

Research Article

Designing Dynamic Delivery Parking Spots in Urban Areas to Reduce Traffic Disruptions

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Received 10 February 2017; Revised 16 May 2017; Accepted 12 June 2017; Published 29 August 2017

Academic Editor: Jose L. Moura

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Pick-up and delivery services are essential for businesses in urban areas. However, due to the limited space in city centers, it might be unfeasible to provide sufficient loading/unloading spots. As a result, this type of operations often interferes with traffic by occupying road space (e.g., illegal parking). In this study, a potential solution is investigated: Dynamic Delivery Parking Spots (DDPS). With this concept, based on the time-varying traffic demand, the area allowed for delivery parking changes over time in order to maximize delivery opportunities while reducing traffic disruptions. Using the hydrodynamic theory of traffic flow, we analyze the traffic discharging rate on an urban link with DDPS. In comparison to the situation without delivery parking, the results show that although DDPS occupy some space on a driving lane, it is possible to keep the delay at a local level, that is, without spreading to the network. In this paper, we provide a methodology for the DDPS design, so that the delivery requests can be satisfied while their negative impacts on traffic are reduced. A simulation study is used to validate the model and to estimate delay compared to real situations with illegal parking, showing that DDPS can reduce system's delay.

1. Introduction

Urban logistic facilities, devoted to the loading and unloading operations from transport companies, are essential for efficient urban deliveries [1]. Thus, urban logistic facilities are widely used and typically placed in city centers with a high level of commercial activities [2]. The existence and the proper management of these facilities are crucial to serve cities' needs. To minimize their negative effects on the surroundings, loading and unloading facilities are normally placed outside driving lanes. However, this is not always feasible due to the limited public space in downtown areas. In some areas, illegal parking is highly used in freight operations. For example, in Paris, illegal double parking is used for up to 50% of the freight movements [3]. Local authorities often face a dilemma on how to allocate public space among loading/unloading activities, traffic, parking, public transport, and so on. To address that, multiuse lanes

have become an innovative yet pragmatic solution. At different times of the day, these lanes can be devoted to different usages such as general traffic, buses only, loading/unloading activities, or residential parking. In Spain, for example, it has been successfully implemented in Barcelona [4] and Bilbao [5]. The multiple uses of the lane can accommodate different activities in a day. However, they block the whole lane (within a given link or potentially across links), even when there is not enough demand of the specific activity to use the entire space. In the case of loading and unloading activities, the demand is rarely high enough to occupy a whole lane throughout a link, not to mention across multiple links. Additionally, on the traffic side, the blockage of the whole lane is simply unwise since the capacity of the street drops drastically. To address that, in this paper, we investigate the provision of Dynamic Delivery Parking Spots (DDPS). DDPS occupy only a portion of the driving lane, and the allowed area changes dynamically over the day to guarantee proper

traffic performance, according to different levels of traffic demand.

DDPS can provide many benefits in practice. The number of dedicated (i.e., fixed) loading/unloading spots can be reduced, since some of the operations might happen in DDPS. Additionally, the city can make a better use of the existing space, for example, by devoting part of the traffic lanes to freight activities when the traffic demand is low. Additionally, DDPS could be regulated with a prebooking parking system [6, 7] that guarantees the optimal use of the devoted space.

Moreover, DDPS can be easily implemented: only few and inexpensive infrastructure changes are required, technological equipment is available, and the existing traffic/parking management and control strategies can be used. For infrastructure, in-pavement lights in the shoulder lane can clearly indicate the area where delivery is allowed, similar to the use of Bus Lane Intermittent Priority (BLIP) [8]. Apart from the use of in-pavement lights, vehicle detectors can be placed at the different spots of the DDPS, for detecting the presence of vehicles. Such detectors can also be used to control the correct use of DDPS. For example, when a vehicle is using incorrectly DDPS, a signal could be automatically sent to the control authorities.

This paper aims to provide basic guidelines for DDPS on urban areas, so that the deliveries can be carried out while traffic disruptions are kept to a minimum. DDPS provide space for loading/unloading activities on the shoulder lane of the street, but they are only allowed if the traffic delay is kept local (i.e., traffic delay is kept on the link and does not spread over the network). In other words, traffic must pass smoothly the upstream intersection, the lane drop at the delivery spot, and the downstream intersection, with no queue spillover to other links in the network. Using the hydrodynamic theory of traffic flow, we analyze the traffic discharge rate at both the upstream and the downstream intersections, taking into consideration that a portion of the shoulder lane is blocked. In particular, we model the relation between the delivery location within the link, the traffic demand arriving from upstream, and the disruptions to traffic. Based on such relation, the location of the DDPS can be regulated as a function of the traffic demand, to reduce the traffic disruptions as much as possible. In order to validate the developed model, show its applicability in a more realistic situation, and analyze the effect of stochastic arrivals, a simulation study is performed. The simulation is also used to evaluate the performance of DDPS in comparison to illegal delivery parking.

The rest of this paper is organized as follows. Section 2 lists and describes the existing literature, highlighting the differences to this paper. Section 3 shows the analytical model where generalized suggestions concerning the location of DDPS are made. Section 4 shows a numerical example to illustrate how the model is applied to a particular case. Section 5 validates the model with simulation in a set of scenarios. Then, it compares the overall delay between the system with DDPS and the current situation with illegal parking. Section 6 summarizes the findings of this study.

2. Literature Review

On-street parking highly influences urban traffic performance, mostly from three different perspectives. First, the parking lanes occupy road space, leading to reduced traffic capacity on the road and the neighboring network [9, 10]. Second, the parking/unparking maneuver itself generates a temporary traffic bottleneck, which blocks vehicles arriving from upstream and causes extra travel time [11–15]. Third, special parking behaviors such as illegal (e.g., double) parking or loading/unloading trucks/buses take space from driving lanes, reducing the road capacity unreasonably and causing inconvenience and confusion to other travelers [16, 17].

As a special case, delivery vehicles can cover all these three negative aspects, and, more importantly, their loading/unloading processes and the ensued traffic issues occur recurrently. It is, therefore, of great importance to improve and optimize the loading and unloading operations to reduce their effects on the traffic performance. To that end, multiple researchers have developed different control schemes [18, 19]. Recent work [20] evaluated the effects of pick-up maneuvers on traffic flows near maximal capacity, which were proved to have a major impact on traffic conditions. In order to evaluate the effects on travel times, a potential tool was developed in [21], and some additional investigations can be found in [22]. Very recently, the macroscopic impacts of deliveries in double lane parking in an arterial corridor were assessed with a simulation study [23]. Our paper, with a different approach, is focused on providing guidelines on the location and the number of spots, avoiding the negative effects at the network level.

Other researchers have evaluated the traffic effects of parking maneuvers [24, 25]. They have proposed a model to analyze the impact of parking maneuvers on a road segment and their influence on the capacity of nearby intersections and the overall network. It is shown that, under certain conditions such as low traffic demand or optimum parking location, parking maneuvers do not affect traffic throughput, even in cases when one-lane road is analyzed. Similar patterns are observed for curbside bus stops [26]. Evidently, loading/unloading operations last normally much longer [2, 27] than the time needed for parking maneuvers and bus stops, but they happen less frequently, and a prebooked schedule, as studied in [6], can be implemented.

From the network perspective, [28, 29] have shown that, at a network level, it is possible to remove lanes or even links to a certain extent without reducing much of the network capacity. Such findings are encouraging, as they indicate that temporarily removing some portions of a lane might not be very disruptive if the effects are kept local.

Implementation of various Information and Technology Systems (ITS) strategies, such as parking guidance or traffic signal control, has proven to be very beneficial for traffic operations at the network level [30]. For example, [31] presented a model for determining the optimal display of parking guidance and information sign configuration that minimizes queue lengths and distance traveled while searching for parking. Similarly, in the fuzzy logic-based model developed by [32], each delivery vehicle can receive information on

whether to park or not, based upon the current given state of the parking (e.g., space availability).

On the other hand, as an important element of ITS, traffic signal systems have been one of the most cost effective investments [33]. For example, an Adaptive Traffic Control System (ATCS) has been developed as the most advanced traffic signal system technology for coordinated network control. ATCSs systems continuously make small adjustments to signal timing parameters in response to changing traffic demand and patterns [34]. These adjustments aim to improve network-wide efficiency by dealing with fluctuations in traffic demand. These systems could also improve the performance of DDPS in case of nonrecurring traffic conditions [35].

The study of urban freight transport and city logistic policies requires specific site-oriented studies to collect data. For example, [2] compared the cities of Rome, Barcelona, and Santander regarding the current distribution patterns and regulations. In different cities, policies to reduce the number of commercial vehicles have been studied and implemented such as urban consolidation centers or off-hour deliveries. Freight flows are determined by the interactions among different actors: shippers, carriers, and receivers. Some of these policies have failed to reduce the demand, as they targeted carriers, which do not usually have enough decision power to change the delivery performance (delivery time, location, etc.). The problems of parking in urban areas considering the specific challenges for freight have been studied in [36]. The work analyzed the balance between the demand for parking and the available on-street supply in a case study on the city of New York. In New York City, off-hour delivery programs have been fostered with money incentives for receivers in a pilot test, providing significant benefits and demonstrating a high potential for full implementation [37]. This paper, on the other hand, focuses on the provision of more parking spaces, when some capacity of the traffic lane is available, but the demand for delivery parking operations remains unchanged.

Recently, [38] developed a simulation framework for planning, managing, and controlling urban delivery schemes. Last-minute reservations were proved to significantly improve the system in terms of the total service time, compared to a scenario without booking. To the best of the authors' knowledge, there is no study modelling the specifics on dynamic usage of a driving lane for loading/unloading purposes. Hence, this paper aims to fill this gap by providing preliminary understanding on how the DDPS could be arranged without significantly affecting the performance of traffic, and by validating the system's parameters in a microsimulation environment. This is considered a first step towards the implementation of DDPS. Further research might be needed to address some more practical issues regarding such implementation.

3. Analytical Model

This section is divided into four subsections: assumptions and definitions; formulations; relaxation of assumptions; summary of the formulations and guidance. In the first subsection, we introduce the scope of the model and the

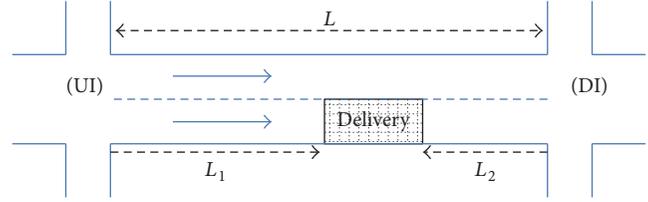


FIGURE 1: General situation of the DDPS on a given link between the upstream intersection (UI) and the downstream intersection (DI). Notice that, in this example, a 2-lane street is presented, but the methodology is generalized to any number of lanes n ($n \geq 2$).

main tools used for the analysis. In the second subsection, we analyze the discharging rate of both the upstream and the downstream intersections, taking into consideration the lane drop at the location of the delivery area. In the third subsection, we discuss the relaxation of some assumptions. Finally, in the fourth subsection, we summarize the formulations and provide a roadmap to guide readers to the correct expression, depending on the local conditions including the traffic demand.

3.1. Assumptions and Definitions. Our analysis focuses on a street with a number of n ($n \geq 2$) lanes per direction. On this street, a dynamic delivery area (an area can consist of several spots) is placed on the link between two consecutive intersections. The total length of the link is L , the distance between the delivery area and the upstream intersection (UI) is L_1 , and the distance between the delivery area and the downstream intersection (DI) is L_2 . Figure 1 depicts the situation with an example of a 2-lane street. Notice that the loading/unloading vehicles would temporarily occupy the dynamic delivery area (gridded) and block a part of the lane, reducing the road capacity. All the notation used within the paper can be found in Table 2 in the Appendix.

We assume that the geometry of the street is the same throughout the link. We also assume for simplicity that the intersections are coordinated with a green wave signal control. Due to the green wave, when no delivery operation is conducted (i.e., there is no blockage), the traffic discharged from the UI should be able to cross the DI without any stop or delay. Naturally, the conditions change when a loading/unloading operation takes place on the dynamic delivery area. Some vehicles arriving on the shoulder lane will have to stop upstream of the dynamic delivery area, while some other vehicles might merge into the other lanes and cross the DI. Depending on how large L_1 is, the queue might (or not) spill over into the UI and affect traffic on the upstream links. Therefore, to limit the impacts of DDPS on traffic, we aim to find the conditions such that there is no queue spillback to UI. To analyze these potential effects under the different traffic states, we define several variables below.

We denote c as the length of the signal cycle and g as the length of the green signal. For the analysis, we assume that these parameters are the same for both intersections. Later in this section, we will discuss how the relaxation of these assumptions would affect the model.

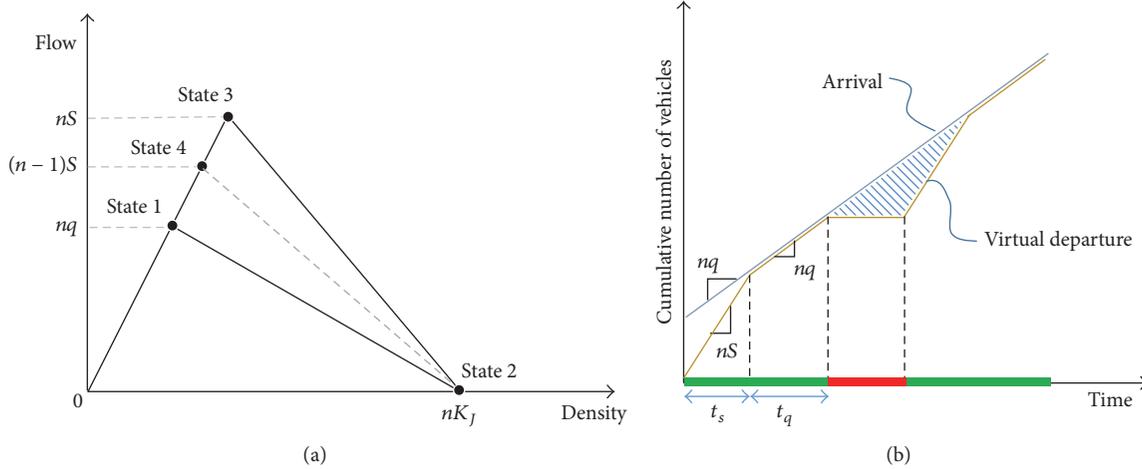


FIGURE 2: (a) Triangular fundamental diagram for the street with a number of n lanes. (b) Illustrative queuing diagram for undersaturated conditions.

For the purpose of modelling traffic conditions, a triangular fundamental diagram (FD) is assumed, based on the hydrodynamic theory of traffic flow. Such assumption has been previously validated with empirical studies [39–42]. Figure 2(a) depicts an illustrative FD with the different traffic states that might be observed on a link. State 1 represents the traffic flow arriving from upstream (q); state 2 represents the stopping traffic in front of the red light; state 3 represents the traffic discharging from the queue at the intersections (assuming there is no queue spillback from downstream); state 4 represents the capacity of the street at the delivery area, where only a number of $n - 1$ lanes can be used. The saturation flow rate per lane is S ; thus, nS is the total saturation flow rate of the street, and $(n - 1)S$ is the link capacity at the location of DDPS. The jam density per lane is K_j (nK_j for the entire road). Notice that we define the arrival flow rate (i.e., traffic demand volume) for the whole street as q , such that $q \in [0, nS]$.

The queuing diagram in Figure 2(b) is given as an illustrative example. It shows the cumulative number of arrivals and departures at the UI without the interruption of loading/unloading vehicles. One can notice that the arrival has a constant flow of q and the virtual departure rate can be at the maximum of nS (i.e., saturation flow) during the green signal; the shaded area is the delay generated by the red signal within a cycle. The queuing diagram can help in visualizing the delay generated by potential delivery operations and will be used in the following subsection to show different cases.

We also assume that most of the flow is arriving from upstream. In other words, only a rather small number of turning vehicles enter the link during the red signal, (q_t) compared to the flow arriving from upstream, (i.e., $q_t \ll q$). For this reason, their effects on the overall traffic operations can be neglected.

Note that the DDPS concept is developed for loading/unloading operations, as they have shown to be crucial in an urban context. However, the facility could serve similar parking operations for other purposes, such as service trips

or on-demand passenger transport services. In cases when other operations are allowed in the area, it is important to ensure that the features of such operations are aligned with the DDPS concept and the model presented here. For instance, the parking duration cannot be unlimited. Long service trips (i.e., more than 2 h) might not be suitable for DDPS locations where the traffic demand changes rapidly, given that the allowed parking area will change accordingly.

3.2. Formulations. In this subsection, we investigate the location of the delivery area, such that no traffic spillover is generated. The location is defined by the distance between the delivery area and the neighboring intersections. We will find the minimum distance values (L_1 and L_2), that guarantee that no traffic spillover is caused to other links. (i.e., minimum values for L_1 and L_2). Denote such minimum distances as d_1 and d_2 . To find their formulations, we first define some new variables.

In the absence of DDPS, the maximum number of vehicles (N) that can be discharged during a cycle, in a street with n lanes, can be calculated using (1). If the intersection is undersaturated ($q \leq n(Sg/c)$), N is the total traffic demand arriving at the intersection in one cycle (qc), given our assumption that the number of turning vehicles is negligible. If the intersection is oversaturated ($q > n(Sg/c)$), N is the maximum number of vehicles that can discharge (at the saturation flow rate) during the green signal (nSg)

$$N = \begin{cases} qc, & \text{if } q \leq n\frac{Sg}{c}, \\ nSg, & \text{if } q > n\frac{Sg}{c}. \end{cases} \quad (1)$$

In the presence of DDPS, the maximum number of vehicles, which can be discharged at the intersection during a cycle by the $n - 1$ lanes that are not blocked, N_d , can be calculated using (2). Note that, due to the merging effects, the number of discharged vehicles will be reduced by a factor of $\beta \in [0, 1]$. A factor equal to 1 represents a perfect merge

of the vehicles on the shoulder lane to the immediate next lane, causing no decrease in the lane capacity. This factor also depends on the number of remaining free lanes: the higher the number of lanes, the smaller the overall effect (i.e., the higher the β). Merging effects and the impact of lane changes have been studied in freeway environments, either with an endogenous model [43–45], simulation [46, 47], or empirical data [48, 49]. In this paper, as it will be later shown, the β parameter can be easily calibrated with a simple simulation experiment performed in a controlled manner.

$$N_d = \begin{cases} qc, & \text{if } q \leq (n-1) \frac{Sg}{c} \beta, \\ (n-1) Sg\beta, & \text{if } q > (n-1) \frac{Sg}{c} \beta. \end{cases} \quad (2)$$

Denote $N_i, i \in \{1, 2\}$, as the maximum number of vehicles that could be accommodated in the distance of d_i , in the lane with the delivery area. Its expression is written in

$$N_i = d_i K_J, \quad \forall i \in \{1, 2\}. \quad (3)$$

N_1 and N_2 are the number of queued (jammed) vehicles that could fit into the space before or after the dynamic delivery area on a single lane. Intuitively, the larger N_1 and N_2 are, the less traffic delay the loading/unloading operation causes. In the case of N_1 , a larger space can guarantee that the queue will not spill over to the UI. In the case of N_2 , a larger space would allow storing enough vehicles in front of the DI, to guarantee that it does not starve from vehicle's flow once the green signal starts.

In other words, to avoid a service rate reduction at the UI, independently of the duration of the operation, N_1 must be equal to or larger than the difference between N and N_d . By formulating $N_1 \geq N - N_d$, we can obtain $d_1 = N_1/K_J$; it is written as (4a), (4b), and (4c) where $\hat{\beta} = (n - (n-1)\beta)$ represents the overall percentage of capacity lost at the DDPS.

$$d_1 = 0, \quad \text{if } q \in \left[0, (n-1) \frac{Sg}{c} \beta\right], \quad (4a)$$

$$d_1 = \frac{qc - (n-1) Sg\beta}{K_J}, \quad \text{if } q \in \left[(n-1) \frac{Sg}{c} \beta, n \frac{Sg}{c}\right], \quad (4b)$$

$$d_1 = \frac{Sg\hat{\beta}}{K_J}, \quad \text{if } q \in \left[n \frac{Sg}{c}, nS\right]. \quad (4c)$$

In other words, when L_1 is larger than d_1 , the service rate at the UI is not affected and the delivery area does not generate lingering delays affecting the upstream traffic performance. Note that, for long links, $L > Sg\hat{\beta}/K_J$, it will be possible to allow DDPS without affecting the UI.

Figure 3 shows the three pieces of linear curves resulting from the plot of the three subequations above ((4a)–(4c)). Each of the three pieces corresponds to a different scenario according to the traffic demand. The traffic demand is analyzed between 0 and the total capacity of the link (nS). The two relevant traffic demand levels where scenarios change are $n(Sg/c)$, representing the traffic capacity at the intersection when using all lanes, and $(n-1)(Sg/c)\beta$ representing the

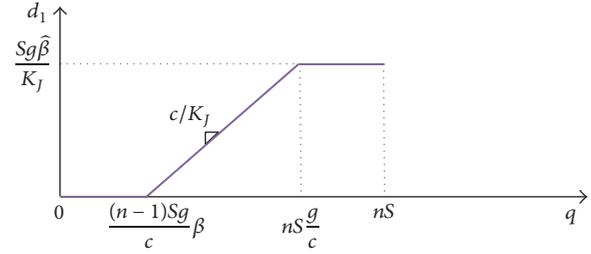


FIGURE 3: Value of d_1 in relation to the traffic demand volume q .

capacity at the intersection when using one less lane (including the merging effects). Recall that g and c are the duration of green time and the length of signal cycle, respectively. This leads to the three different scenarios described below.

Scenario 1. The UI is very undersaturated, $q \in [0, (n-1)(Sg/c)\beta]$ (4a), as the demand is very low. Recall that $(n-1)(Sg/c)$ represents the capacity of an intersection when using $n-1$ lanes, and β accounts for the merging effects. With such low demand, the site remains undersaturated, even if one lane is completely blocked by DDPS. In other words, the other $n-1$ available lanes can serve all the traffic demand, given that the arrival flow is small enough ($N - N_d = 0$). As a result, d_1 is also zero (i.e., the delivery area can occupy all the way back to the UI, and the UI would still be able to fully discharge the arriving traffic within every cycle).

Scenario 2. The UI is undersaturated in the absence of a delivery area, $q \in [(n-1)(Sg/c)\beta, n(Sg/c)]$ (4b). However, the intersection would become oversaturated if the right lane was to be completely occupied. In other words, the demand is lower than the capacity of the intersection using all lanes, $n(Sg/c)$, but higher than the capacity of the intersection with one lane blocked, $(n-1)(Sg/c)\beta$. Hence, to ensure that the intersection remains undersaturated, we need to provide some storage space, that is, $L_1 > 0$. The storage space required is equivalent to $N - N_d = qc - (n-1)Sg\beta$. The distance, evidently, increases as the traffic demand (q) grows.

Scenario 3. The intersection is oversaturated in any case, with or without the delivery area, $q \in [n(Sg/c), nS]$ (4c). The demand exceeds the capacity of the intersection even with all available lanes, $n(Sg/c)$. In other words, all the lanes discharge traffic at the saturation flow rate (S) during the whole green signal. DDPS can only be allowed if the space remaining on the same lane is able to accommodate the vehicles blocked; that is, the vehicles arriving from upstream that cannot be accommodated in the $(n-1)$ lanes, $N - N_d = Sg(n - (n-1)\beta)$. To guarantee this, we need a minimum distance $d_1 = Sg\hat{\beta}/K_J$ with $\hat{\beta} = (n - (n-1)\beta)$. Notice that this is independent of the value of q , as the amount of vehicles entering the intersection is limited by the traffic signal, not by the traffic demand.

With d_1 already defined, we can now formulate d_2 , (i.e., the minimum length of L_2 , distance between the delivery area and the DI, such that the DI does not starve for traffic).

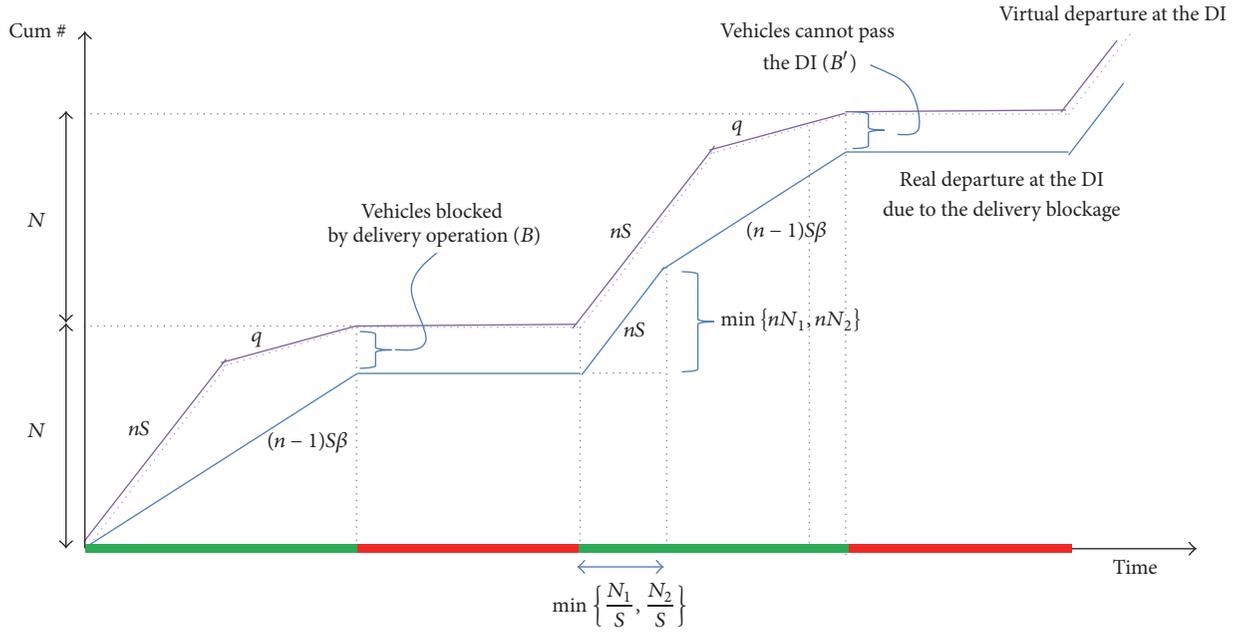


FIGURE 4: Virtual departure and real departure curves at the DI for the cases where the service rate at DI is not affected.

One should note that the computation of the d_2 distance at the DI is different from the case of the UI, for two reasons. First, the arrival pattern has changed since we need to account for vehicles affected by the delivery operations, which can be stored before or after the dynamic delivery area. Second, the signal control is correlated between these two intersections, that is, green wave. Therefore, the vehicles that successfully departed the UI and are not blocked by the delivery operation can also directly depart the DI. However, the vehicles which are held behind the dynamic delivery area can only arrive at the DI later than they were supposed to (in the worst case, all vehicles will arrive during the following red signal and will be forced to discharge during the next cycle). In any case, even when some vehicles are forced to wait for the next cycle, the right value for d_2 can limit the disruptions to traffic so that the service rate is not reduced. We will find d_2 that satisfies this condition.

The queuing diagram of Figure 4 depicts the virtual departure at the DI and the real departure at the DI due to the delivery blockage. The virtual departure refers to the potential departure at the DI in the absence of DDPS (i.e., the same as the departure from the UI assuming no platoon dispersion and perfect coordination). Due to the traffic signal coordination (i.e., green wave), during the first cycle of blockage, the discharging rate at the DI is $(n-1)S\beta$, since the blockage makes the full shoulder lane useless, and the rest of the lanes will be affected by the merging maneuvers. Some of the vehicles from the first cycle cannot cross the DI in time and are stored in front of the red signal, using all lanes available downstream of the parking area. During the second cycle of the blockage, at the beginning, the DI can discharge at the saturation flow, nS , given that vehicles stored in the L_2 area discharge using all available lanes. This lasts for a period equivalent to the $\min\{N_1/S, N_2/S\}$, as the $\min\{N_1, N_2\}$

is the number of vehicles that will be stored within the link. Afterwards, the discharging rate drops again to the saturation flow of $n-1$ lanes, that is, $(n-1)S\beta$, until either the queue clears up or the green signal ends.

Note that, for the departure curve, we assume that once the green signal is activated, vehicles start discharging at the maximum flow. It is true that the effects of perception-reaction time and acceleration time will make the time discharging at the maximum flow slightly longer. However, this will happen at both intersections (UI and DI) when traffic flows are critical (Scenarios 2 and 3 of Figure 3). With the presence of DDPS, there will be vehicles waiting in front of the traffic light, not only for the UI, but also for the DI.

The queue left at the end of the second cycle depends on the value of L_2 and its relation to L_1 . When $L_2 \leq L_1$, the number of vehicles that can discharge DI is limited by the smallest distance, that is, L_2 . When $L_2 \geq L_1$, the number of vehicles that can discharge DI is fixed by L_1 ; that is, N_1 vehicles can discharge. We compare the queue at the DI at the end of the first and second green signal to see if the queue diminishes. We aim to find the critical length of L_2 , for which the queue gets smaller over cycles, independently of the duration of the blockage. Geometrically, based on Figure 4, we can obtain the number of vehicles that cannot pass the DI at the end of both the first and the second cycle of blockage. Let us denote B as the number of vehicles queuing at the DI at the end of the first green signal and B' as the number of vehicles after the second green signal. Their expressions are written as

$$B = \begin{cases} 0, & \text{if } q \in \left[0, (n-1) \frac{Sg}{c} \beta\right], \\ N - (n-1) Sg\beta, & \text{if } q \in \left[(n-1) \frac{Sg}{c} \beta, nS\right], \end{cases} \quad (5)$$

$$B' = \begin{cases} 0, & \text{if } q \in \left[0, (n-1) \frac{Sg}{c} \beta\right], \\ 2N - 2(n-1)Sg\beta - N_2, & \text{if } q \in \left[(n-1) \frac{Sg}{c} \beta, nS\right]. \end{cases} \quad (6)$$

Eq. (5) calculates the number of vehicles queuing at the DI at the end of the first green signal. When q is below the threshold, no vehicles queue, as, even with the blockage, the DI is able to serve all the vehicles within its green signal. Above this threshold, the number of vehicles queuing is given by the difference between N (the maximum number of vehicles that can be discharged during a cycle) and $(n-1)Sg\beta$ (the number of vehicles that can be discharged with one lane blocked).

In a similar way, we calculate in (6) B' , the number of vehicles queuing at the DI after the second green signal. Once again, when the demand is below the given threshold, no vehicles queue. Above this threshold, the queuing vehicles are calculated as the sum of the three following components: $+2N$, the maximum number of vehicles that can be discharged during the two cycles (first and second); $-2(n-1)Sg\beta$, the number of vehicles that can be discharged with one lane blocked during the two cycles; and $-N_2$, the number of vehicles that could not pass the DI during the first cycle and were stored in front of the delivery area, ready to be discharged in the second cycle. In both equations, the threshold represents the maximum flow for which no vehicles are delayed during one cycle. Below this threshold, no vehicles queue at the DI at the end of the cycle.

In the case when the number of blocked vehicles decreases after the second cycle, the delay decreases over time. Otherwise, the delay increases over time. From this aspect, if $B' < B$, the delivery operation is acceptable; in the opposite case, the delivery operation should be avoided, since the delay will linger over time and, sooner or later, will spread over the network. Denote d_2 as the minimum distance of L_2 that would allow this to happen; it is written as (7), where $\hat{\beta} = (n - (n-1)\beta)$:

$$d_2 = \begin{cases} 0, & \text{if } q \in \left[0, (n-1) \frac{Sg}{c} \beta\right], \\ \frac{qc - (n-1)Sg\beta}{K_J}, & \text{if } q \in \left[(n-1) \frac{Sg}{c} \beta, n \frac{Sg}{c} \beta\right], \\ \frac{Sg\hat{\beta}}{K_J}, & \text{if } q \in \left[n \frac{Sg}{c} \beta, nS\right]. \end{cases} \quad (7)$$

In other words, if $L_2 \geq d_2$, then the service rate at the DI can recover over time. DDPS could also be considered when the lingering delay for the duration of the blockage is not significant and can be cleared some cycles after the blockage ends. However, this is not considered here and will be developed in future work. Although d_1 and d_2 are derived with different approaches, interestingly they lead to the same expression. In other words, for any given traffic demand (q), the minimum distance to the upstream intersection and the minimum distance to the downstream intersection are equivalent to each other. In the end, both intersections have a similar performance with the blockage after the first cycle. Both intersections have exactly the same traffic demand that has to be served within one cycle. The traffic demand is

served with the nonblocked lanes plus the storage capacity. Considering that the capacity of the nonblocked lanes is the same, the storage space in front of or after the blockage area is also equivalent.

Figure 5 shows the necessary area to allow the provision of DDPS in relation to the traffic demand (q). As can be seen in Figure 5, there are two possible situations when dynamic delivery areas can be provided:

- (i) In Figure 5(a), as the link length is larger than $2Sg\hat{\beta}/K_J$, the dynamic delivery area is always possible between $Sg\hat{\beta}/K_J$ and $L - Sg\hat{\beta}/K_J$. However, if q is smaller than $n(Sg/c)$, the allowed area can be even larger. In the extreme case, where the demand is rather low, $<(n-1)(Sg/c)\beta$, the whole lane between the UI and DI can be used for DDPS.
- (ii) In Figure 5(b), when the link length is smaller than $2Sg\hat{\beta}/K_J$, but the traffic demand is also small, dynamic delivery areas are still possible. Denote q_{\max} as the maximum traffic demand volume with which DDPS are possible; it can be found based on $d_1 = L - d_2$. Its expression is written in

$$q_{\max} = \frac{LK_J + 2(n-1)Sg\beta}{2c}. \quad (8)$$

If the link is seen as between location 0 (the start of the link in the considered traveling direction) and L (the end of the link), the parking area can be provided within $[d_1, L - d_1]$.

3.3. Relaxation of Assumptions. Some of the model assumptions will be relaxed and discussed here. Regarding the signal control, the model assumes equality of signal cycle lengths and equality of green signal lengths for both intersections. The case for different signal cycle lengths requires a new model formulation, which would need to particularly study the traffic behavior within different combinations of signal cycle length. For example, if the UI signal cycle length is twice as long as the DI signal cycle length, the model would need to be adapted to account for the behavior of the traffic flow until the same pattern is repeated. Notice, however, that it is very common for cities to have the same signal cycle length at nearby intersections. In such cases, the DDPS model presented here will be valid.

On the other hand, the same signal cycle length at nearby intersections does not guarantee the same green signal length. However, unless there are specific reasons to define it differently, many consecutive intersections have similar values for the green signal length. Otherwise, bottlenecks or capacity loss would occur, leading to an inefficient signal coordination. In case when the green signal lengths of the UI and the DI are not exactly equal, the results of the model would slightly change. We denote g_1 and g_2 as the green time for the UI and the DI, respectively. In this case, the levels of demand that determine the different possible scenarios of Figure 3 will be computed as in (4a), (4b), and (4c), but substituting $g = \min\{g_1, g_2\}$. In other words, different demand thresholds will be determined by the minimum of the green signal length

TABLE 1: Provision suggestions on the dynamic delivery areas under various conditions.

Scenarios	Provision	Area to provide	Number of delivery spaces to provide	
If $L \geq \frac{2Sg\hat{\beta}}{K_j}$	If $q \in \left[0, (n-1) \frac{Sg\hat{\beta}}{c}\right]$	$[0, L]$	$\frac{L}{x}$	
	Yes If $q \in \left[(n-1) \frac{Sg\hat{\beta}}{c}, n \frac{Sg}{c}\right]$	$\left[\frac{qc - (n-1)Sg\hat{\beta}}{K_j}, L - \frac{qc - (n-1)Sg\hat{\beta}}{K_j}\right]$	$\frac{L - 2[qc - (n-1)Sg\hat{\beta}]/K_j}{x}$	
	If $q \in \left[n \frac{Sg}{c}, nS\right]$	$\left[\frac{Sg\hat{\beta}}{K_j}, L - \frac{Sg\hat{\beta}}{K_j}\right]$	$\frac{L - 2Sg\hat{\beta}/K_j}{x}$	
If $L < \frac{2Sg\hat{\beta}}{K_j}$	If $q \leq q_{\max}$ Yes	If $q \in \left[0, (n-1) \frac{Sg}{c}\beta\right]$	$[0, L]$	$\frac{L}{x}$
		If $q \in \left[(n-1) \frac{Sg}{c}\beta, q_{\max}\right]$	$\left[\frac{qc - (n-1)Sg\hat{\beta}}{K_j}, L - \frac{qc - (n-1)Sg\hat{\beta}}{K_j}\right]$	$\frac{L - 2[qc - (n-1)Sg\hat{\beta}]/K_j}{x}$
	If $q > q_{\max}$ No	—	—	—

TABLE 2: Parameters, acronyms, and scenarios.

Parameters	
B	Number of vehicles queuing at the DI at the end of the first green signal
B'	Number of vehicles queuing at the DI at the end of the second green signal
K_j	Jam density per lane
L	Total length of the link
L_1	Distance between the delivery area and the upstream intersection
L_2	Distance between the delivery area and the downstream intersection
N	Maximum number of vehicles that can be discharged during a cycle
N_d	Maximum number of vehicles that can be discharged at the intersection during a cycle by the $n-1$ lanes that are not blocked
$N_i, i \in \{1, 2\}$	Maximum number of vehicles that could be accommodated in the distance of d_i in the lane with the delivery area
S	Saturation flow rate per lane
c	Length of the signal cycle
d_1	Minimum distance value of L_1 that guarantees that no traffic spillover is caused to other links
d_2	Minimum distance value of L_2 that guarantees that no traffic spillover is caused to other links
g	Length of the green signal
g_1, g_2	Green time for the UI and the DI
n	Number of lanes per direction
q	Traffic flow arriving from upstream
q_{\max}	Maximum traffic demand volume with which DDPS are possible
x	Distance needed for each delivery space
β	Factor that represents the merge effect of the vehicles on the shoulder lane to the immediate next lane
$\hat{\beta}$	$(n - (n-1)\beta)$. Transformation of the β parameter to simplify the notation
Acronyms	
ACTS	Adaptive Traffic Control System
DDPS	Dynamic Delivery Parking Spots
DI	Downstream intersection
FD	Fundamental Diagram
ITS	Information and Technology Systems
UI	Upstream intersection
Scenarios	
S0	Illegal parking with random arrival and location
S1	DDPS
S2	DDPS with prebooking system
V1	DDPS
V2	One lane blocked

4. Illustration of the Model

In this section, we use a numerical example (divided into two parts), to illustrate the application of the proposed methodology. Given the data for a particular link, we exemplify how the results from the analytical formulation could aid the design of a DDPS. The results show how the model can be used in a two-lane ($n = 2$) link under realistic conditions. The following values are assumed: saturation flow rate $S = 1800$ veh/hr/lane, jam density is $K_j = 150$ veh/km/lane, distance needed for each delivery space is $x = 8.5$ meters [50], and link length $L = 120$ meters. The green signal (g) lasts 35 seconds and the cycle length (c) is 70 seconds.

In the first part, we analyze the traffic demands for which we can allow DDPS on a given link, the location of the parking spots, and the number of spots allowed to be placed. In the second part, we assume a given daily traffic demand pattern and provide an overview of how the DDPS should change over the length of the day.

As mentioned before, the calibration of the β parameter is performed with a simple simulation experiment. We compare the total number of served vehicles on the one-lane link (without a blockage) and the two-lane link (with a blockage). In case of the one-lane link, we simply calculate the total number of vehicles served during the simulation period. Given that the used traffic demand is large enough to saturate the intersection, this is the maximum number of vehicles that the link can handle, due to the signalized intersection. Then, under the same traffic conditions, a two-lane link is simulated with a blockage on the right (shoulder) lane. In this case, we calculate the effect of the merging vehicles. Due to the blockage, the vehicles circulating on the shoulder lane need to merge to the left lane, causing less vehicles (originally arriving at the left lane) to be served, compared to the one-lane link scenario. This reduction was calculated for different simulation settings considering diverse lengths of merging areas, and the average value found was $\beta = 0.92$.

4.1. Location of DDPS. We will first analyze whether it is possible to provide a dynamic delivery area and the locations of such provision. Following Table 1 we detect which are the possible scenarios.

Step 1. $2Sg\hat{\beta}/K_j = (2 \cdot 1800(35/3600)1.08/150) \cdot 1000 = 252$ meters.

Step 2. Is $L \geq 2Sg\hat{\beta}/K_j$? No; therefore, we can only provide dynamic delivery when $q \leq q_{\max}$.

Step 3. Based on (8), $q_{\max} = (LK_j + 2(n-1)Sg\beta)/2c = 1290$ veh/hr.

Step 4. Area to provide provision:

- (i) if $q \in [0, (n-1)(g/c)S\beta]$, that is, if $q \in [0, 828]$ veh/hr, the area to provide dynamic delivery is within $[0, L]$, that is, $[0, 120]$ meters.
- (ii) if $q \in [(n-1)(g/c)S\beta, q_{\max}]$, that is, if $q \in [828, 1290]$ veh/hr, the area to provide dynamic delivery is

within $[(qc - (n-1)Sg\beta)/K_j, L - (qc - (n-1)Sg\beta)/K_j]$, that is, $[0.13q - 107.33, 227.33 - 0.13q]$ meters.

Step 5. Number of delivery spaces to be provided:

- (i) if $q \in [0, (n-1)(g/c)S\beta]$, that is, if $q \in [0, 828]$ veh/hr, we can provide L/x , that is, 14 spaces.
- (ii) if $q \in [(n-1)(g/c)S\beta, q_{\max}]$, that is, if $q \in [828, 1290]$ veh/hr, we can provide $(L - 2(qc - (n-1)Sg\beta)/K_j)/x$, that is, $39.37 - 0.03q$ spaces.

The results of the case study are presented in Figure 6(a).

4.2. Temporal Variations across the Day. In this example, we analyze the link during the entire day and show how the dynamic delivery area changes according to the traffic demand. The graph on the top of Figure 6(b) shows traffic demand variations during a given day (an input to the model), with the two peak hours (morning and afternoon). The graph at the bottom shows the time-space diagram for the dynamic delivery area.

During the times of the day when traffic demand is lower than $(n-1)(g/c)S\beta$, we can allow DDPS on the full link, given that the traffic demand is low enough. In other words, the other free lane can accommodate all the demand. Furthermore, when traffic demand is between $(n-1)(g/c)S\beta$ and q_{\max} , the dynamic delivery area is reduced linearly in relation to the demand, until no space can be provided. Finally, during the decrease of the traffic demand after midday, we can provide a delivery area for some hours using the lane capacity that the decrease of traffic demand leaves unoccupied.

5. Validation and Evaluation of the Model

In this section, the results of a simulation study based on the numerical example described above are presented. The objectives of the simulation are twofold: (1) to validate the results of the analytical model in more realistic scenarios (e.g., stochastic vehicle's arrival) and (2) to evaluate the performance of the proposed DDPS concept through a comparison with the current situation of illegal delivery parking. This section is divided into two subsections, one for the model validation and one for the DDPS performance evaluation.

Simulation experiments are conducted using a VISSIM microsimulation platform [51]. To account for the stochastic nature of vehicles' arrival in the simulation model, multiple VISSIM simulation runs with various random seeds were executed for all scenarios. Each simulation was one hour and 15 minutes long, with a 15-minute warm-up time and one hour of evaluation time.

5.1. Model Validation. For the validation of the analytical model, two different scenarios representing different management strategies of the delivery parking operations are analyzed. The first scenario (V1) considers the provision of DDPS in the central part of the link, with the length (number of spots) determined according to the analytical formulation. The length for DDPS is determined in each case according to

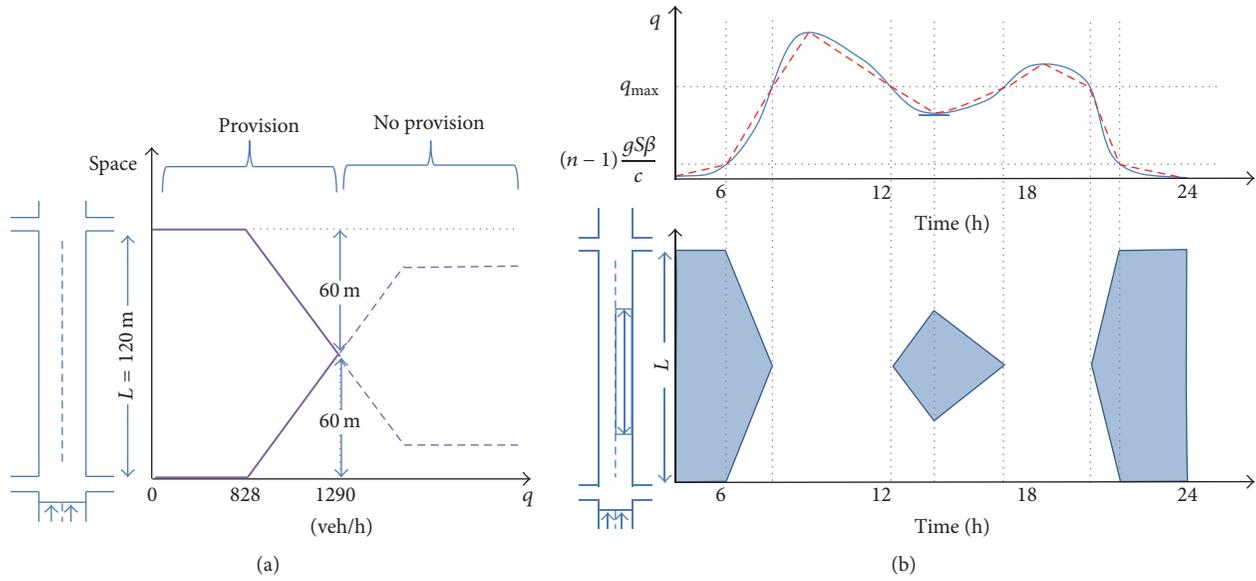


FIGURE 6: (a) Values of d_1 and d_2 in relation to the traffic demand volume q . (b) Dynamic delivery area variations across the day.

the traffic demand and signal timing parameters (see Table 1). In this scenario we also assume that the spots are occupied all the time due to a prebooking system. Secondly, we evaluate a hypothetical scenario (V2) in which one lane is completely devoted to the delivery parking. In total, three levels of traffic demand (988, 1090, and 1190 veh/h) are used as an input in the simulation platform, for each scenario. The levels of demand are chosen such that they correspond to the provision of 9, 6, and 3 DDPS spots of 8.5 meters, respectively, in the case of V1.

For comparison purposes, we analyze two performance measures: the average queue length in the UI and the latent demand. The latter represents the number of vehicles that cannot be served during the simulation (i.e., due to the spillback at the UI).

Results reveal that no latent demand is generated in scenario V1, suggesting that the presence of DDPS does not cause spillbacks. However, when the portion of the road space devoted to DDPS is larger than what is recommended by the proposed analytical model (the case of V2 scenario), there is a latent demand at the end of the simulation (2%, 15%, and 24% for the traffic demand of 988, 1090, and 1190 veh/h, resp.), causing spillbacks. In addition, one can observe from Figure 7 the average queue length in each scenario and for each traffic demand. In the V2 scenario the queue length nearly reaches the length of the upstream link, which is another sign of the spillback effect.

In reality, when parking is not available, delivery vehicles might park illegally to perform loading and unloading operations, affecting the overall network performance. Therefore, we conduct another set of simulation experiments in order to investigate the benefits of DDPS, compared to the potentially illegal parking maneuvers. Tested scenarios and the results of these experiments are provided in the next subsection.

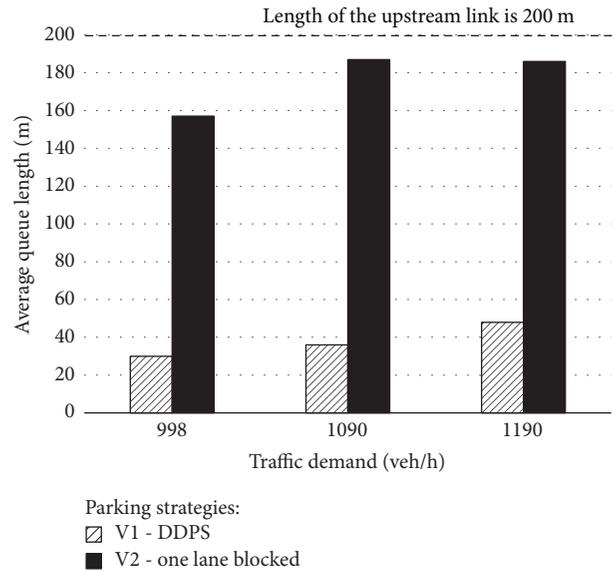


FIGURE 7: Average queue length (m) in the validation scenarios: V1 and V2.

5.2. DDPS Performance Compared to Illegal Parking. In this subsection the performance of DDPS is analyzed with the three following scenarios:

- (1) S0 scenario, representing the current situation, where some delivery vehicles perform random illegal parking in the shoulder lane (see Figure 8(a)). In reality, the delivery parking location is usually chosen based on the proximity to the destination. In our simulation, we assume that delivery vehicles choose a random location within the link, arriving with a random pattern during the simulation period. From that

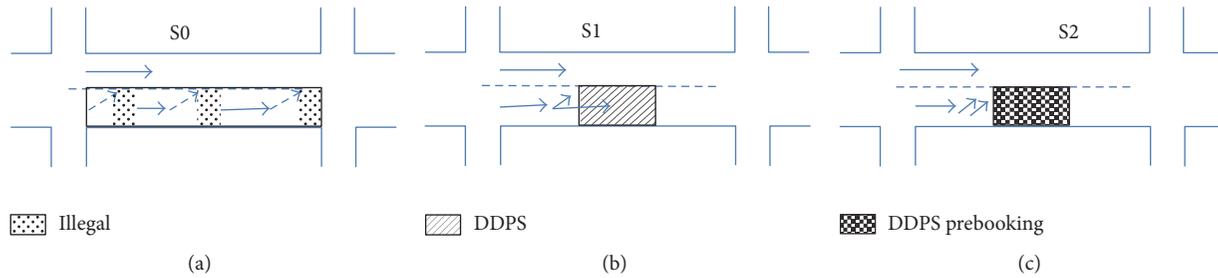


FIGURE 8: (a) S0, illegal parking with random arrival and location; (b) S1-DDPS; (c) S2-DDPS with prebooking system.

perspective, five different random arrival patterns are tested.

- (2) S1 scenario, representing the dynamic operations of DDPS, where the shoulder lane is blocked only when there are delivery vehicles operating (see Figure 8(b)). Vehicles operate only in the DDPS area determined according to the given traffic demand and signal timing parameters. In other words, delivery vehicles do not park at a random location, but within the area assigned according to the DDPS formulation (Table 1). The same random arrival patterns of delivery vehicles from the previous scenario are used.
- (3) S2 scenario, representing the operation of a DDPS combined with a prebooking system. When a prebooking system is used, delivery vehicles are assigned a given parking time in advance, according to their preferences, which respects the capacity of the facility at all times [6]. Given the provision of DDPS spots with a prebooking system, we assume that the delivery parking demand can be higher and uses the facility during most of the time (at the maximum capacity). For that reason, in this scenario, other vehicles cannot use this part of the lane at all (see Figure 8(c)). In this case, delivery vehicles have a preassigned time; therefore the arrival pattern is not random.

In scenarios S0 and S1, we assume that there will be a demand of 9 delivery vehicles per hour, which will perform delivery operations at the studied link. In the S0 scenario, delivery vehicles decide to park illegally, as no facility is available at all; in the S1 scenario, delivery vehicles use one of the available parking spots provided. In contrast, S2 can serve an increased number of delivery vehicles per hour, as the DDPS is used with a prebooked assignment and parking spots can be used all the time.

The average duration of loading/unloading operations varies depending on the type of goods and also across different cities. For example, in the city of Barcelona, the average delivery time is around 18 minutes [25] and vehicles are allowed to park in dedicated areas for a maximum of 30 minutes. Other cities such as Valencia, Lyon, Rome, or Westminster have similar time restrictions for delivery parking [2, 3, 52]. In the city of New York, the average parking time can reach 1.8 h [37], as multiple customers are served

from the same parking location. Also, some cities allow other activities such as service vehicles to use these parking facilities. In general, DDPS is a solution for parking times up to a maximum of 30 minutes, given that, for longer parking periods, traffic conditions might change and DDPS might not be available anymore. In cases where parking time is much longer, other alternatives should be considered for parking. In this simulation study, we consider three different parking times (10, 20, and 30 minutes) and analyze their impact on the traffic performance. Note that the variation of parking times would not affect the provision of DDPS, but the number of vehicles that could be served, that is, the capacity of the parking facility.

To investigate the impact of each scenario (S0, S1, and S2) on the traffic performance, the average delay per vehicle is used, as shown in Figure 9. Note that the average vehicle delay of scenario S0 (illegal parking) is significant. A system without delivery parking (enforced regulation) was also simulated, and the average delay registered ranged from 16 to 17 sec/veh. Moreover, the average delay increases with both the length of the loading/unloading operations and the traffic demand.

With DDPS in S1 scenario, we show that this delay can be significantly reduced, if the same delivery demand uses the facility located in the center of the link (defined according to the analytical method in Table 1).

Nevertheless, when the traffic demand is high and/or loading/unloading operations last long, DDPS might not have enough capacity to serve the randomly arriving delivery vehicles, (i.e., it might not be possible to position all delivery vehicles within DDPS spots at a given time). These cases for S1 have not been simulated and are represented with \emptyset symbol. Instead, the S2 scenario where DDPS is combined with a prebooking system is a much better option, as it allows us to optimally assign the delivery demand to parking spots and increase the capacity of DDPS. In this case, we assumed that the DDPS area will be blocked for the total simulation period, so that other vehicles cannot use it. The delay caused in the system with a prebooking DDPS (in dashed lines in Figure 9) is lower than illegal parking, except for only one case: when traffic demand is low and parking time is only 10 minutes. In all other cases, DDPS with a prebooking system causes lower delay in the system, and, in exchange, it offers much more delivery parking capacity for the DDPS users.

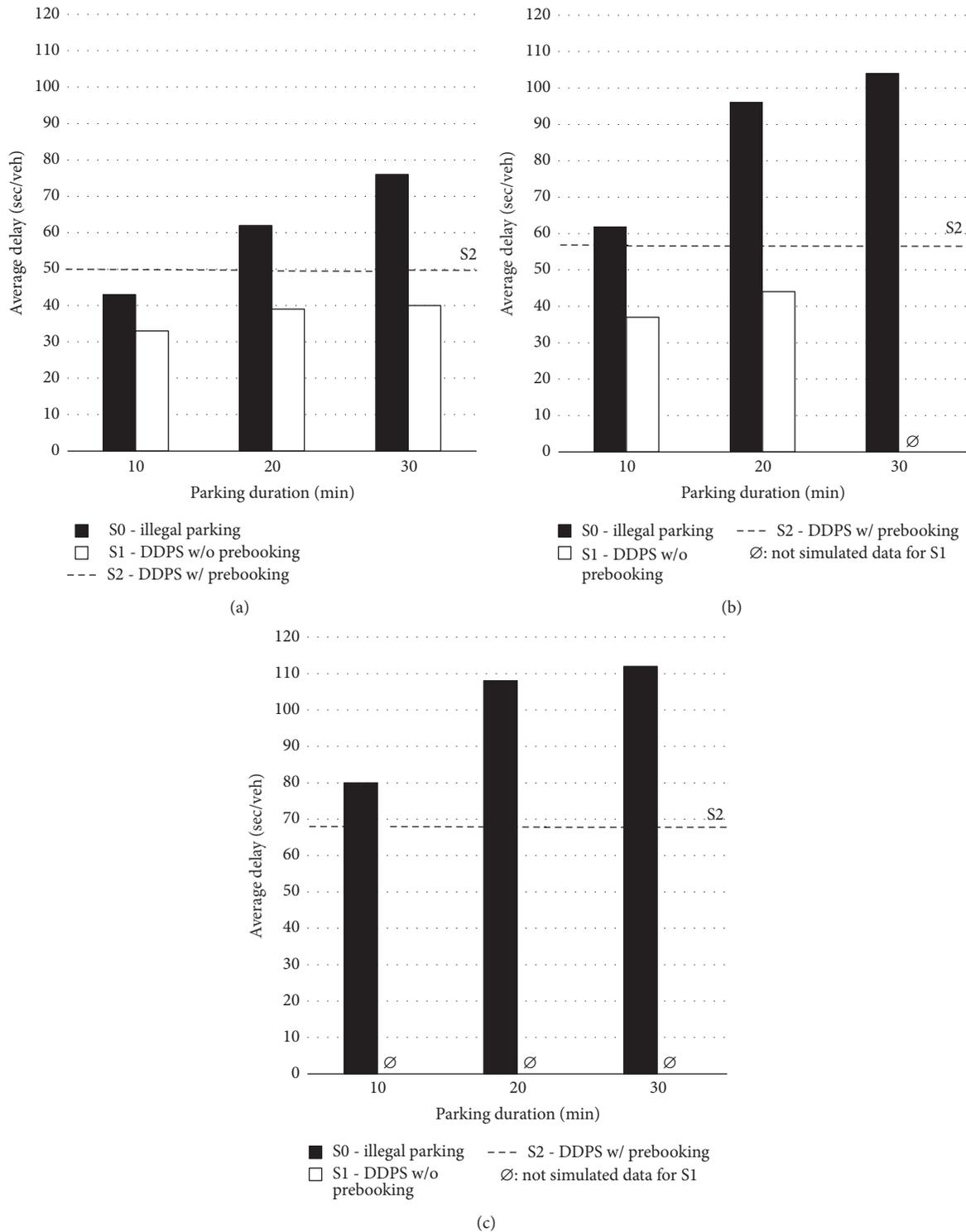


FIGURE 9: Average delay (sec/veh) in scenarios S0, S1, and S2 in case of traffic demand: (a) 988 veh/h; (b) 1090 veh/h; (c) 1190 veh/h.

6. Conclusions

In this paper we have introduced the concept of Dynamic Delivery Parking Spots (DDPS), a novel solution for loading and unloading operations in urban areas. DDPS are delivery

facilities located on the shoulder lane of a link that are activated dynamically, keeping the traffic delay to a minimum.

Current loading and unloading operations happen either in dedicated areas outside traffic lanes or, when these lanes are full or nonexistent, in curbside parking or illegally, as

in-lane parking. DDPS can be a solution to provide delivery operations, reducing the negative effects on traffic at the same time.

DDPS temporarily block the shoulder lane, creating traffic disruptions. However, within certain conditions, it is possible to keep these disruptions at the local level, that is, without generating network effects. Thanks to this, DDPS can make a more efficient use of the scarce urban space, that is, taking traffic lane capacity for loading/unloading activities when possible.

In this paper, we develop the detailed analytical formulations to quantify the traffic effects of DDPS and find the conditions required to keep the delay at the local level. Some simplifications are needed, but with this, clear guidelines on where and when to allow DDPS are provided.

Simulation experiments are carried out to validate the results of the formulation and to further show the applicability of the proposed concept in realistic scenarios. Moreover, we are able to compare the delay caused by the DDPS to the real situation, where there might be illegal delivery parking in the shoulder lane.

In summary, DDPS can be located on a link if, even with the blocked lane, the remaining capacity of the link plus the storage capacity of the blocked lane is able to cope with the traffic demand. If this criterion is met, then DDPS should be located at the center of the link, that is, far from intersections, and leaving some capacity of the blocked lane for traffic that will later merge or diverge to other lanes of the link. As shown with the simulation experiments, DDPS can reduce the vehicle delay compared to the case when delivery vehicles park illegally.

Future research steps could extend the analytical model to incorporate different assumptions. For example, the effects of turning vehicles or pedestrian crossings could be incorporated. Additionally, small lingering delays could also be accepted to allow DDPS. The accumulated delays can be quantified to allow a number of DDPS that minimize or limit the delay, given the number of cycles of the blockage.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was partially supported by ETH Research Grant ETH-40 14-1 and the Project CALog funded by the Hasler Foundation. The authors thank Dr. Qiao Ge for providing support with the simulation used in this manuscript.

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