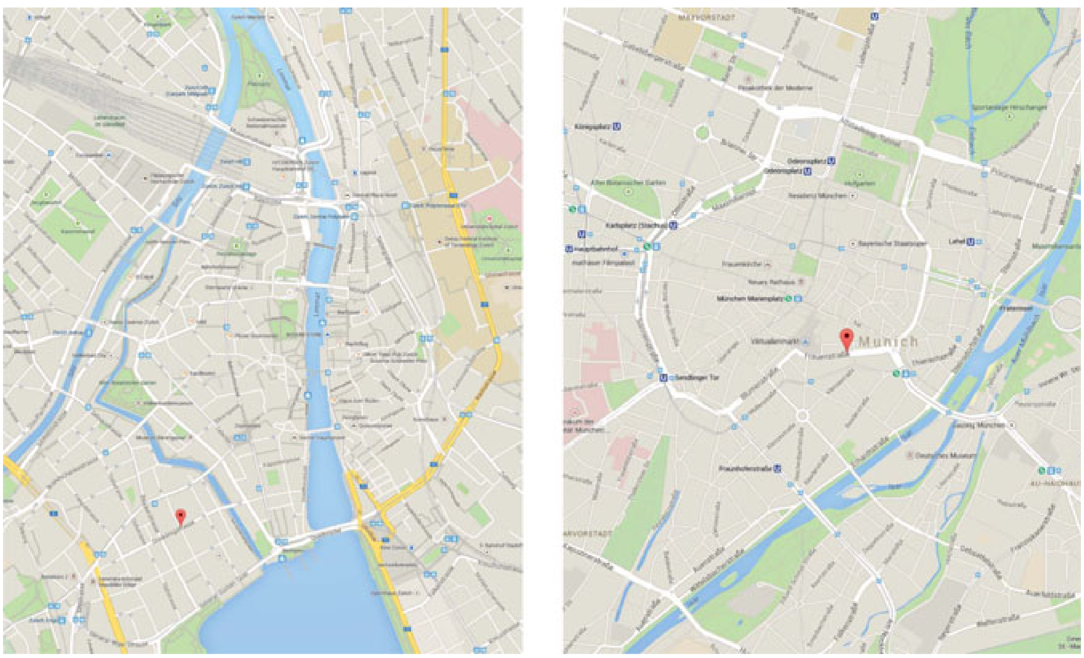
$\Delta t > 0$: The larger Δt is, the later the parking vehicle passes the intersection. Hence, fewer cars are affected by the parking maneuver. In such case, the minimum distance is actually smaller than that shown in Figure 6. The value of Δt, although not included in Figure 6, is considered in the model (Equation (12)) and the validation part.

Multiple maneuvers happen in the same cycle: This might lead to longer delays or multiple temporary bottlenecks on the segment of the road. Therefore, in such case, the minimum distance is actually larger than the result obtained from Equation (12).

3. MODEL VALIDATION AND APPLICATION

3.1. Validation

In this section, we use real data to validate the model proposed in the preceding text, specifically the value of μ (i.e., service rate). Two sets of data were collected with the aid of video camera during July and October 2013. We define the real service rate with a parking maneuver as μ_{real}. The validation is based on the comparison between μ (from the model) and μ_{real} (from the data collected). The survey locations are shown in Figure 7.



(a) Dreikönigstrasse, Zürich, Switzerland. (b) Frauenstrasse, Munich, Germany.

Figure 7. Survey locations for the two data sets.

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3.1.1. Data set 1 (Zurich, Switzerland)

The observed section of Dreikonigstrasse has two lanes (only one direction). Along the street, downstream of the intersection between Beethovenstrasse and Dreikonigstrasse, there are 22 parking stalls: 10 on the left side and 12 on the right. We assume both lanes have the same traffic demand, and a parking maneuver occurring on one side does not influence traffic on the other side. Hence, variables such as q and μ_{real} are estimated as half of the observed values to be suitable for the model (one-lane street). More than 70 maneuvers were recorded, but only 37 maneuvers caused delay ($p > 0$ and $q > 0$) and were used for validation: 26 of them caused a throughput reduction and hence a lingering delay ($\overline{\mu} - \mu > 0$), and 11 only caused a local delay ($\overline{\mu} - \mu = 0$). The analysis of the other 33 maneuvers ($p = 0$ or $q = 0$) is trivial and does not require a model.

From the video, fixed-value variables were obtained: $g = 20$ seconds, $c = 50$ seconds, $K_J = 125$ veh/km, and $S = 1620$ veh/h. K_J and S are averaged values across multiple cycles, K_J was measured with the queue at the red signal, and S was the saturation flow rate discharging from the queue (both are considered for one lane). Other values such as Δt, p, l_d, and q were found based on the specific parking maneuver.

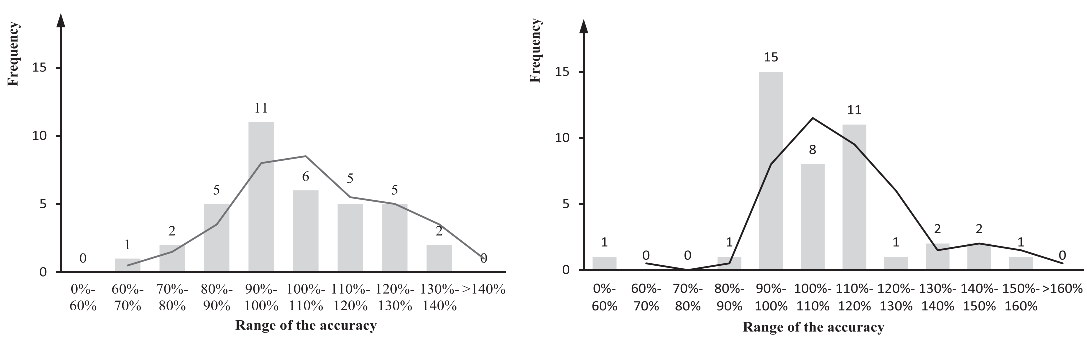
Plotting the observed values into the model, α, β, x, and $\overline{\mu}$ were found, as well as μ. The histogram of accuracy (of μ to μ_{real}) levels obtained is shown in Figure 8(a). The x-axis shows different ranges of the accuracy (i.e., values below 100% indicate we underestimated the service rate of the intersection), and the y-axis stands for the frequency of observations with such accuracy.

The accuracy ranged between 63% and 133%. There were 17 cases (46% of the cases) with an error smaller than 10% (accuracy between 90% and 110%). The average accuracy was 103%. The largest error was 37%, and it was observed only once. There are two possible reasons for the inaccuracy. First is turning vehicles at the intersection (they are counted as served in μ_{real} but not in μ). Even though the number of turning vehicles is small, it leads to an underestimation of the service rate, as the queue length after the parking vehicle is, in reality, shorter than what the model predicts, because of turning cars not joining the queue. Second is some disturbances from pedestrian sidewalk and bicycles; these disturbances lead to an overestimation of the throughput. Despite such inaccuracies, overall the model seems to perform quite reasonably. It predicts the throughput reduction with an error smaller than 20% in at least 73% of the cases (27 cases).

3.1.2. Data set 2 (Munich, Germany)

The observed section of Frauenstrasse has one lane per direction. There are 25 parking stalls along the street, downstream of the intersection between Frauenstrasse and Reichenbachstrasse (towards Thomas–Wimmer–Ring direction). Here, we used 42 maneuvers for validation, 15 of which caused a throughput reduction and hence a lingering delay ($\overline{\mu} - \mu > 0$), and 27 only caused a local delay ($\overline{\mu} - \mu = 0$). Data were extracted and processed as in Zurich. The fixed-value variables were $g = 60$ seconds, $c = 80$ seconds, $K_J = 125$ veh/km, and $S = 1548$ veh/h.

The histogram of accuracy levels obtained is shown in Figure 8(b). The accuracy ranged between 59% and 157%. There were 35 cases (80% of the cases) with an error smaller than 20% (accuracy



(a) (b)

Figure 8. Histogram of accuracy levels (i.e., μ/μ_{real}) based on data obtained through the survey; note that the scales of the two graphs are different. (a) Data set from Zurich, Switzerland. (b) Data set from Munich, Germany.

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between 80% and 120%). The average accuracy was 109%. Overall, the results overestimated the throughput with a parking maneuver. This was mostly driven by multiple parking maneuvers happening during one cycle due to the long green light and abundant supply of parking stalls.

For both histograms shown in Figure 8, the patterns seem similar to normal distribution, and for both histograms, more than 70% of the cases are covered within the accuracy range of [80%, 120%]. However, they do show slight differences from one another. Figure 8(a) shows more underestimations using the data collected in Zurich, while Figure 8(b) shows more overestimations using the data collected in Munich. This difference, as explained earlier, is due to the specific conditions of the surveyed street including the street and parking layout (e.g., number of lanes and parking spaces), the turning vehicles, and other disturbances such as pedestrian and cyclists.

Another interesting difference between the two datasets includes the values of p and l_d. They are 7.7 seconds and 35.9 m for the dataset collected in Zurich, and 10.6 seconds and 82.3 m for the dataset collected in Munich. Notice that the ratio between maneuvers that generated a reduction on the service rate and the ones that did not generate reduction in this data set cannot be generalized to other situations/locations. Recall that all maneuvers for which either $p=0$ or $q=0$ were excluded from the analysis. Hence, the data presented here cannot be used to justify a high frequency of parking maneuvers influencing traffic.

3.2. Application

In this section, we illustrate the use of the model through three examples. Some of them employ empirical data (shown in Figure 9) from the city of Zurich, Switzerland. We first introduce the data.

p represents only the time during which the parking maneuver blocked traffic, and not the total duration of the parking maneuver. Data for p were collected at six intersections (Stampfenbachstrasse, Nueschelerstrasse, Staufacherquai, Talstrasse, Dreikoenigstrasse, and Museumstrasse) during April and May 2013. Data includes 66 parking maneuvers that were videotaped. l_d represents the distance between the intersection and the nearest on-street parking stall downstream of the intersection. Data for l_d were extracted from 161 intersections in the central area of the city (zone 10) and only cover signalized intersections with parking downstream.

As shown in Figure 9, the value of p ranges from 2 to 19 seconds, with an average of 8.94 seconds. The value of l_d ranges from 10 to 190 m, with an average of 70.6 m.

We now present three examples showing possible applications of the model proposed earlier.

3.2.1. Example 1

Determine L to avoid the reduction on the intersection service rate (considering $\Delta t=0$) based on $q=500$ veh/h, $S=1500$ veh/h, $K_J=200$ veh/km, $c=60$ seconds, $g=24$ seconds, and $p=8.94$ seconds.

Step 1. Find basic values, $\alpha=0.3725$ (Equation (1)), $\beta=50$ m (Equation (2)), and $x=0.83 \in (1-\alpha, 1]$ (Equation (3)).

Step 2. Find $L=41.5$ m (Equation (12b)).

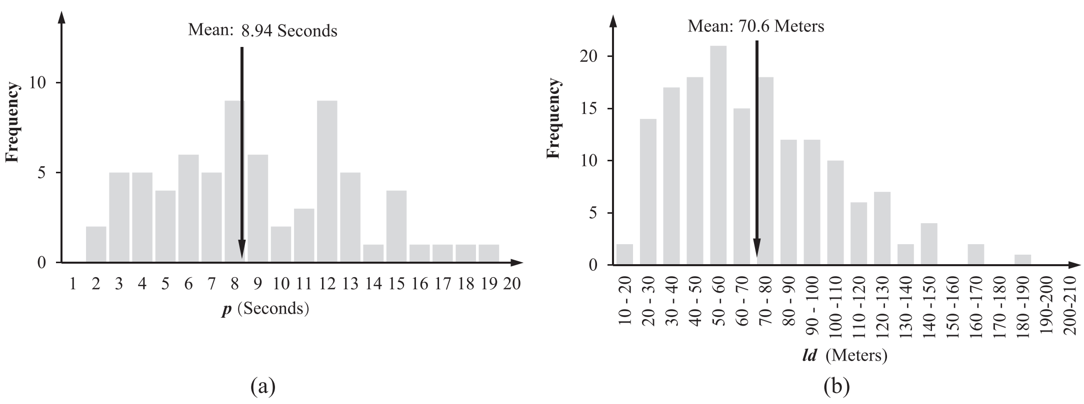

Figure 9. Frequency of p and l_d in the city of Zurich, based on real data. (a) Frequency of p and (b) frequency of l_d.

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3.2.2. Example 2

Determine the service rate reduction based on a known value of $l_d = 25$ m, the average observed value of p (i.e., 8.94 seconds), and the same values of Δt, g, c, S, K_J, and q as in the preceding text.

Step 1. As found earlier, $\alpha = 0.3725$; $\beta = 50$ m; $x = 0.83$; and $x \in (1 - \alpha, 1]$.
Step 2. Find $l_1 = 31.375$ m (Equation (8)), and therefore, $l_d \in [0, l_1]$.
Step 3. Find $\overline{\mu} = 500$ veh/h (Equation (5a)) and $\mu = 376.5$ veh/h (Equation (10b)).
Step 4. Find $\overline{\mu} - \mu = 123.5$ veh/h (Equation (12b)).

That means, the service rate of the intersection is reduced by 123.5 veh/h, or in other words, 24.7% (i.e., $(\overline{\mu} - \mu)/\overline{\mu}$).

3.2.3. Example 3

Estimate the overall conditions considering the throughput reduction for a set of intersections. Assume all intersections are oversaturated, $x \in (1, \ c/g]$. Use Figure 9(b) as the distribution of l_d for the intersections, and the values of p, g, and c remain the same as in example 2.

Step 1. As found in the preceding text, $\alpha = 0.37$, $l_1 = 31.375$ m.
Step 2. Find $l_2 = 50$ m (Equation (9b)) and $\overline{\mu} = 600$ veh/h (Equation (5b)). We can draw Figure 10 according to Figure 5(c) and Equation (11b).
Step 3. The reduction occurs when $l_d \le 50$ m. The maximum reduction, 37.25% (i.e., (600–376.5)/600), occurs when $l_d \le 31.375$ m. Based on the distribution of l_d of surveyed intersections in the city of Zurich shown in Figure 9(b), the percentage of intersections that might be disrupted by parking maneuvers downstream and the extent of such disruption are shown in Figure 11.

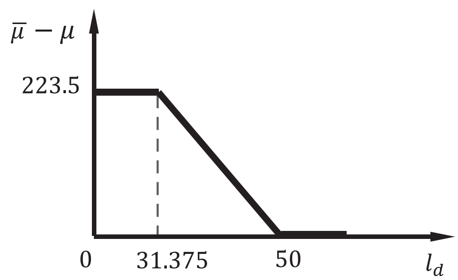

Figure 10. The relation between $\overline{\mu} - \mu$ and l_d, for example, 3 where $x \in (1, c/g] = (1, 2.5]$.

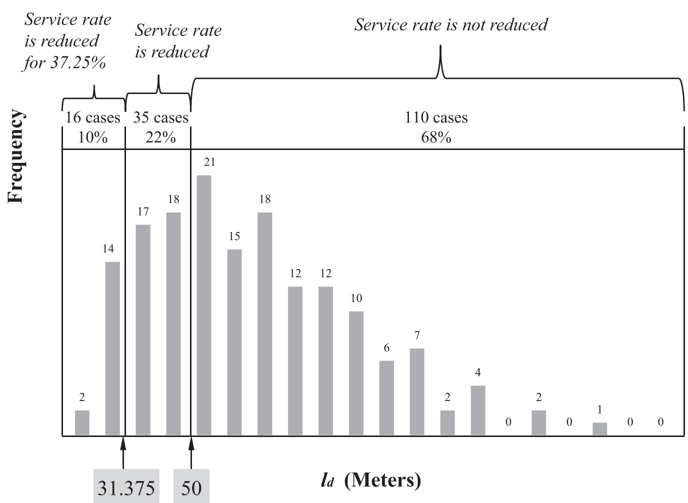

Figure 11. Overall conditions considering the throughput reduction for a set of intersections. Example 3, $x \in (1, c/g] = (1, 2.5]$.

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We can see the following;

- Intersections with $l_d \leq 31.375$ are shown on the left side and represent 10% of the 161 intersections surveyed. For these 10% intersections, they will have a high reduction (37.25%) of the service rate.
- The middle part represents intersections with $l_d \in (31.375, 50]$. These intersections (22%) will endure some kind of reduction of the service rate (although smaller than 37.25%).
- The rest of the intersections, 68%, should not be affected.

Notice that for a more accurate macroscopic analysis of the impact of parking maneuvers at a network level, one must also consider the actual frequency of parking maneuvers (i.e., proportion of cycles in which parking maneuvers occur), the actual distribution of l_d and Δt, and the temporal/spatial variations of traffic demand.

4. CONCLUSION

In this paper, we study the negative effects that a parking maneuver can have on traffic, especially on the discharging flow of a signalized intersection. We provide a methodology to calculate the reduction in the service rate as a function of the parking location (with respect to the intersection), and a minimum distance to avoid such reduction. Notice that the service rate reduction could also be found based on other methodologies such as queueing theory [5].

We consider multiple factors such as signal control, arriving traffic flow rate, and the duration of the parking maneuver. As a result, the model is general enough to fit different background conditions for single-lane streets.

For streets with multiple lanes, lane changes (or overtaking maneuvers) may lead to a higher traffic throughput, that means, our model could underestimate the resulting service rate at the intersection. To account for that, one can either assume an overtaking rate or discount the time length for which a parking vehicle blocks traffic.

The volume-to-capacity ratio indicates the saturation condition of the intersection, and it was found essential to the result. Notice, however, that exact traffic volumes might be difficult to use for policy or design purposes. Instead, we can estimate different saturation levels based on time of day. We now summarize the findings based on 3 different levels of saturation.

- The intersection is very undersaturated.

When volume-to-capacity ratio is lower than $1 - p/g$, the intersection is undersaturated with or without a parking maneuver. In other words, the parking maneuver has no effect on the throughput as the arriving flow rate is so low that the duration of the blockage, p, does not reduce the service rate.

Therefore, under this condition, no reduction can be caused regardless of the location of the parking area. Based on this, one can justify a large parking supply in certain streets (e.g., local streets) where the intersections are normally uncongested.

- The intersection is near saturation level.

When volume-to-capacity ratio is higher than $1 - p/g$, but smaller than 1, the intersection can become oversaturated when the parking maneuver occurs (it remains undersaturated in the absence of a parking maneuver). In this case, when the traffic demand (arriving flow rate) rises, a longer distance is required to avoid the reduction on the service rate. If $l_d < L$, then the magnitude of the reduction grows with a larger traffic demand.

Consider a fixed demand, then, the larger the distance between the parking area and the intersection is, the less the service rate is reduced. As a matter of fact, it is possible to completely avoid the reduction by ensuring that $l_d > x\beta$ (recall that $x\beta$ is the minimum space required to store all the vehicles arriving in the cycle, and β is the minimum space required to store the maximum number of vehicles that can pass with the green signal). To be completely safe, one could always make $l_d > \beta$ (in this case, $x\beta < \beta$).

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- The intersection is oversaturated.

When volume-to-capacity ratio is higher than 1, the intersection is oversaturated with or without the parking maneuver. This is the most problematic situation out of the three.

In this case, the minimum distance, L, stays at a constant value of β, corresponding to the amount of space required for storing the maximum number of vehicles that can pass with the green signal. Compared with the previous situation (same background data), for the same parking location with $l_d \leq \beta$, the service rate reduction is larger in this situation (recall Figure 5).

Under this condition, the parking area should not be located closer than β. By the same token, it is not necessary to make $l_d \gg \beta$, as any $l_d > \beta$ should avoid the reduction.

As shown with the validation experiments, this model, despite its simplicity, can provide reasonably accurate results. Note that the model does not consider parking maneuvers that last longer than the green signal, nor the lower speeds that vehicles often adopt when approaching the parking stall. In addition, the model is, by design, rather conservative, in order to minimize the effects of all possible parking maneuvers. Nonetheless, it is still able to predict more than 73% of the cases with at least 80% accuracy.

The model proposed here is extended to find the effects of parking maneuver upstream of intersection [18]. The ultimate goal is to further generalize this methodology in order to cover larger areas (i.e., networks with multiple intersections). This could allow city agencies to better plan the location of on-street parking in a city and/or implement traffic management strategies for diminishing the negative effects in situations where they cannot be completely avoided. A similar methodology could also be used to evaluate the effects of other types of fixed disruptions nearby signalized intersections.

The general guidelines proposed in this paper only consider how the location of the parking area affects the service rate of nearby intersections, but it does provide a generalized relation between the intersection service rate and signal design, or duration of parking maneuvers. Nevertheless, for the proper design of parking areas, other factors (out of the scope of this paper) must also be considered (e.g., benefits to parking drivers, pedestrians, and businesses). The final decision about parking supply (including location) cannot be based only on traffic operations considerations but also on a more holistic analysis of the transportation system and local urban planning policies.

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