Increasing the Flow Capacity of Signalized Intersections with Pre-signals: Theory and Case Study

by

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Abstract

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The dissertation proposes a new "tandem design" to reorganize traffic and increase the flow capacity of signalized intersections. In the tandem design, a mid-block pre-signal is used to sort left-turning vehicles (LVs) and through-moving vehicles (TVs) in tandem, rather than leaving them side by side, as in the conventional design. For intersections with separate through and left-turn phases, the tandem design outperforms the conventional one because more lanes can be used to discharge traffic during at least one of the intersection signal phases. We find that the tandem design can increase the intersection capacity by 10% to 20% in its simplest form. We also study the length requirement of blocks to fully realize the capacity benefit, and modifications of the tandem design to reduce this length requirement. We then conduct a case study at a signalized intersection in the city of Chengdu, China. The case study shows that the tandem design can effectively increase intersection capacity. Moreover, the case study shows that together with enforcement of the bus-lane restriction, both cars and buses can benefit.

Finally, we demonstrate how the idea of tandem sorting with pre-signals can be extended to increase intersection capacity of multimodal traffic, using as an example the case of cars and buses. This extension hinges on an assumption that the discharge times of different modes of transport is additive, and this assumption is confirmed with a natural experiment.

To Yan Yan,

more than words can describe.

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Chapter 1

Introduction

This dissertation focuses on the problem of increasing the flow capacity (i.e., the maximal vehicle flow that can be sustained) of signalized intersections, and discusses how to do this with a mid-block pre-signal to more efficiently use the given road space.

Increasing the capacity of the current infrastructure is an important problem. This is because travel demand has grown at a faster rate than what the current infrastructure can provide, resulting in increasing congestion. For example, it is reported that in 87 out of 101 metropolitan areas in the US the demand grew 10% faster than capacity between the years 1982 and 2009, and that the total cost of congestion has been on the rise: from $24 billion in 1982, to $85 billion in 2000, and to $115 billion in 2009 (all in 2009 dollars) (Texas Transportation Institute, 2010). The congestion delay that occurs on streets (as opposed to on freeways) accounts for about 40% of the total. The problem is even worse in numerous developing countries, which face rapid population growth, motorization, and increasing congestion. For example, urban traffic congestion frequently occupies the headlines in China and how to get rid of it has become a national topic that is heatedly discussed. Increasing the capacity of current infrastructure is also important because building new infrastructure is expensive, and minor modifications that may increase the capacity of the current infrastructure are likely to be the most cost effective.

In the dissertation, we seek the maximal capacity that can be achieved by a signalized intersection, and how to achieve this with a mid-block pre-signal. The pre-signal is a set of signal heads that are installed upstream of the intersection. With vehicles of different modes (e.g., car or bus) or different movements (left-turning or through-moving) segregated into different lanes, the pre-signal alternates giving green time to vehicles in different lanes, sorting them into select patterns that help increase the flow capacity of intersections. The focus of this dissertation is on the scale of a single signalized intersection. This is because an individual intersection is the basic building block of a street network, and we need to understand the building blocks before we can have a good understanding of the system.

Study on the network-wide level will be left for future work. Further, the dissertation deals with the maximal flow through a signalized intersection under oversaturated conditions, i.e., when demand exceeds capacity and any increase in capacity would greatly reduce delay.

Admittedly, capacity-increasing strategies need to be applied cautiously in a real transportation system. Simply increasing the capacity of an intersection may make things worse, due to Braess' Paradox (Braess, 1968; Braess *et al.* , 2005), or due to induced demand (Hansen & Huang, 1997; Litman, 2001). This dissertation only focuses on how to increase capacity, rather than on when and where to apply these strategies.

The rest of the dissertation is organized as follows. Chapter 2 presents an overview of the existing strategies to increase intersection capacity, and of mid-block pre-signals. Chapter 3 describes a proposed "tandem sorting" concept, achieved with a mid-block pre-signal. Chapter 4 analyzes the capacity increase and spatial requirement of the proposed tandem design. Chapter 5 discusses operational issues, including the operation of the pre-signal and the compliance of drivers. Chapter 6 presents a case study from a signalized intersection in the city of Chengdu, China, which demonstrates how the idea of tandem sorting with pre-signals can benefit both cars and buses. Chapter 7 demonstrates how the tandem sorting concept can be extended to multimodal traffic, and uses empirical evidence to validate an important assumption in the formulation of capacity. Chapter 8 provides a conclusion and directions for future work.

Chapter 2

Literature Review

2.1 Intersection Capacity

It is well understood that intersection capacity can be greatly restricted by the introduction of an extra signal phase[1] to serve left turns. To see why, imagine an intersection that prohibits left turns. Only two signal phases are needed to serve all traffic at this intersection: one phase for each of the two opposing directions. The entire width of each approach can be used during its green phase, so the discharge rate is as high as it can possibly be. However, separate protected left-turn phases are needed if there is a significant proportion of left-turning traffic (Newell, 1989). Note that each intersection approach now has its own through phase and left-turn phase, and lane markings segregate left-turning and through-moving vehicles on different lanes. As a result, only part of the approach width is used during each phase. The introduction of protected left-turn phases therefore means that intersection capacity is wasted.

The problem with left turns has been addressed by generic optimization methods devised to determine the duration of the signal phases (Webster, 1958; Allsop, 1972), which were later generalized to include the grouping of streams into phases (Improta & Cantarella, 1984; Gallivan & Heydecker, 1988; Silcock, 1997), and more recently to determine the number of lanes that should be made available to the streams (Wong & Wong, 2003). But still, only part of the approach width can be used during either the left-turn phase or the through phase. So, there is a limit to what signal timing optimization can do for capacity.

In reality, more capacity can be achieved by banning left turns, or rerouting traffic to eliminate them from the intersection vicinity. The jughandle intersections (in Figure 2.1(a)), the

[1]A signal phase is defined by the Manual on Uniform Traffic Control Devices (Federal Highway Administration, 2009) to be the right-of-way, yellow change, and red clearance intervals in a cycle that are assigned to an independent traffic movement or combination of traffic movements.

median U-turn intersections (in Figure 2.1(b)), and the super-street design (in Figure 2.1(c)) are just some examples of the rerouting designs that have been used for this purpose (University of Maryland ATTAP, 2006; Rodegerdts *et al.* , 2004). The rerouting strategies eliminate the need for extra signal phases by rerouting either the left turns or the side street traffic. The strategies can be beneficial if the traffic to be rerouted has low demand. However, for a major-major intersection with heavy left turns, the strategies would not be practicable. Another disadvantage is that most rerouting designs involve construction and require substantial space, which may not be available in an urban area.

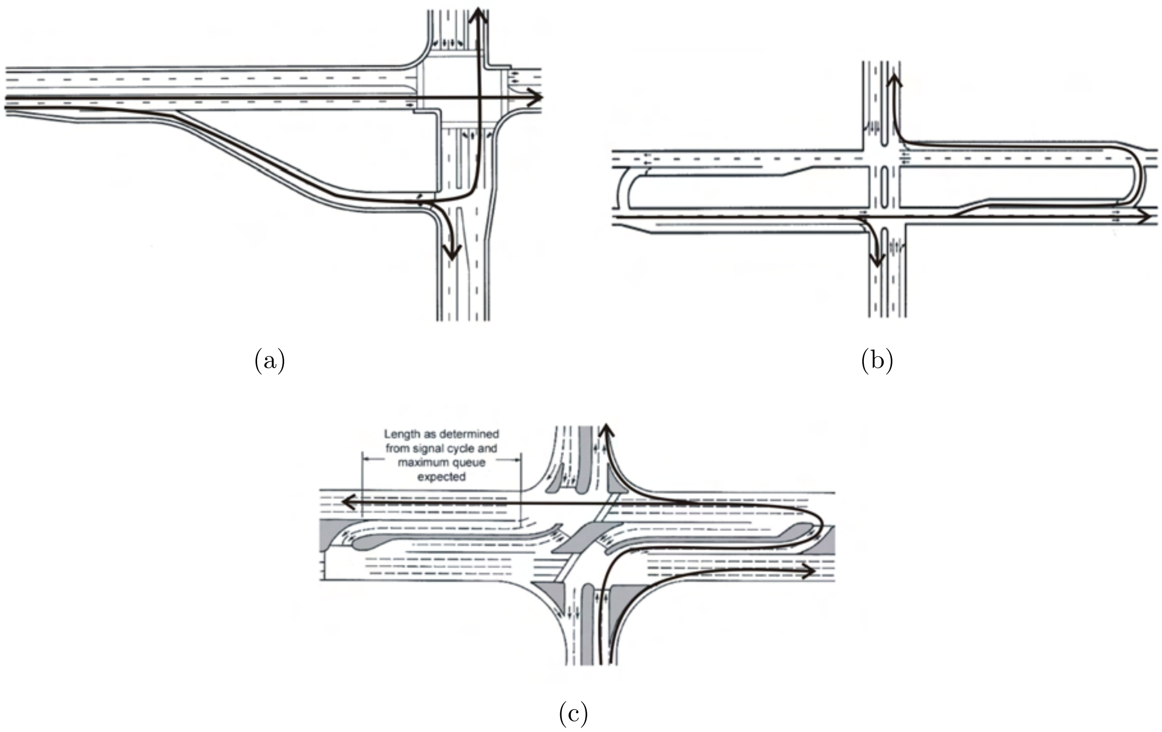


Figure 2.1. Unconventional intersection designs. (a) Jughandle intersection. (b) Median U-turn intersection. (c) Super-street.

2.2 Pre-signal

Mid-block pre-signals have been widely used to promote priority for buses (Oakes *et al.* , 1994; Wu & Hounsell, 1998; Sirivadidurage *et al.* , 2007) by generating gaps in car traffic and enabling these modes to bypass car queues at intersections. They have also been proposed in the case of bicycles (Kuijper, 1982; Heys & Vrefeveld, 1983; Salomons, 1985; Wheeler *et al.* , 1993; Wheeler, 1995), though the bicycle demand is usually too low to justify this (Wheeler, 1995).

Pre-signals have also been used in an unconventional geometric design, called a continuous flow intersection (CFI, as shown in Figure 2.2), to resolve the conflicts between the left-turning and opposing through-moving traffic at intersections (Al-Salman & Salter, 1974; Goldblatt *et al.* , 1994). With pre-signals, the left-turning traffic swaps position laterally with its opposing through-moving traffic. As a result, there is no conflict between any two streams on the two opposing approaches, and only one signal phase is needed to serve them. However, CFI has several setbacks: (a) to convert a conventional intersection into a CFI, permanent re-striping (which cannot change with the time of day) is needed; (b) when deployed on a four-way intersection, CFI has to involve at least two (opposing) approaches; (c) bus stops cannot be located on the far side of a CFI; (d) pedestrians must be negatively affected for CFI to achieve its full benefit; (e) numerous pavement markings are needed to channel traffic, which can be confusing to drivers.

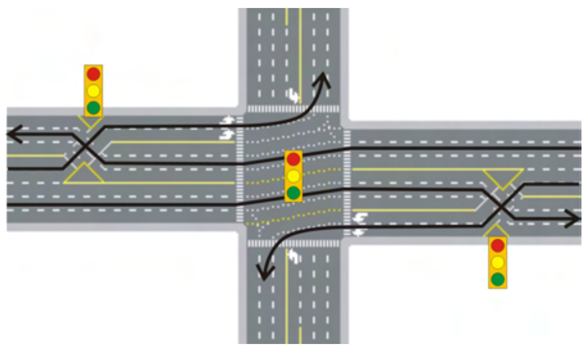


Figure 2.2. Continuous flow intersection design.

The above shows that no good solutions currently exist to increase the capacity of a major-major intersection with heavy left turn traffic and constrained road space. The possible solutions are to use CFI, whose setbacks have been discussed, or to convert the intersection into a grade-separated intersection, which requires space, and expensive, irreversible construction. However, there is an inexpensive space-efficient way to increase intersection capacity, which will be presented next.

Chapter 3

Concept

It is assumed that the intersections to be improved serve left-turning vehicles (LVs) and through-moving vehicles (TVs) with separate phases. The problem with this type of intersection is that during either the through phase or the left-turn phase, only some of the lanes on an approach can discharge. For example, the conventional layout as shown in Figure 3.1 has three lanes in total. However, only part of the approach width can be used to discharge traffic during the green time: only one lane for LVs during the left-turn phase, and only two lanes for TVs during the through phase. This is why the conventional design is inefficient.

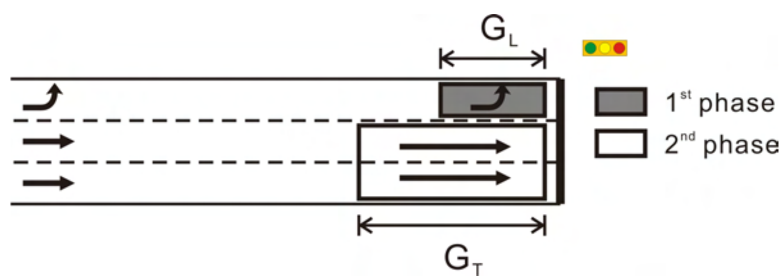
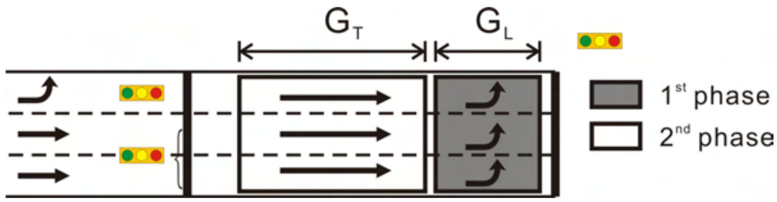


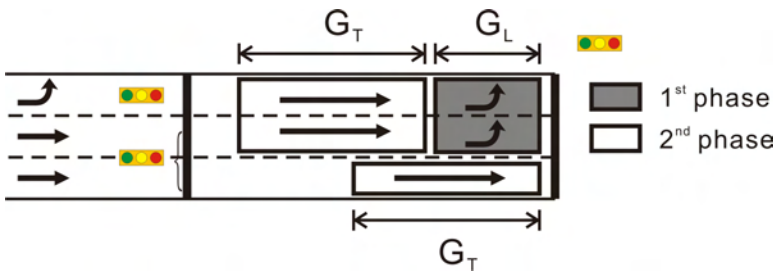
Figure 3.1. Typical geometric layout of a conventional intersection approach. Note that the LV queue (gray rectangle) and the TV queue (white rectangle) are typically segregated side by side. The rectangles represent the physical location of the queues.

Greater capacity could be achieved if all three lanes could discharge during both phases. This potential capacity increase can be realized with the help of a pre-signal (as illustrated in Figure 3.2(a)). The operation of a pre-signal design is described next, focusing on only one intersection approach and assuming that the same can be done to other approaches.

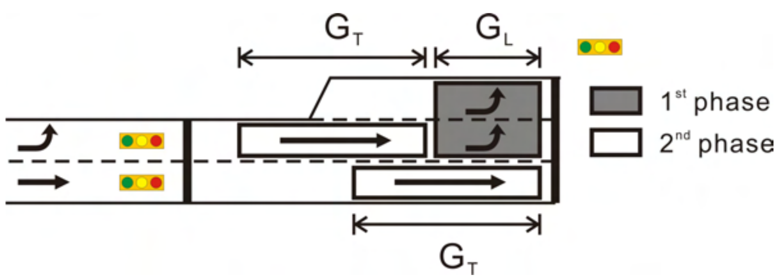
Refer to Figure 3.2(a). To fully use all lanes, vehicles are first presorted by movement (i.e.,



(a)



(b)



(c)

Figure 3.2. Geometric layout of an intersection approach with tandem sorting. (a) Full tandem with 3 tandem lanes. (b) Partial tandem with 2 tandem lanes. (c) Partial tandem with left turn pocket and 1 tandem lane. The LV queue (gray rectangle) and the TV queue (white rectangle) are segregated in tandem over some or all lanes. The rectangles represent the physical location of the queues.

left-turning or through-moving[1]) immediately upstream of the pre-signal. Vehicles presort themselves at the pre-signal stop line just as they do when they approach conventional intersection stop lines. Roadside signs are needed upstream of the pre-signal to provide warning and give drivers enough time to maneuver to their designated lane. The pre-signal then alternates the allocation of green times to LVs and TVs. The vehicles, after passing through the pre-signal, follow a different lane designation on the section of road between the pre-signal and the intersection signal. This section of road is termed the “sorting area”. In the example illustrated in Figure 3.2(a), LVs receive green time at the pre-signal and enter the sorting area first, followed by TVs. After they pass the pre-signal, both vehicle types use all lanes to queue up. The two queues are segregated in tandem, giving rise to the name “tandem sorting”. This tandem design is different from the conventional design, where the LV queue and the TV queue are segregated side by side. Note that with the tandem design, LVs and TVs discharge into the intersection during their designated signal phases using all lanes on the approach.

It should be obvious that the benefit of the tandem design comes from the fact that more lanes are used to discharge traffic during both phases, which is not possible in the conventional design. Note that a lane with LVs and TVs sorted in tandem is different from a conventional shared lane with LVs and TVs in random order. To distinguish the two situations, the former will be called a “tandem lane”, and latter will be called a “shared lane”. In Figure 3.2(a), LVs and TVs are sorted in tandem over all three lanes. Therefore, there are three tandem lanes, and this kind of tandem sorting with all lanes as tandem lanes is termed “full tandem”. If vehicles behave deterministically, it can be shown that sorting vehicles in a full tandem fashion can achieve the same capacity as if there are no left turns. It can also be shown that the resulting capacity is the maximal rate that can be achieved with an at-grade intersection.

In reality, however, a full tandem design may not always be feasible. The number of tandem lanes will depend on the intersection geometry. For example, if there are only two lanes downstream for LVs, then a partial tandem design with two tandem lanes as shown in Figure 3.2(b) should be considered. Or, if there are only two lanes downstream for both LVs and TVs, a partial tandem design with one tandem lane as shown in Figure 3.2(c) should be considered. The figure shows that the tandem concept can be quite flexible and tailored for specific sites. Since the full tandem design is just a special case of the partial tandem (with the number of tandem lanes equal the total number of lanes of the approach), the word “partial” shall be dropped. The number of tandem lanes is treated as a parameter, and is determined by various factors like the existing geometry and the target capacity.

[1]Right-turning vehicles are combined with through-moving vehicles for the rest of the study, as they can generally discharge together. Thus, TVs refer to the combination of through-moving and right-turning vehicles.

Chapter 4

Analysis

The proposed tandem design is analyzed in detail in this chapter. The questions to be addressed include how much capacity can be increased under the proposed concept (Section 4.2), and how much space is needed to achieve this gain (Section 4.3).

4.1 Assumptions and Notations

We focus on only one approach of a four-way signalized intersection. For demonstration purposes, the intersection signal is assumed to be pre-timed. The end of Section 4.2.1 discusses the relaxation of this assumption. It is also assumed that the intersection signal has two separate green phases for the approach: a protected left-turn phase and a through phase. The order of the green phases does not matter, so the left-turn phase can be either leading or lagging. The assumption that the approach only has two green phases will be relaxed in Chapter 6. Additional assumptions as stated before are that LVs and TVs are presorted by movement at the pre-signal and that there is no shared lane for LVs and TVs at the pre-signal. Section 5.3 discusses the relaxation of this last assumption.

A special unit system is adopted for this study to simplify notation. In this unit system, one unit of time equals the cycle length of the intersection signal, and one unit of vehicle flow equals the saturation flow per lane. In a conventional unit system, flow is represented by the product of the saturation flow per lane, the green duration, and the number of lanes. Therefore, in the dimensionless unit system, dimensionless flow can be represented by the product of dimensionless green time (or green ratio, the ratio of the green time and the cycle length) and the number of lanes available to discharging vehicles. Now that all the variables in this study are dimensionless, the word "dimensionless" will be omitted unless a distinction needs to be made between the conventional unit system and this new unit system.

The following notation is defined for the analysis of the flow capacity. Letters g, n, and q are used to denote duration of green time, number of lanes, and flow capacity, respectively. Lower case letters g, n are for those variables at the pre-signal, and capitalized letters G, N are for those at the intersection signal. The subscripts "L" and "T" denotes left-turning or through-moving; no subscript indicates the "total" of both movements combined. The superscript "0" denotes the status quo or a conventional design; no superscript indicates the tandem design.

4.2 Capacity Analysis

The flow capacity related to a tandem design is discussed here. Although delay is more intuitive to drivers (and will be briefly discussed in Section 4.4), capacity is the critical metric under oversaturated conditions. In Section 4.2.1, it is assumed that drivers follow the traffic rules and behave deterministically, i.e., the saturation headway between vehicles is assumed constant. Determinism simplifies formulation but provides an optimistic assessment of the tandem design. This assumption is then relaxed in Section 4.2.2 and the saturation headway between vehicles is allowed to vary.

The benchmark for comparison in both the deterministic and stochastic analyses is the capacity of a conventional pre-timed design, with two green phases (left-turn and through) for the approach, and with traffic served in side-by-side manner. Although in reality, vehicle-actuated signal control is often used instead of pre-timed control, the former can only reduce delay on undersaturated approaches (Greenough & Kelman, 1999; Peck *et al.* , 1999; Sussman, 2000) by dynamically assigning green time to accommodate cyclic fluctuations. Vehicle-actuated signals can do little to increase the capacity of an approach (Newell, 1989; Lo & Chow, 2004). So, using a pre-timed design for a benchmark is justified.

4.2.1 Deterministic capacity analysis

In this section, capacity formulae are derived for both the conventional design and the tandem design, assuming that the saturation headway is a constant. The following parameters are given: the total green time available to the approach (G), the total number of lanes (n at the pre-signal and N at the intersection signal), and the left-turn ratio (l). The decision variables are the signal timing (G_L^0, G_T^0 at the intersection signal for the conventional design; g_L, g_T at the pre-signal and G_L, G_T at the intersection signal for the tandem design) and lane designations (N_L^0, N_T^0 at the intersection signal for the conventional design; n_L, n_T at the pre-signal and N_L, N_T at the intersection signal for the tandem design).

The capacity for the status quo, where LVs and TVs are segregated side by side, can be formulated as the following mathematical programming (MP), and will be called the conventional MP (CMP)

$$(CMP) \quad \max_{G_L^0, G_T^0, N_L^0, N_T^0} q^0 \tag{4.1a}$$

$$q_L^0 = q^0 l, \; q_T^0 = q^0(1-l), \tag{4.1b}$$

$$q_L^0 = G_L^0 N_L^0, \; q_T^0 = G_T^0 N_T^0, \tag{4.1c}$$

$$G_L^0 + G_T^0 \le G, \tag{4.1d}$$

$$N_L^0 + N_T^0 \le N, \tag{4.1e}$$

$$G_L^0, G_T^0, N_L^0, N_T^0 \ge 0; N_L^0, N_T^0 \text{ are integers.} \tag{4.1f}$$

Equation 4.1a indicates that the goal of optimization is to maximize capacity; Equation 4.1b splits the total capacity for LVs and TVs according to the left-turn ratio, which is defined as the ratio of vehicles that turns left; Equation 4.1c defines the achieved flow in our dimensionless unit system; Equations 4.1d and 4.1e define bounds on the decision variables (total green ratio G and total number of lanes N at the intersection signal); Equation 4.1f states the non-negativity and integer constraints.

If the vehicles are sorted in tandem over N_{TL} lanes, the capacity formulation shall be called the tandem MP (TMP), which is as follows:

$$(TMP) \quad \max_{G_L, G_T, g_L, g_T, N_L, N_T, n_L, n_T} q \tag{4.2a}$$

$$q_L = ql, \; q_T = q(1-l), \tag{4.2b}$$

$$q_L = G_L N_L = g_L n_L, \; q_T = G_T N_T = g_T n_T, \tag{4.2c}$$

$$G_L + G_T \le G, \; g_L + g_T \le 1, \tag{4.2d}$$

$$N_L + N_T \le N + N_{TL}, \; n_L + n_T \le n, \tag{4.2e}$$

$$G_L, G_T, g_L, g_T \ge 0; 0 \le N_L, N_T \le N, 0 \le n_L, n_T \le n; N_L, N_T, n_L, n_T \text{ are integers.} \tag{4.2f}$$

The role of the above equations is similar to those in CMP, except that Equation 4.2c stipulates flow conservation at the pre-signal and the intersection signal; and Equations 4.2d and 4.2e have extra constraints due to the introduction of the pre-signal.

It may look like the capacity of the TMP is lower than that of the CMP due to the extra constraints. However, there are two reasons why this is not the case. The first reason is that the extra constraints due to the pre-signal in Equations 4.2d and 4.2e are generally not binding when G is around 0.5. The physical explanation for this is that the intersection signal only has about half the cycle to discharge traffic, while the pre-signal has the whole cycle to discharge the same amount of traffic, and thus is generally not the active bottleneck. The second reason is that a binding constraint, Equation 4.1e, of the CMP is relaxed in the TMP, via Equation 4.2e. The bound, N, on the sum of N_L and N_T in Equation 4.1e is increased to $N + N_{TL}$ in Equation 4.2e. This allows the capacity to be greatly increased.

The physical explanation is that due to the pre-signal and tandem sorting, the number of lanes actively discharging the two streams (N_L and/or N_T) increases. This is the direct reason for the capacity increase.

The two MPs we have just defined are nonlinear integer programs. Fortunately, they are not hard to solve. If the integer decision variables regarding lane designations ($N_L^0, N_T^0, n_L, n_T, N_L, N_T$) are taken as given, the MPs turn out to be linear programs (LPs), which can actually be solved analytically. Furthermore, typical values of n and N generally only allow for a few possible lane designations. The solutions to the MPs thus can be obtained by enumerating and evaluating the analytic solutions of all possible lane configurations.

To identify the domain of application, the CMP and the TMP are solved for a few typical geometric layouts shown in Figure 4.1. This collection of approach geometries is not exhaustive, but includes the most common geometric layouts. Figure 4.2 shows the capacity increase for these geometric layouts. The shading indicates the ratio of the capacity of the tandem design over the capacity of the conventional design.

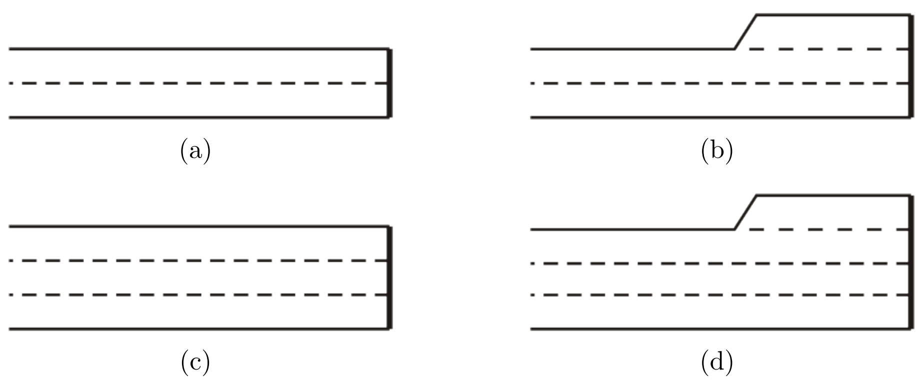
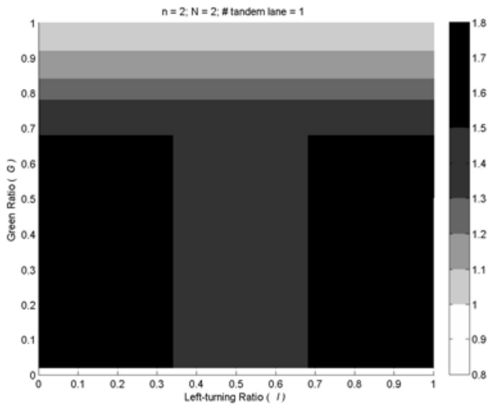


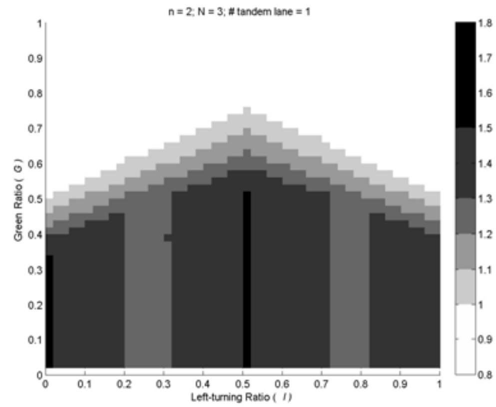
Figure 4.1. Typical geometric layouts of intersection approaches. (a) $n = N = 2$. (b) $n = 2, N = 3$. (c) $n = N = 3$. (d) $n = 3, N = 4$.

The figure shows that the tandem design can increase intersection capacity for all possible values of the green ratio and the left-turn ratio, if the intersection approach does not have a left-turn bay ($n = N$). For the rest of the cases, capacity can still be increased significantly, by about 20% to 30% for the most common values of green ratio ($G \approx 0.5$). Note that in all cases only one tandem lane is used, which can provide the least improvement. Higher capacities can be achieved by a tandem design with more tandem lanes.

For the analysis, it is implicitly assumed that vehicles will distribute themselves evenly across the lanes available to them. This assumption is normally reasonable, if the objective of drivers is to get through the intersection as quickly as possible, i.e., they will move forward as much as possible. However, this may not always be the case in reality, if drivers anticipate their next movement. For example, imagine there are two lanes for TVs at the current intersection, and the majority of the TVs want to turn left at the next intersection. In this



(a)



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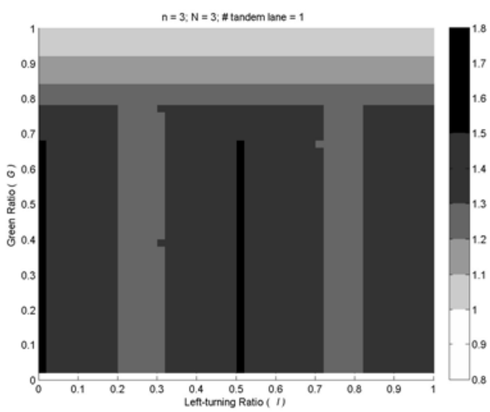

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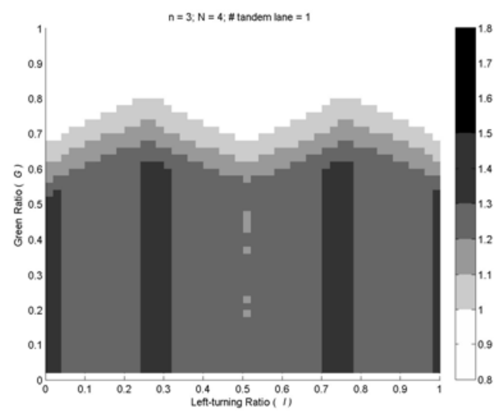


(d)

Figure 4.2. Capacity increase with deterministic saturation headways, for the typical layouts in Figure 4.1. The shading shows the ratio of the capacity of the tandem design over the capacity of the conventional design. (a) $n = N = 2$ as in Figure 4.1(a), with one tandem lane. (b) $n = 2, N = 3$ as in Figure 4.1(b), with one tandem lane. (c) $n = N = 3$ as in Figure 4.1(c), with one tandem lane. (d) $n = 3, N = 4$ as in Figure 4.1(d), with one tandem lane.

case, TVs at the current intersection may not distribute themselves evenly across both lanes; the through lane on the left may be more crowded than the through lane on the right. The analysis of these situations involves assumptions of driver behavior, which is challenging to characterize. Therefore, we will stick to the assumption that vehicles are evenly distributed across the lanes available to them, with the understanding that there can be complications to this assumption in reality.

We have also assumed that the intersection signal is pre-timed. This does not have to be the case. The assumption is made only because in each cycle the durations of the pre-signal phases are decided by the durations of the intersection signal phases. But the pre-signal can also be operated if the intersection signal is adaptive, as long as the durations of the intersection signal phases are determined at least one cycle ahead of their execution time.

4.2.2 Stochastic capacity analysis

The analysis above shows why tandem sorting is superior, but the analysis is optimistic in that it assumes that the saturation headway is deterministic. In reality, the number of vehicles discharged in a given green time is not a constant number, even under saturation flow. Rather, the number is stochastic, dependent on driver behavior. This means that if, for example, some LVs fail to be discharged during the left-turn phase with the tandem design in Figure 3.2(a), they will have to wait in the sorting area until the left-turn phase of the next cycle. As a result, the lane occupied by these residual LVs is temporarily blocked, and TVs can only be discharged using the other lanes during the through phase. Similarly, TVs can block LVs as well. Therefore, the existence of a residual queue due to stochastic saturation headways can reduce capacity.

To mitigate the effect of these residual queues, one possible solution is to reduce the number of LVs and TVs into the sorting area each cycle, by reducing the green duration at the pre-signal, but not at the intersection. The reduction needs to be properly chosen: too large a reduction results in capacity loss when there is no residual queue; too small a reduction results in frequent residual queues and capacity loss. The choice of the number of LVs and TVs is the result of this tradeoff.

We argue that residual queues can be detected almost immediately with loop detectors located right upstream of the intersection stop line, or with a video camera. For example, during the through phase, stopped vehicles over the loop detectors in the tandem lanes must be residual LVs. The residual TVs can be detected similarly. Once a residual queue is detected, we would adopt an alternative signal timing plan at the pre-signal, with shorter green periods to avoid overcrowding in the sorting area. The normal pre-signal timing plan would only be restored after the residual queues have vanished.

If we also assume that drivers do not change lanes in the sorting area, lanes can be treated independently for the purpose of analyzing flow. This means we can analyze the capacity of a single tandem lane and scale it properly for the intersection capacity. To facilitate discussion, we temporarily switch to the conventional unit system from the dimensionless one, i.e., the green time and flow capacity are no longer dimensionless. We use a prime to indicate green time and flow capacity in the conventional unit system. Let us assume that H_i is the saturation headway of the i^{th} vehicle. The H_i's are independently and normally distributed with mean H and variance $(\gamma' H)^2$. The parameter γ' is the coefficient of variation of H_i. We also assume that the duration of the left-turn phase or the through phase at the intersection signal is

$$G'_X = m_X H \text{ (with } X \text{ being either } L \text{ or } T\text{)}, \tag{4.3}$$

which allows m_X vehicles to be discharged in the deterministic case. If there are m^s_X vehicles to be discharged (the superscript 's' stands for stochastic), the probability that a residual queue occurs can be formulated by the following expression:

$$p_X = \Pr\left\{\sum_{i=1}^{m^s_X} H_i \geq m_X H\right\} \approx \Phi\left(-\frac{m_X - m^s_X}{\sqrt{m^s_X}\gamma'}\right). \tag{4.4}$$

where $\Phi(.)$ is the cumulative distribution function of the standard normal distribution. The saturation headways H_i's are independently and identically distributed, thus the sum of the H_i's is approximately normally distributed by virtue of the central limit theorem.

We define two new dimensionless parameters k_L and k_T to be the decision variables, where k_X (X being either L or T) is the number of standard deviations between m_X and m^s_X.

$$k_X \triangleq (m_X - m^s_X)/(\sqrt{m^s_X}\gamma'). \tag{4.5}$$

If we assume that m_X is given, both p_X and m^s_X can be expressed in terms of k_X:

$$p_X = \Phi(-k_X), \tag{4.6a}$$

$$m^s_X = m_X - \frac{k_X\gamma'}{2}\left(\sqrt{(k_X\gamma')^2 + 4m_X} - k_X\gamma'\right) \approx m_X\left(1 - \frac{k_X\gamma'}{\sqrt{m_X}}\right). \tag{4.6b}$$

The approximation in Equation 4.6b is good because for common values of the parameters (e.g., $k_X = 3, \gamma' = 0.2, m_X = 5$), $4m_X \gg (k_X\gamma')^2$.

Every time a residual queue occurs, a whole cycle is wasted on that blocked lane. For example, if a tandem lane is blocked by the residual LVs, no TV can discharge on the lane during the through phase and the residual LVs clear only during the left-turn phase of the next cycle, resulting in a waste of a whole cycle. The same is true if the residual queue is composed only of TVs. If both LVs and TVs fail to be discharged during their green phases, two cycles will be wasted, i.e., it would take three cycles to discharge the same amount of LVs and TVs that would otherwise take just one cycle if there were no residual queue. Therefore, it takes $1 + p_L + p_T$ cycles on average to discharge m_L^s LVs and m_T^s TVs on a tandem lane.[1]

The new capacity accounting for stochastic saturation headways can now be expressed as follows.

$$
\begin{aligned}
q^{s\prime} &= \frac{N_L m_L^s + N_T m_T^s}{C(1 + p_L + p_T)} \\
&= \frac{N_L m_L(1 - k_L\gamma'/\sqrt{m_L}) + N_T m_T(1 - k_T\gamma'/\sqrt{m_T})}{C(1 + \Phi(-k_L) + \Phi(-k_T))} \\
&= \frac{N_L G_L'/H(1 - k_L\gamma'/\sqrt{G_L'/H}) + N_T G_T'/H(1 - k_T\gamma'/\sqrt{G_T'/H})}{C(1 + \Phi(-k_L) + \Phi(-k_T))}.
\end{aligned}
\tag{4.7}
$$

The coefficients $1 - k_X\gamma'/\sqrt{G_X'/H}$ in the numerator are the ratio of the reduction in batch size, m_X^s/m_X. The coefficient $1 + \Phi(-k_L) + \Phi(-k_T)$ in the denominator accounts for the lost cycles due to residual queues.

Recall that all the variables in Equation 4.7 are in the conventional unit system. To make the capacity comparable to the dimensionless ones in Section 4.2.1, we reorganize Equation 4.7 with dimensionless variables. This is done by replacing G_X' and $q^{s\prime}$ with $G_X C$ and q^s/H, respectively to obtain:

$$
q^s = \frac{N_L G_L(1 - k_L\gamma'\sqrt{H/C}/\sqrt{G_L}) + N_T G_T(1 - k_T\gamma'\sqrt{H/C}/\sqrt{G_T})}{1 + \Phi(-k_L) + \Phi(-k_T)}. \tag{4.8}
$$

Furthermore, if we define $\gamma = \gamma'\sqrt{H/C}$ to be the counterpart of γ' in the dimensionless unit system, then

$$
q^s = \frac{N_L G_L(1 - k_L\gamma/\sqrt{G_L}) + N_T G_T(1 - k_T\gamma/\sqrt{G_T})}{1 + \Phi(-k_L) + \Phi(-k_T)}. \tag{4.9}
$$

As the objective function, Equation 4.9 is to be maximized with respect to k_L and k_T. This objective function is very complicated. Fortunately, we observe that the objective function is insensitive to the values of k_L and k_T around the optimum.

Figure 4.3 illustrates the ratio of the capacity in the stochastic situation, q^s, over that under the deterministic situation, q. We see that the ratio varies little around the optimum. Furthermore, the optimal values of k_L and k_T do not change much with respect to the parameters. For example, given $H = 2.5$ seconds, $G = 0.5$, $\gamma' = 0.2$, with C ranging from 30 seconds to 180 seconds, and l ranging from 0.1 to 0.9, the optimal k_L and k_T always fall within the range from 1.5 to 2.5. If we just choose $k_L = k_T = 2$, the resulting q^s is always larger than 99% of the optimal q^s. Therefore, instead of maximizing Equation 4.9 with respect to k_L and k_T using complicated algorithms, we will just choose $k_L = k_T = 2$.

[1] The probability of one cycle is $(1 - p_L)(1 - p_T)$, that of two cycles is $p_L(1 - p_T) + (1 - p_L)p_T$, and that of three cycles is $p_L p_T$. Therefore, $1 + p_L + p_T$ cycles are needed on average.

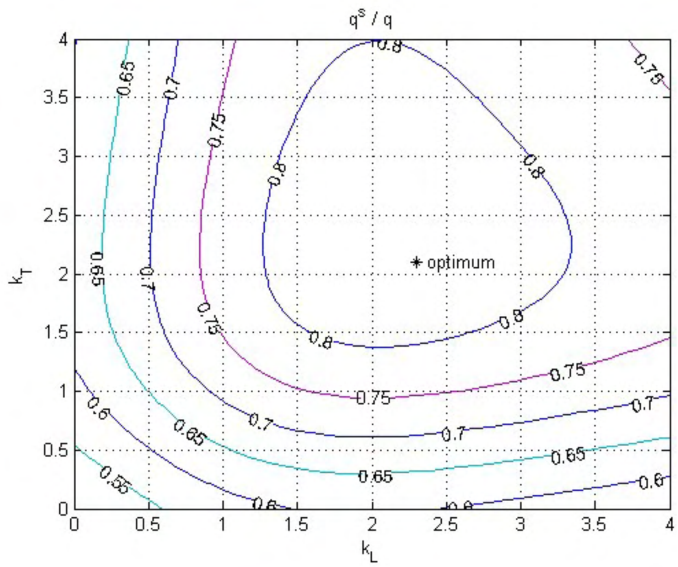


Figure 4.3. Capacity loss due to stochastic saturation headways. The contours show the ratio of the capacity under the stochastic situation (q^s) over that under the deterministic situation (q). The following parameters are used: $G = 0.5$, $\gamma' = 0.2$, $H = 2.5$ seconds, $C = 90$ seconds, and $l = 0.3$. Note that the ratio is very insensitive to the decision variables (k_L and k_T) around the optimum.

To make the story complete, the decision variables k_L and k_T need to be translated into signal timing. Given that we know how to solve the TMP, and that the signal timing at the intersection signal does not change, we only need to reduce the duration of the pre-signal green phases from g_X to g_X^s, defined as follows:

$$g_X^s = g_X(1 - k_X\gamma/\sqrt{G_X}). \tag{4.10}$$

With this complication, the capacity achieved is lower than that predicted by the TMP, but still higher than the CMP for most situations. We can see this by comparing the capacity with stochastic saturation headways, q^s, with the capacity of the status quo, q^0. Figure 4.4 shows the same batch of figures as in Figure 4.2, accounting for stochastic saturation headways and assuming $C/H = 48$. For the most common values of G (around 0.5), there is a capacity increase of at least 10% compared with the status quo. This is realized with just one tandem lane. If the capacity increase is not sufficient, more tandem lanes can be used. Figure 4.5 shows the results of the capacity increase with more than one tandem lane, still with $C/H = 48$ and accounting for the effect of stochastic saturation headways. A capacity increase on the scale of at least 20%-30% can be expected.

In reality, the traffic may comprise a mixture of vehicle classes, including cars, SUVs, and trucks, whose operation characteristics like acceleration and deceleration could be different.

In this situation, H will represent the average headway, and the value of γ will be larger to represent the heterogeneity of the traffic.

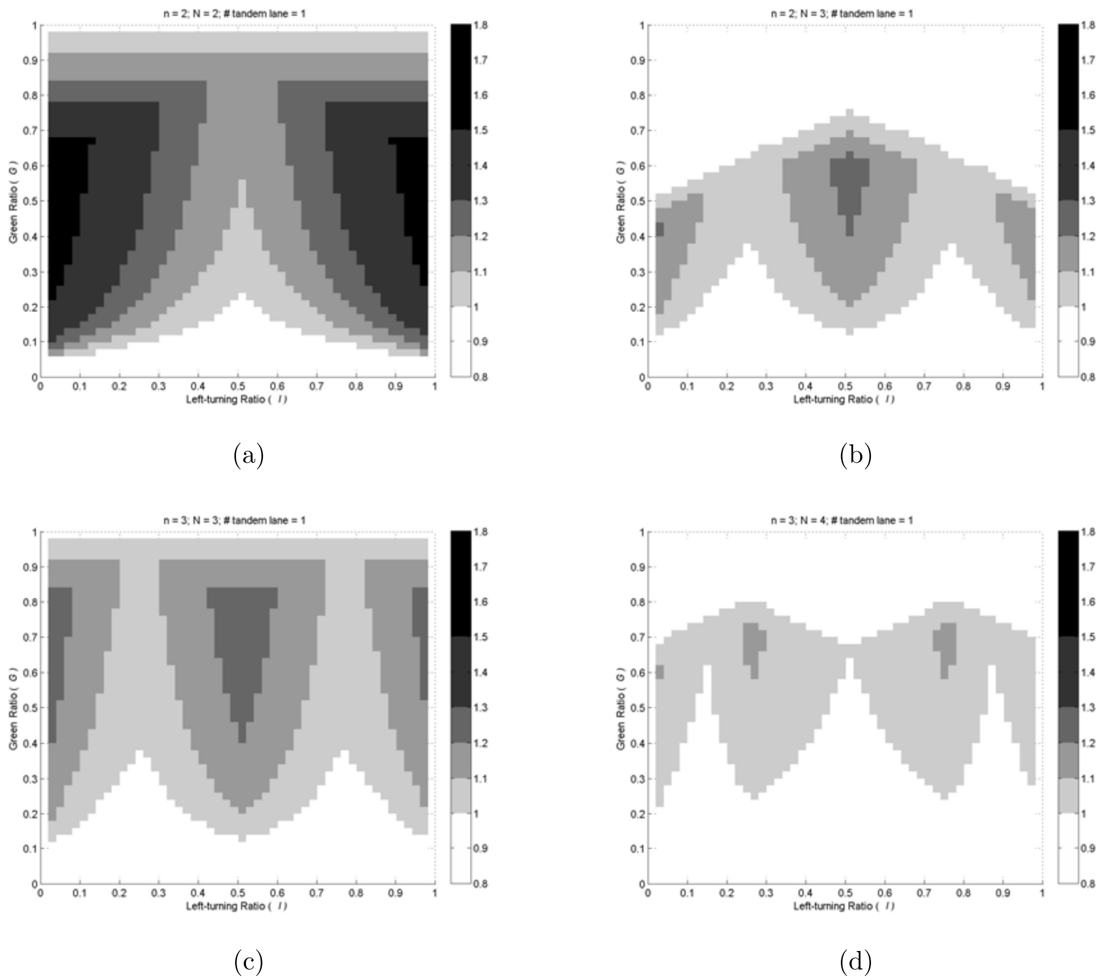


Figure 4.4. Capacity increase with stochastic saturation headways, for the typical layouts in Figure 4.1 and $C/H = 48$. The shading shows the ratio of the capacity of the tandem design over the capacity of the conventional design. (a) $n = N = 2$, with one tandem lane. (b) $n = 2, N = 3$, with one tandem lane. (c) $n = N = 3$, with one tandem lane. (d) $n = 3, N = 4$, with one tandem lane.

4.3 Spatial Analysis

So far, we have assumed that the street block containing the approach is long enough to accommodate the sorting area between the intersection signal and the pre-signal. The assumption simplifies our analysis because then the two bottlenecks (one at the intersection signal and the other at the pre-signal) are independent and do not interact with each other.

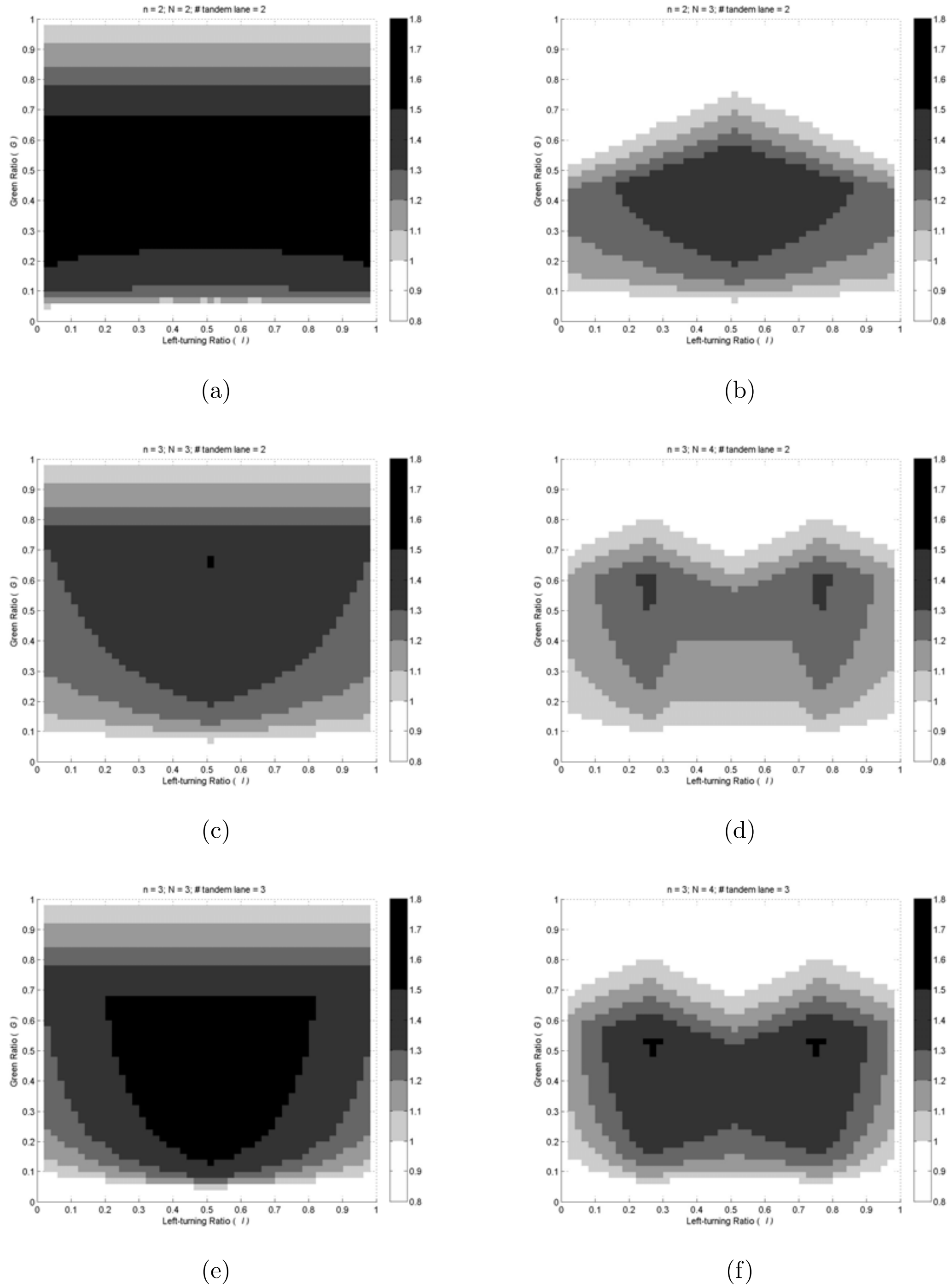


Figure 4.5. Capacity increase with stochastic saturation headways and more than one tandem lane, for the typical layouts in Figure 4.1 and $C/H = 48$. The shading shows the ratio of the capacity of the tandem design over the capacity of the conventional design. (a) $n = N = 2$, with two tandem lanes. (b) $n = 2, N = 3$, with two tandem lanes. (c) $n = N = 3$, with two tandem lanes. (d) $n = 3, N = 4$, with two tandem lanes. (e) $n = N = 3$, with three tandem lanes. (f) $n = 3, N = 4$, with three tandem lanes.

In this section, we specify the minimal length requirement of the sorting area so that the capacity analysis performed this far is applicable. We also discuss the impact that insufficient length has on capacity and modifications of the timing strategy that reduce this length requirement.

4.3.1 Minimal length requirement

The sorting area needs to be long enough to hold all the vehicles to be discharged from a tandem lane in a cycle at jam density. To see this, we show in Figure 4.6 how the traffic states evolve in space for a full tandem design with $n = N = 2$ and saturated demand. Traffic states are shown on the fundamental diagram in Figure 4.6(a), with S and J indicating saturation state (with the highest possible flow) and jammed state (with the highest possible density) respectively. The subscript 1 or 2 indicates the number of lanes involved for the traffic states. For example, S_1 means vehicles discharge with saturation flow on one lane, and J_2 means vehicles are queued with jam density over two lanes. The states A_L and A_T are for the arriving LVs and TVs. The time-space diagrams in Figures 4.6(b) and 4.6(c) illustrate how the LV and TV traffic evolve in space if the demand is just saturated. Note that in the sorting area (i.e., between the two horizontal dashed lines marking the locations of the pre-signal and the intersection signal), both LVs and TVs arrive in one lane, spread themselves over the two lanes and form queues. TVs queue behind the LVs using both lanes, and the two streams are discharged in their corresponding intersection signal phases. Although it is assumed here that the intersection signal has a leading left-turn phase, the process is similar for a lagging left-turn phase. Also note that the maximal queue length within the sorting area (assuming the sorting area is long enough) is the queue length of all LVs and TVs to be discharged from a tandem lane at jam density.

If we define K_j to be the jam density per lane, the minimal length of the sorting area can be formulated as

$$D_1 = D_{1L} + D_{1T}. \tag{4.11}$$

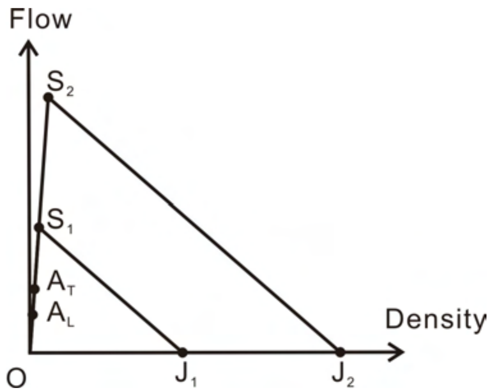
The queue length of LVs in the sorting area, D_{1L}, and that for TVs, D_{1T}, are shown in Figures 4.6(b) and 4.6(c). Their expression can be derived as follows from Equations 4.3, 4.7, 4.8, and 4.9:

$$D_{1X} = m_X^s / K_j, \tag{4.12}$$

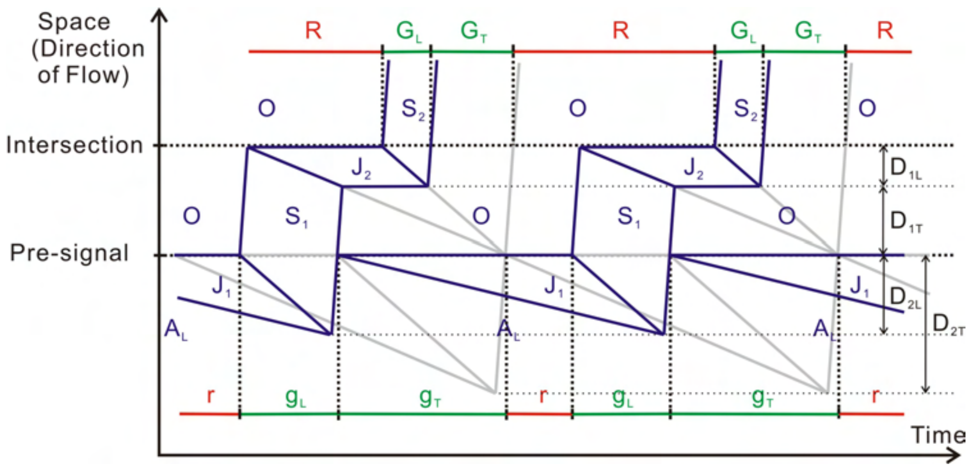
$$m_X^s = G_X (C/H)(1 - k_X \gamma / \sqrt{G_X}). \tag{4.13}$$

with X being either L or T.

Besides the length of the sorting area, we might also be interested in the minimal distance between the pre-signal and the nearest upstream intersection, to determine whether the tandem design can fit into a street block. This minimal distance, D_2, can be expressed as



(a)



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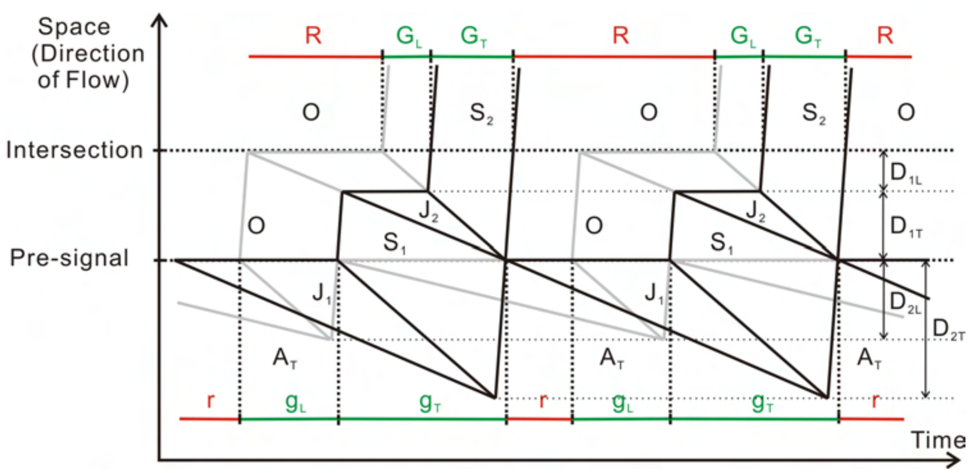


(c)

Figure 4.6. Evolution of traffic states in time and space for a tandem design with $n = N = 2$ under saturated demand. (a) Triangular fundamental diagram with different traffic states. (b) Time-space diagram of the LVs (with that for TVs in light gray color). (c) Time-space diagram of the TVs (with that for LVs in light gray color).

follows:

$$D_2 = \max\{D_{2L}, D_{2T}\}, \tag{4.14}$$

where D_{2L} is the maximal queue length of LVs upstream of the pre-signal, and D_{2T} is the maximal queue length of TVs upstream of the pre-signal when both input flows are at saturation. For uniform arrivals, D_{2L} and D_{2T} are shown in Figures 4.6(b) and 4.6(c). Some simple traffic engineering can be applied to calculate them:

$$D_{2X} = g^s_X(C/H)/K_j, \tag{4.15}$$

with X being either L or T.

4.3.2 Capacity with short blocks

The capacity analysis in Section 4.2 deals with the situations when the block of interest is longer than $D_1 + D_2$. If this is not the case, pre-signals may still increase the intersection capacity, albeit to a lesser extent.

Different assumptions may be employed for the analysis of the capacity under this situation. One simple assumption is that the length of the sorting area, the durations of signal phases (at both the pre-signal and the intersection signal) and the capacity achieved all reduce proportionally with the block length. Note that the assumption is conservative, and yields a lower bound for the capacity that can be achieved. This is because we have assumed that the number of vehicles discharged per cycle is constrained by the number of vehicles that the sorting area can hold, which is true when the blocks are long. However, we see in Figure 4.7 that when blocks are short, the number of vehicles discharged per cycle (all vehicles discharged during G_L and G_T) can be more than that the sorting area can hold (all vehicles discharged in G_L and those using 2 lanes during the beginning of G_T). Therefore, when blocks are short, we can say that this assumption is conservative.

4.3.3 Modified design: phase swap

The length of the sorting area can be estimated by performing a back-of-the-envelope calculation. It is based on Equations 4.11, 4.12, and 4.13. Assuming that the stochastic effects are ignored (i.e., $\gamma = 0$, for an upper bound estimation), and adopting the following parameters: jam density $K_j \approx 1/7$ vehicle/meter, total green ratio $G \approx 0.5$, average saturation headway $H \approx 2.5$ seconds, the length of the sorting area D_1 is estimated to be about 84 meters per minute of cycle length. Note that the conventional design only requires a block length similar to D_2, while the tandem design requires an additional length of D_1. Therefore, it may be challenging to find blocks that is sufficiently long to implement the tandem design. Furthermore, modifications that reduce the block length requirement can make the tandem design much more feasible.

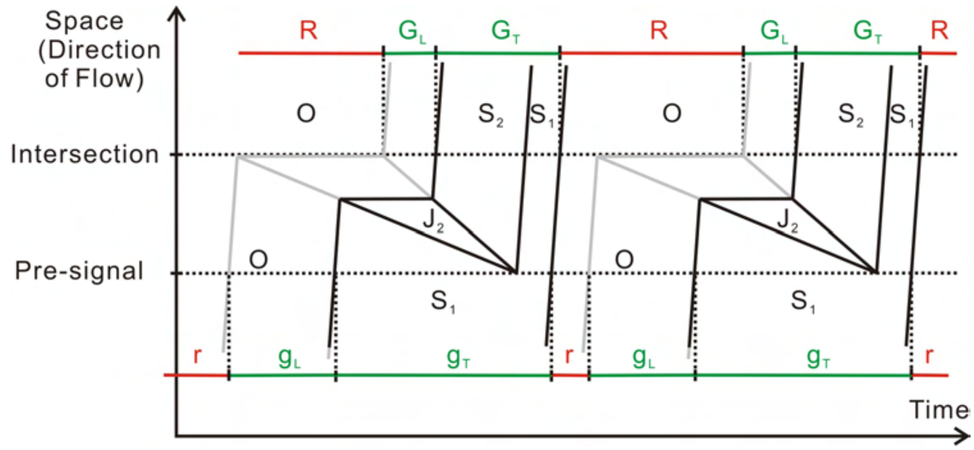


Figure 4.7. Time-space diagram of TVs (in dark color, with that of LVs in light gray color) for a tandem design with $n = N = 2$ and limited block length. Note that the number of vehicles discharged per cycle (all vehicles discharged in G_L and G_T) is more than that the sorting area can hold (all vehicles discharged in G_L and those using 2 lanes during the beginning of G_T).

In this section, we discuss one such modification which involves swapping phases of the intersection signal. In Figure 4.6(b) or 4.6(c), we see that the LV and TV queues are stacked on each other. Correspondingly, the length of the sorting area is the sum of the lengths of the LV and TV queues as in Equations 4.11. All these are because the left-turn phase is followed immediately by the through phase. However, the left-turn phase and the through phase do not have to be back to back; see how the order of phases 2 and 3 can be swapped at an intersection signal in Figure 4.8. As a result, the LV and TV queues do not have to be stacked on each other, as shown in Figure 4.9(a), and the length requirement of the sorting area, instead of Equation 4.11, can be reduced to

$$D_1 = \max\{D_{1L}, D_{1T}\}, \tag{4.16}$$

where Equations 4.12 and 4.13 still hold. The reduction in the length of the sorting area depends on the values of D_{1L} and D_{1T}, or similarly, the left-turn ratio l. When the left-turn ratio is about 0.5, the reduction is greatest; i.e., by about 50%.

Note from Figure 4.9(a) that to separate the two queues in time, the durations of the red phases need to satisfy the following requirement: $R_1 \geq g_L - G_L$ and $R_2 \geq g_T - G_T$. If this is not the case, the two queues will be partially stacked on each other, and the length of the sorting area may be more than that predicted in Equation 4.16. Figure 4.9(b) illustrates the situation when $0 < R_2 < g_T - G_T$. We see two queues: the first has all LVs and some TVs, and the second has only TVs. The length of the sorting area in this situation can be expressed as:

$$D_1 = \max\left\{D_{1L} + D_{1T}\left[1 - \frac{R_2}{g_T - G_T}\right], D_{1T}\right\}. \tag{4.17}$$

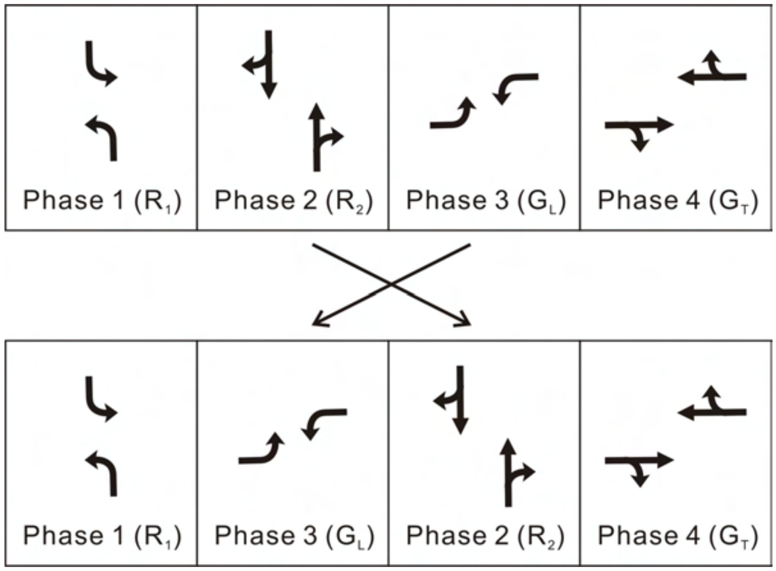


Figure 4.8. Phase sequence of the intersection signal before and after the swap.

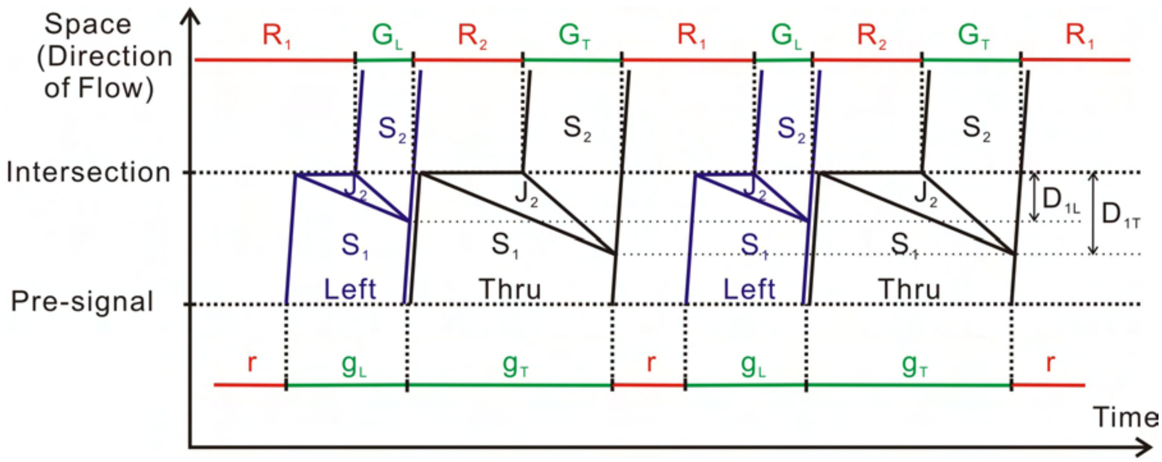
The two components of the maximum operator correspond to the lengths of the two queues in the figure. The expression for D_1 when $0 < R_1 < g_L - G_L$ can be derived similarly, and the length of the sorting area can be expressed as:

$$D_1 = \begin{cases} \max\left\{D_{1L} + D_{1T}\left[1 - \frac{R_2}{g_T - G_T}\right], D_{1T}\right\} & \text{if } 0 < R_2 < g_T - G_T, \\ \max\left\{D_{1L}, D_{1L}\left[1 - \frac{R_1}{g_L - G_L}\right] + D_{1T}\right\} & \text{if } 0 < R_1 < g_L - G_L. \end{cases} \tag{4.18}$$

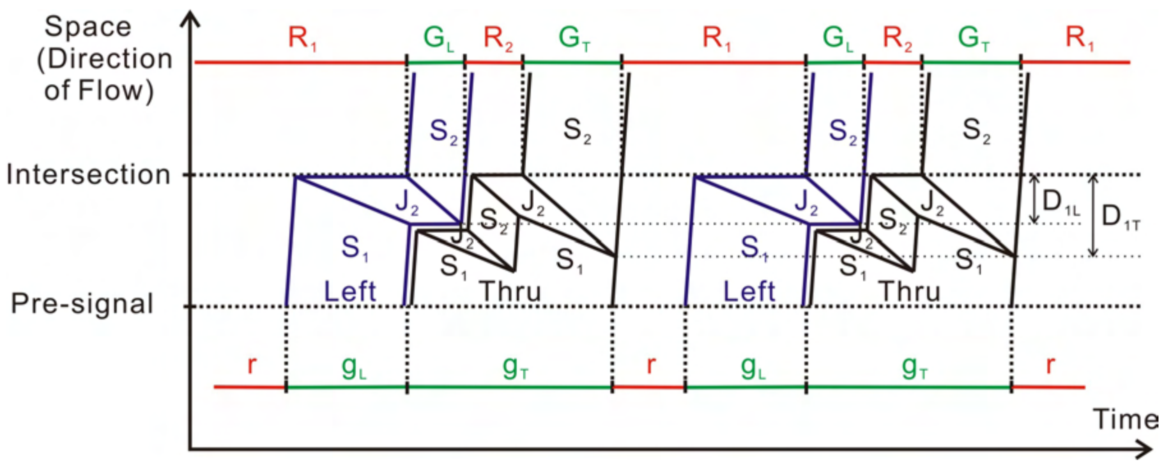
Note that the two conditions $0 < R_1 < g_L - G_L$ and $0 < R_2 < g_T - G_T$ will not be satisfied simultaneously, otherwise the pre-signal would be an active bottleneck and would not be very beneficial. Equation 4.18 can be rewritten into a single expression:

$$D_1 = \max\left\{ \begin{aligned} & D_{1L} + D_{1T}\max\left[0, 1 - \frac{R_2}{g_T - G_T}\right], \\ & D_{1L}\max\left[0, 1 - \frac{R_1}{g_L - G_L}\right] + D_{1T} \end{aligned} \right\}. \tag{4.19}$$

We have shown that with the phase swap at the intersection signal, the length requirement of the sorting area can be significantly reduced. For traffic from other directions, the duration of the green time does not change much with the phase swap, and the impact on the flow on other approaches is minor. The only impact is that with the new phase sequence, vehicles need slightly longer time to clear the intersection. Therefore, the lost time between consecutive signal phases is slightly increased and the effective green time is slightly reduced.



(a)



(b)

Figure 4.9. Time-space diagram of LVs and TVs with $n = N = 2$ and a phase swap at the intersection signal. (a) The situation when the duration of phase 2 is longer than $g_T - G_T$. The LV and TV queues are not stacked on each other but separated in time. (b) The situation when the duration of phase 2 is shorter than $gT - GT$. The TV queue is partially stacked on the LV queue.

4.4 Discussion of Delay

As stated in the introduction, the focus of the dissertation is on oversaturated intersections. In this situation, increasing capacity can reduce the number of vehicles that wait for multiple cycles to pass the intersection, as well as their delay. The same is true for the number of stops that vehicles make, which is an important contributor to emissions.

We have also performed some preliminary delay analysis when intersections are undersaturated. We find that it is possible to modify the tandem design so that at least one movement (e.g. the TVs) can go through the intersection with no extra delay due to the pre-signal. However, the main benefit of the tandem design, i.e., increased capacity, is not very helpful to this situation. Therefore, the delay analysis for the undersaturated situation is skipped.

In reality, no intersection would be oversaturated all the time, and undersaturated situations need to be addressed. Fortunately, pre-signals can be turned off when traffic demand is undersaturated. This is discussed next in Section 5.1.

Chapter 5

Operational Issues

In this chapter, we discuss issues that are related to the implementation of the tandem design, e.g., switching pre-signals on/off to account for different traffic conditions, and issues with driver compliance.

5.1 Switching the Pre-signal On and Off

As per our discussion in the last section, tandem design with a pre-signal is needed during the peak period when demand is overwhelming, but not so for undersaturated situations when demand is low. Fortunately, the pre-signal can be simply turned off when it is not needed. As a result, the tandem design to be implemented in reality needs the functionality to switch the pre-signal on or off depending on the traffic conditions.

Let us start with the undersaturated condition when the pre-signal is turned off. As traffic demand increases, the queue length during each cycle will increase as well. When the end of queue reaches the location of the pre-signal, i.e., when the sorting area is filled, not all vehicles can be discharged in one cycle. Therefore, extra capacity is needed and the pre-signal should be switched on. When switching on the pre-signal, there is a transition period when the pre-signal should be set to all red until all vehicles in the sorting area are cleared, i.e., there is no residual queue in the sorting area. The existence of a residual queue can be detected by either loop detectors located right upstream of the intersection stop line, or video cameras. After the sorting area is cleared, the pre-signal should adopt its normal timing plan as designed.

The traffic demand can be monitored by inspecting the number of vehicles in the sorting area per cycle. This can be done similarly with loop detectors or video cameras. When demand has dropped below the capacity of the conventional design, the pre-signal should be switched off. No transition period is required in this situation, and vehicles will automatically fill the sorting area after the pre-signal is turned off.

5.2 Compliance and Enforcement

So far, we have implicitly assumed that drivers always comply with the new lane designation imposed by the tandem design. While the validity of the assumption can only be tested in the field, it is important to realize the consequences of noncompliance and why some drivers do not comply.

Noncompliance to the lane designation can result in residual queues in the sorting area. For example, if a TV goes through the pre-signal using the lane designated to LVs (no matter the reason), the TV will not turn left and may block the LVs behind it from turning left. This would produce a residual queue similarly to the situation described in Section 4.2.2, and intersection capacity could be significantly reduced. Therefore, noncompliance is very undesirable.

Noncompliance can be discouraged through both enforcement and design. Enforcement can be done with video cameras. Noncompliant drivers will use the lanes designated for LVs at the pre-signal and the lanes designated for TVs at the intersection signal, or the other way around. Therefore, if we track the lanes used by vehicles, noncompliance can be detected. Noncompliance would likely reduce eventually if noncompliant drivers were to face large fines.

To address noncompliance from the design point of view, we need to understand why drivers do not comply. Drivers may do this for at least three different reasons: the first is that they are confused by the new design; the second is that they change their mind at the last minute; the last is that they want to game the system to benefit themselves (e.g., to reduce their travel times). To address the first reason, signs can be added far upstream of the pre-signal to remind drivers of the new design and explain the lane designation. Hopefully given enough time, drivers will become accustomed to the tandem design and there will be less confusion. Not much can be done to address the second reason. Drivers that change their mind at the last minute have to comply and incur some inconvenience, which is true even with the conventional design. To address the third reason of noncompliance, we find that it is possible to modify the tandem design so that the pre-signal and the intersection signal function as a first-in-first-out (FIFO) system for most drivers. Therefore, most drivers do not have much incentive to game the system. One such modification is briefly described in the next section.

5.3 Shared Lane at the Pre-signal

The tandem design so far requires LVs and TVs to be presorted into different lanes at the pre-signal. According to Equation 4.15, the queue length in a LV (or TV) lane upstream of the pre-signal is proportional to the duration of the pre-signal LV (or TV) phase, or the demand of LVs (or TVs). Therefore, the LV queue upstream of the pre-signal can be quite short if there are only a few LVs per cycle. When there are only two lanes at the pre-signal as in Figure 3.2(c), it is a waste of space to allocate a whole lane to LVs. This may also encourage noncompliance of TVs, if they see a very long TV queue and a very short LV queue.

However, vehicles at the pre-signal do not necessarily have to be segregated by movement into different lanes. As illustrated in Figure 5.1, a lane can be a shared lane (i.e., to hold both LVs and TVs). Figure 5.1 illustrates how vehicles are supposed to move during the two pre-signal phases: a green phase for the left lane upstream of the pre-signal (upper part of the figure) and a green phase for the right lane upstream of the pre-signal (lower part of the figure). In the sorting area, LVs are allowed into the two lanes on the left during the first pre-signal phase, while TVs are only allowed in the rightmost lane. During the second pre-signal phase, TVs may use the two lanes on the right in the sorting area. Note that with the shared lane, there will be no noncompliance for the TVs at the pre-signal since they can use either lane, as they see fit. Also note that for this modified design to work, the lane designation in the sorting area needs to change dynamically.

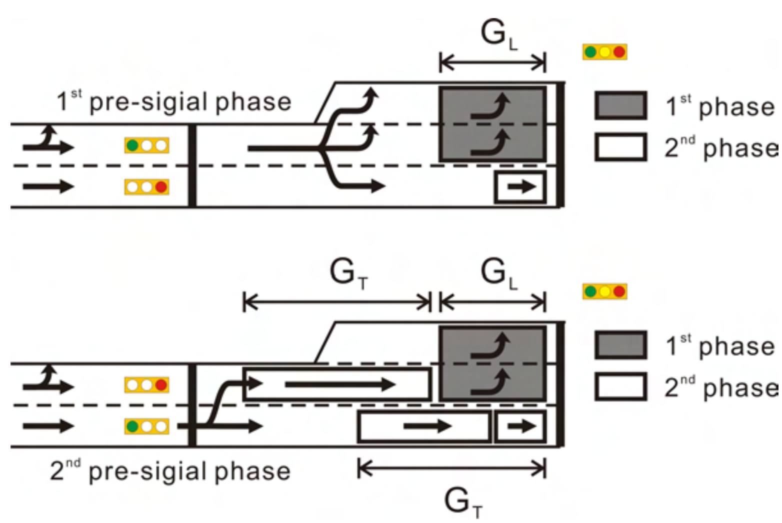


Figure 5.1. Shared lane at the pre-signal. The upper and lower parts of the figure illustrate vehicle movements during the two pre-signal phases respectively.

Also note that the modified design in Figure 5.1 yields the same capacity as the design in Figure 3.2(c). After passing the pre-signal, hopefully drivers will distribute themselves evenly across all lanes that are available to them, to reduce their travel time. Therefore, modified designs with a shared lane at the pre-signal may greatly reduce the frequency of noncompliance, though the possibility of noncompliance can never be eliminated completely.

Chapter 6

Case Study

In this chapter, we present a case study at a signalized intersection in the city of Chengdu, China. The case study shows how the tandem design with a pre-signal can be used to benefit both cars and buses on the site, despite many real-world complications.

6.1 Status Quo and Its Problems

The site of interest is the southbound approach at the intersection of the First-Ring Road and Gaoshengqiao Road. The block is more than 400 meters long. The approach has three lanes and a 100-meter long left-turn pocket, as shown in Figure 6.1. There is also a side street about 100 meters upstream of the intersection. Lane 3 is a dedicated bus lane, but the current regulation also allows right-turning cars. Note that the lane designations for car traffic are labeled according to the current behavior of drivers, not the current regulation. For example, through-moving cars frequently enter the bus lane (lane 3) in violation of the regulation. Thus, the lane designation for the bus lane in the figure includes through-moving cars. Another example is that lane 1 is actually designated for through-moving cars only, but in reality drivers behave as if lane 1 allows both left-turning and through-moving cars, as labeled in the figure.

Currently, the intersection signal is pre-timed, but this timing changes with the time of the day. The cycle length is more than 3 minutes during the peak hours, and total green time available for the approach is about half the cycle length. The current capacity is about 1580 vehicles/hour during the morning peak and 1140 vehicles/hour during the evening peak. The fraction of left-turning cars on the intersection approach is very high, at about 57% in the morning peak and 37% in the evening peak, presumably because left turns go to the city center.

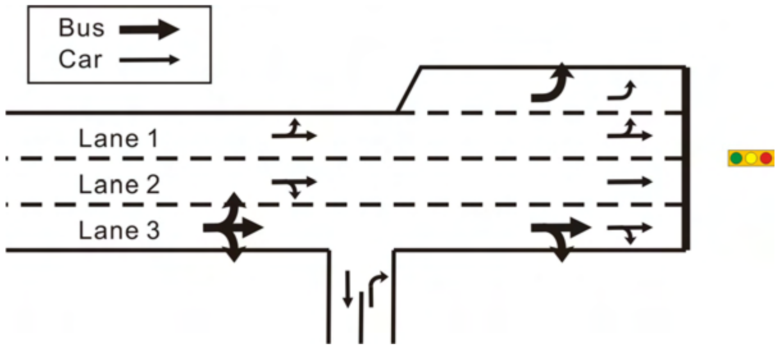


Figure 6.1. Current geometry of the approach of our case study.

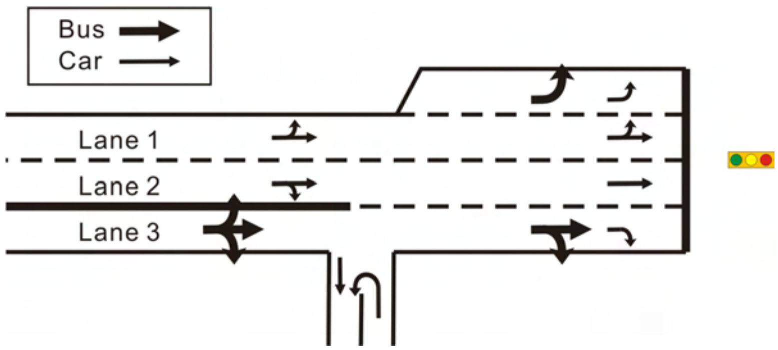
There are two main problems at the present time. The first problem is that buses in the dedicated lane experience severe delay. This extra delay has two sources. One is the through-moving car traffic that enters the bus lane against the regulation. The other source is the side street car traffic that must weave through the bus lane but gets stuck in the bus lane due to congestion on the approach. The second problem is the severe congestion caused by heavy traffic demand that temporarily exceeds the intersection capacity available during the peak period. The queue very often backs up into the upstream intersection.

The fact that lane 1 becomes a de facto shared lane exacerbates the second problem. The left-turning drivers may feel compelled to use lane 1 because of: (a) the high left-turn ratio (between 37% and 57%) and (b) the limited green time (less than 1/6 of the cycle length for left turns) and (c) the small left-turn pocket. But their behavior causes problems. During the through phase, the first left-turning car in lane 1 will block the through-moving cars behind it from discharging from this lane, and vice versa during the left-turn phase. If this mutual blocking phenomenon can be alleviated, the intersection capacity could be increased, and congestion would decline as a result.

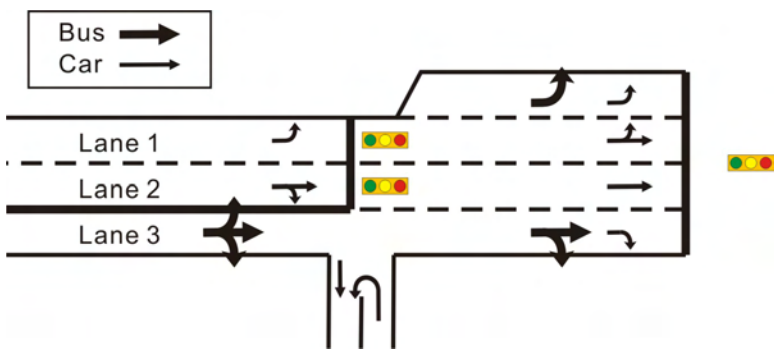
6.2 Proposed Solution

We seek to solve these two problems to benefit both cars and buses. The first problem can be solved by enforcing the bus lane regulation, as illustrated in Figure 6.2(a). Our proposal includes (a) adding a physical barrier between lanes 2 and 3 to avoid incursion of through-moving cars into the bus lane; and (b) detouring side street cars so that the bus lane is immune from their disruptions. The proposed bus lane enforcement strategies would hopefully reduce delay of buses due to disruptions from car traffic. However, doing this alone would likely reduce intersection capacity, increase congestion, and make the enforcement of the bus lane regulation more challenging. Cars would suffer a penalty.

Therefore, besides bus lane enforcement, we propose to use the tandem design with a



(a)



(b)

Figure 6.2. Proposed geometry of the approach of our case study. (a) Bus lane enforcement only, including adding physical barrier between lanes 2 and 3, and detouring side street traffic. (b) Bus lane enforcement as well as the tandem design for car traffic.

mid-block pre-signal to increase the intersection capacity. The pre-signal will only control car traffic coming from lanes 1 and 2. Vehicles need to be presorted at the pre-signal stop line, with LVs in lane 1 and TVs in lane 2. Roadside signs are needed upstream of the pre-signal to provide warning and give drivers enough time to maneuver to their designated lane. The lane designation in the sorting area for a tandem sorting strategy with one tandem lane is shown in Figure 6.2(b). If two tandem lanes are needed, lane 2 can be designated to allow for both LVs and TVs in the sorting area.

There is another complication with regard to the use of the tandem design described in Chapter 3. In the present case, the intersection signal does not have only two green phases for the approach, but rather three green phases: after the through phase and before the left-turn phase, there is an extra phase serving both TVs and LVs (red light for the opposite approach). The design is depicted by the first three phases in Figure 6.3, where the intersection approach of interest goes in the direction from left to right. This kind of design is justified by the asymmetry of traffic demand on the subject approach and its opposing approach. The pre-signal phases can be designed accordingly: instead of two green phases (one for the LVs and the other for the TVs), the pre-signal will also have three green phases, with an extra phase serving both the LVs and the TVs.

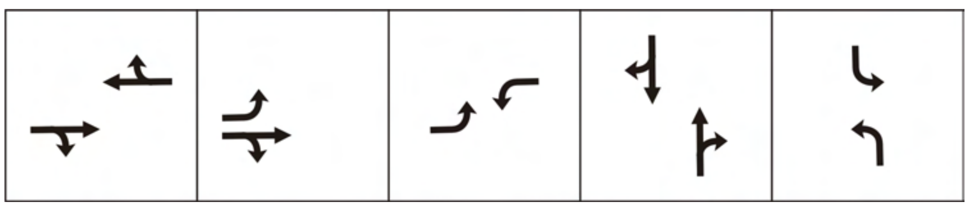


Figure 6.3. Signal timing of the intersection signal. The intersection approach of interest goes in the direction from left to right. The second phase from left is the source of complication.

6.3 Estimated Benefit

We videotaped the intersection approach of interest to obtain a benchmark for comparison. A video snapshot is shown in Figure 6.4. The video, as well as microsimulation, was used to test the potential benefit of the bus lane enforcement in combination with the tandem design.

The bus delays for the status quo and for the status quo with bus lane enforcement alone were both empirically calculated from the video. We first searched off-peak periods of the video to identify buses that were not delayed on the approach. The amounts of time these buses spent on the approach were averaged to obtain the free flow travel time of buses. The delay of each bus for the status quo was obtained by subtracting the travel time of each bus from the free flow time. The delay comes from both the intersection signal and disruptions from car traffic. With the proposed bus lane enforcement, we assume that the disruptions

Figure 6.4. A video snapshot of the site. The intersection is located on the upper left corner of the image. Traffic on the intersection approach of interest moves from the lower right corner to the upper left corner.

would be gone and only buses and right-turning cars would remain in the bus lane. The departure time of each vehicle can then be determined as is standard in queuing theory by taking the maximum of two components. The first component is the saturation headway of that vehicle (2.3 seconds for cars and 3.9 seconds for buses, both empirically obtained) plus the departure time of the previous vehicle. The second component is the departure time with no delay, i.e., the time that vehicle shows up in the video plus free flow travel time. The differences between the calculated departure times for all the buses and the free flow travel time are the bus delays with bus lane enforcement.

The capacity of the status quo was obtained from the video. The capacity with bus lane enforcement alone and with both bus lane enforcement and the tandem design were obtained through microsimulation. We used CORSIM (Federal Highway Administration, 2007), and calibrated its parameters (free flow speed, saturation flow, intersection signal timing, input flow, etc.) with measurements from the video. Interested readers may refer to the link http://www.its.berkeley.edu/volvocenter/pre-signal/Tandem_Design.html for a sample simulation video. The simulation video includes the aforementioned mutual blocking phenomenon and phase swap, but for illustration purposes only adopts a 4-phase intersection signal timing. A snapshot of the video is shown in Figure 6.5.

Table 6.1 compares three scenarios: (a) status quo, (b) bus lane enforcement alone, and (c) bus lane enforcement plus the tandem design. Due to disruptions from car traffic, some buses miss the green time and have to wait for the next cycle (with an extra red time of about 2 minutes). Delay is reduced by eliminating these disruptions. The table shows that bus lane enforcement reduces the average delay per bus by 40% or more, and the standard

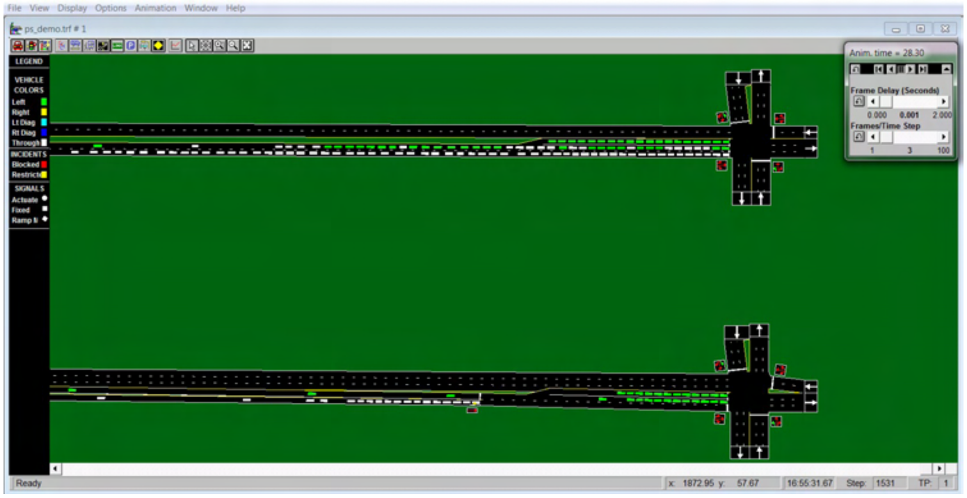


Figure 6.5. A snapshot of the CORSIM simulation. The upper part is for the situation with bus lane enforcement only, and the lower part is for the proposed tandem design. The vehicles are color coded by their movement: green (or light gray) for LVs, white for TVs. Note that for the status quo, LVs and TVs are randomly mixed in lane 1, resulting in the mutual blocking phenomenon.

deviation of bus delay by 30% or more. Therefore, buses are delayed less and their on-time performance is improved. The residual bus delay is due to the intersection signal, since we did not do signal preemption for buses (or bus signal priority).

Table 6.1 also shows the capacity of the three different scenarios. With bus lane enforcement alone, the intersection capacity would decline by about 10%. There are two reasons for this reduction. The most obvious one is that through-moving cars cannot use the bus lane to discharge. Less obvious is that the mutual blocking phenomenon becomes more severe when the through-moving cars from lane 3 are pushed onto lanes 1 and 2. Fortunately, adopting the tandem design with one tandem lane can restore the capacity during the morning peak. And for the evening peak, the capacity can be increased by about 10% compared with the status quo.

Although bus lane enforcement alone can effectively reduce bus delay, the reduced capacity for car traffic would greatly increase congestion. The disparity would make the benefit to buses challenging to sustain, as drivers either voice their discontent to decision makers (more popular in developed countries), or simply violate the regulations (more popular in developing countries). Thus, the proposal with both bus lane enforcement and the tandem design would benefit both cars and buses, and its benefits are likely to be accepted without discontent.

To be complete, we should also address the strategy's effect on right-turning cars and left-turning buses. The right-turning cars (which account for only 5% of the car traffic) will

Table 6.1. Comparison among the status quo, bus lane enforcement alone, and bus lane enforcement as well as tandem sorting

		Status quo (100% as baseline)	Bus lane enforcement alone	Bus lane enforcement and tandem design (with 1 tandem lane)
Bus delay (seconds/bus)	Morning peak	111 (100%)	59 (53%)	
	Evening peak	110 (100%)	66 (60%)	
Standard deviation of bus delay (seconds/bus)	Morning peak	75 (100%)	46 (61%)	
	Evening peak	55 (100%)	39 (71%)	
Capacity (vehicles/hour)	Morning peak	1586 (100%)	1405 (89%)	1568 (99%)
	Evening peak	1145 (100%)	1019 (89%)	1249 (109%)

not see much change except that they now have to stop in lane 2 at the pre-signal. After entering the sorting area, they shall use lane 3 to turn right.

There are some changes to how left-turning buses (which account for 10% to 20% of the bus traffic) would operate. Under the status quo, left-turning buses cannot easily change lanes from lane 3 to the left-turn pocket due to the congested approach. As a result, they generally have to leave the bus lane well upstream of the intersection to reach the left-turn pocket. This lane change maneuver becomes much easier with the pre-signal, since it creates gaps in car traffic. This is actually the original function of the pre-signal (Oakes *et al.* , 1994). Now left-turning buses can stay in the bus lane until reaching the pre-signal (they do not have to stop at the pre-signal), and then change lanes to the left-turn pocket.

Chapter 7

Serving Multimodal Traffic

So far, the discussion on tandem sorting with pre-signals has been limited to a single mode, i.e., cars. The case study does involve buses, but the buses are segregated from car traffic, and as a result the two modes can be analyzed separately. However, the tandem sorting concept with a pre-signal can also be used to sort two or more transport modes. A simple theory on how to increase the capacity by sorting cars and buses is shown next.

7.1 Theory

The theory to be proposed is similar in spirit to Wu & Hounsell (1998). Let us assume that buses travel on a dedicated lane on which right-turning cars are not allowed, and focus only on the interaction between through-moving buses and right-turning cars. To draw insights, simplified models are used to study possible ways to increase the capacity for these two vehicle classes. More realistic situations will be considered in Section 7.2.

Left to their own devices, conflicts will arise between the right-turning cars and the through-moving buses, such that both vehicle classes cannot simultaneously discharge into the intersection during a green time. This case is labeled in Figure 7.1 as "side-by-side operation with conflicts". These conflicts can be resolved by using a pre-signal to reorganize the two vehicle classes. The pre-signal alternates allocating green times to each class. Vehicles pass through the pre-signal and move to their assigned lanes in the sorting area. Two possible sorting strategies are shown in Figure 7.1. Both resolve the conflicts between the two vehicle classes. In the first strategy, labeled "side-by-side operation with no conflicts", the vehicle classes are laterally swapped in position within the sorting area. In the second strategy, the two classes are sorted in a tandem fashion, such that each class discharges into the intersection in sequence.

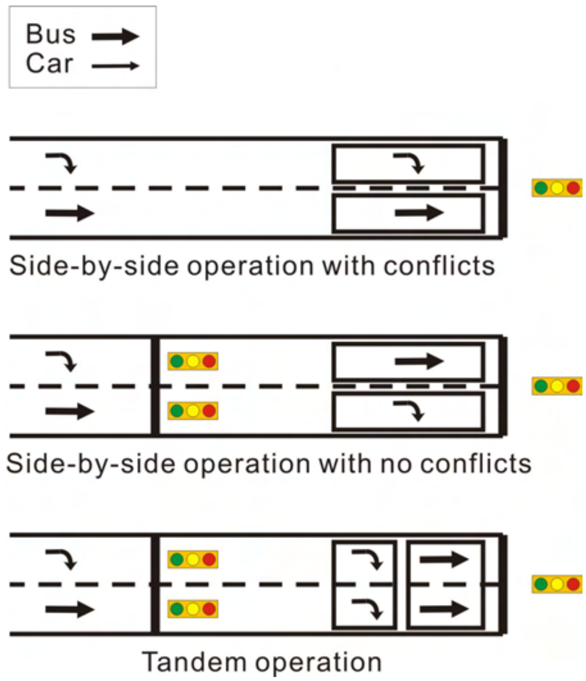


Figure 7.1. Different sorting strategies (including do-nothing).

Now we determine the capacity of the three cases in Figure 7.1. Consistent with our discussion in Section 4.2, we adopt a dimensionless unit system such that the cycle length of the intersection signal is the unit of time, and the saturation flow per lane for car traffic is the unit of flow. To convert car flow (in cars/hour) into its dimensionless counterpart, car flow is normalized by the saturation flow per lane for cars (in cars/hour/lane). Bus flow, on the other hand, is normalized by the saturation flow per lane for buses (in buses/hour/lane). As before, the dimensionless capacity can be represented by the product of dimensionless green time and the number of lanes available to discharge.

We assume that: (a) the approach has 2 lanes as in Figure 7.1, and the green ratio at the intersection signal, G, is given; (b) the lost time between the pre-signal phases is negligible; (c) the two vehicle classes in question are each characterized by their dimensionless demand q_{cr} (right-turning cars) and q_{bt} (through-moving buses). The capacity constraint for side-by-side operation with conflicts can then be expressed as

$$q_{bt} + q_{cr} \leq G, \tag{7.1}$$

because only one vehicle class can discharge at a time. The capacity constraints for side-by-side operation with no conflicts are

$$q_{bt} \leq G, q_{cr} \leq G, \tag{7.2a}$$

$$q_{bt} + q_{cr} \leq 1. \tag{7.2b}$$

The first constraint pertains to the intersection signal, and the second to the pre-signal. The capacity constraints for the tandem case are:

$$q_{bt} + q_{cr} \leq 2G, \tag{7.3a}$$
$$q_{bt} + q_{cr} \leq 1. \tag{7.3b}$$

Equation 7.3a assumes that both vehicle classes distributed themselves evenly across the two lanes, and the factor "2" on the right-hand side arises because both lanes can discharge simultaneously during the whole green phase. Note as well from the summation on the left-hand side of Equation 7.3a that we are assuming that the time it takes to discharge a mixture of vehicle classes (cars and buses here) equals the sum of the times that it would take to discharge the vehicle classes separately. This linear superposition assumption is verified in Section 7.3.

Figure 7.2 shows the capacity constraints derived above when $G \leq 1/2$. In this situation, the capacity constraint at the pre-signal as shown in Equations 7.2b and 7.3b is never binding. This is because the total green time at the intersection signal is equal to or less than half of the cycle length, while the pre-signal can use the whole cycle to sort traffic. Side-by-side sorting with no conflicts increases capacity, especially when the flows of buses and right-turning cars are similar. Tandem sorting increases capacity even more, especially in instances when the flows of buses and right-turning cars are unbalanced. This happens because the tandem scheme makes full use of all lanes, as long as there is sufficient demand. Though the 2-lane model is simplistic, it nonetheless illustrates the potential of tandem sorting strategy to increase intersection capacity. Generalizations are easy to study using similar logic; e.g. as in Section 7.2.

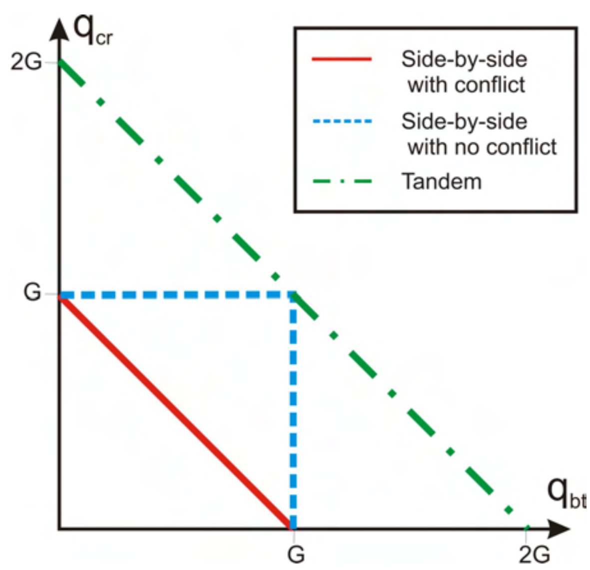


Figure 7.2. Capacity constraints for different sorting strategies when $G \leq 1/2$.

In real-world settings, complications can arise to diminish the effectiveness of the tandem strategy. For example, conflicts may arise between the last few through-moving buses to discharge in the right lane and the first few right-turning cars in the left lane. To remedy this type of problem, the tandem strategy can be modified so that only one lane is operated in tandem. Two ways of implementing these idea are shown in Figure 7.3(a). The capacity constraints for these modified strategies are easily derived and are displayed in Figure 7.3(b). Note that the bounds in this figure fall between those of the standard tandem strategy and those of the side-by-side operation with no conflicts (see again Figure 7.2). The type of modification should be based on the relative demand for the two vehicle classes: example 1 if there are more through-moving buses then right-turning cars, and example 2 otherwise.

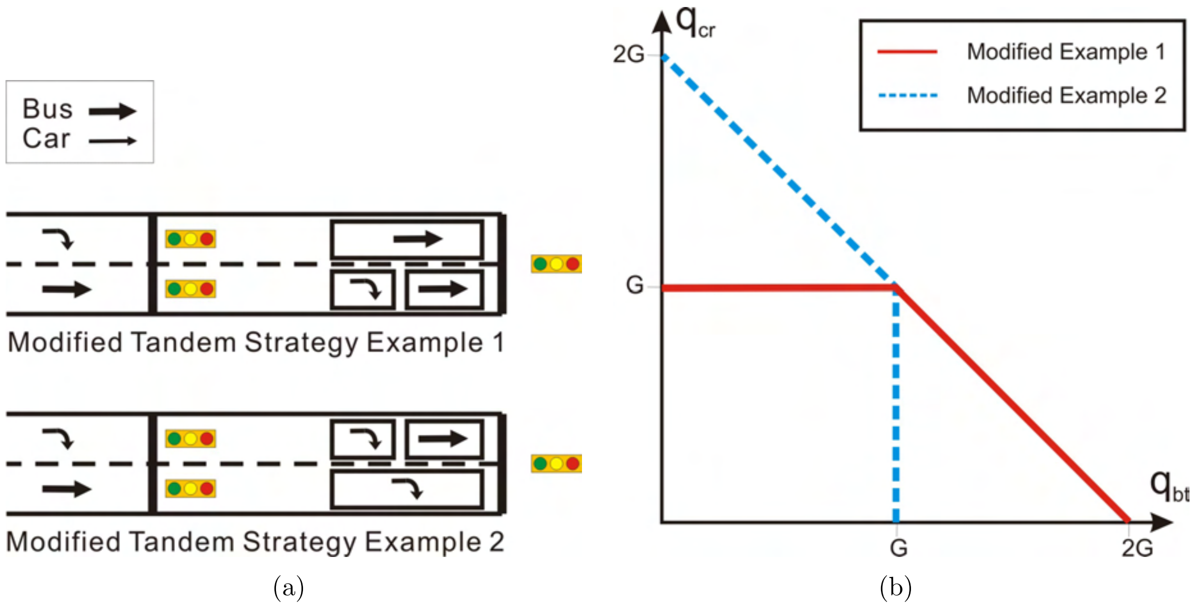


Figure 7.3. Modified tandem strategies. (a) Graphic illustrations; (b) capacity constraints.

7.2 A Proposed Design

We use the same site as in the case study of Chapter 6. The geometry of the approach is shown in the top half of Figure 7.4. It has three lanes: two for cars (lanes 1 and 2, plus a left turn pocket) and one that is dedicated to buses (lane 3). The current regulation is that cars are only allowed to use the bus lane to turn right. However, bus demand is very low (about 2 buses/minute) and the bus lane is underutilized even with the inclusion of right-turning cars, as proposed in Chapter 6, Figure 6.2(b). At the same time, demand for car traffic is very heavy on the approach.

To increase capacity on the approach while still providing preferential treatment to buses, the pre-signal can also allow for through-moving cars on lane 3, as proposed in Xuan *et al.* (2010) for this site. In this proposed design, which is depicted on the bottom half of Figure 7.4, the pre-signal displays two green phases: one for buses (only), the other for cars.

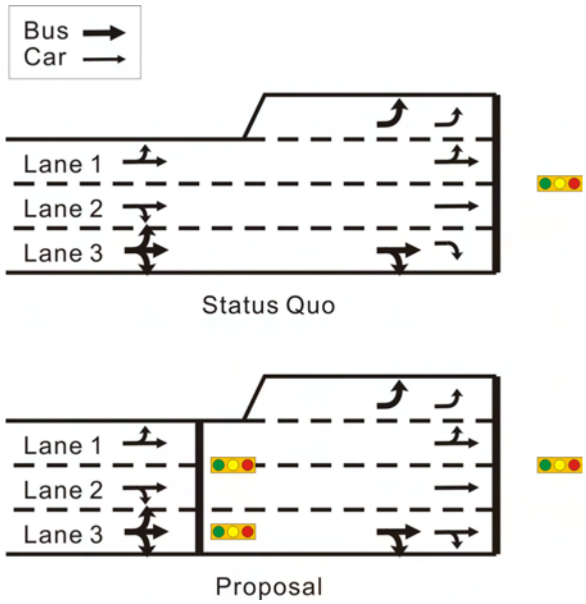


Figure 7.4. Geometry of the approach of our case study, status quo and proposal.

The lane markings differ from Figure 6.2(b) only in that through-moving cars are allowed to use lane 1 downstream of the pre-signal.

Design variables include: (a) the lane designations in the sorting area, (b) the duration of the pre-signal phases, (c) the offset between the pre-signal and the intersection signal, and (d) the physical length of the sorting area. These are described next.

(a) The lane designations in the sorting area allow through-moving cars in the bus lane, to avoid underutilizing that lane.

(b) The pre-signal phases should be long enough in duration to serve the bus demand (e.g., allowing 10 seconds per bus). The pre-signal switches to the bus phase whenever a bus arrives (which assumes that bus arrivals can be detected), to make sure buses are never delayed by the pre-signal. The duration of the car phase should be capped such that all the cars and buses passing through the pre-signal during each cycle are able to discharge into the intersection without forming residual queues. The remaining time in the cycle, if any, is added to the bus phase duration.

(c) The offset between the pre-signal and the intersection signal is set to minimize the delay in the sorting area; i.e., so that the last car that discharges from the pre-signal during its car phase can discharge into the intersection without delay.

(d) The length of the sorting area needs to be long enough to hold all the vehicles that are to be discharged in one cycle, plus some buffer space for vehicle maneuvering. For the approach of interest, the length of the sorting area was calculated to be about 150 meters. A sorting area of this size easily fits within the block, which is more than 400 meters long.

Since lane 1 is unaffected by the pre-signal, our capacity analysis can be confined to lanes 2 and 3 (see again Figure 7.4). The derivations of the capacity constraints are similar to those in Section 7.1, where distinct vehicle classes are characterized by their demand q_{ct}, q_{bt}, q_{cr}, q_{br} with the first subscript denoting mode (**c**ar or **b**us) and the second denoting movement (**t**hrough or **r**ight). Clearly, the capacity constraints for the status quo are

$$q_{ct} \leq G, \text{ (lane 2)} \tag{7.4a}$$

$$q_{bt} + q_{br} + q_{cr} \leq G. \text{ (lane 3)} \tag{7.4b}$$

Note that Equation 7.4b is not binding here because the bus lane is underutilized.

Consideration also shows that the capacity constraints with a pre-signal are

$$q_{bt} + q_{br} + q_{cr} \leq G, \text{ (lane 3 is underutilized)} \tag{7.5a}$$

$$q_{ct} + (q_{bt} + q_{br} + q_{cr}) \leq 2G, \text{ (lanes 2 and 3 at the intersection)} \tag{7.5b}$$

$$(q_{bt} + q_{br}) + (q_{ct} + q_{cr}) \leq 1. \text{ (lanes 2 and 3 at the pre-signal)} \tag{7.5c}$$

Note that Equation 7.5b assumes linear superposition. Also note that in this case only this equation is binding because the bus lane is underutilized (Equation 7.5a not binding) and because $G \approx 0.3 < 1/2$ (Equation 7.5c not binding).

7.3 Natural Experiment

Contrary to the regulation, drivers of through-moving cars frequently avail themselves of the bus lane, in apparent attempts to reduce their own delays. This behavior is even encouraged by the traffic police that are stationed at the intersection, as it increases the use of the bus lane. The outcome of this behavior mimics what would occur in a more organized way, if lanes were designated in the sorting area as per the proposed tandem strategy, but the pre-signal was replaced by a yield sign for cars. This configuration would produce capacity constraints identical to those in Equation 7.5, if the assumption of linear superposition holds. We thus have a natural experiment to test this assumption and to verify the benefits of using a pre-signal.

The approach was videotaped during the evening peak on June 11, 2009. Vehicle counts are furnished by mode and by movement for 10 signal cycles in Table 7.1. Note that through-moving cars in lane 3, the bus lane, are in violation of the regulation, but would be legal under the proposed system.

Table 7.1. Field observations

Signal Cycle #	Signal Cycle Starting Time	Lane #	Through Bus Counts	Right Bus Counts	Through Car Counts	Right Bus Counts	Effective Green Time (sec)
1	5:54pm	2	0	0	18	0	43
		3	3	1	4	7	38
2	5:59pm	2	0	0	19	0	41
		3	4	1	8	4	44
3	6:05pm	2	0	0	19	0	49
		3	4	2	2	4	43 *
4	6:13pm	2	0	0	23	0	49
		3	5	1	4	7	53
5	6:16pm	2	0	0	21	0	47
		3	5	0	6	1	33 *
6	6:28pm	2	0	0	25	0	54
		3	3	1	8	6	52
7	6:30pm	2	0	0	24	0	51
		3	4	1	5	7	50
8	6:33pm	2	0	0	20	0	57
		3	8	0	3	11	57
9	6:36pm	2	0	0	18	0	42
		3	2	1	5	5	42
10	6:39pm	2	0	0	20	0	49
		3	4	1	9	5	49

* Lane became vacant before the end of green time.

The saturation flows estimated from the data for cars (1550 cars/hour/lane) and for buses (920 buses/hour/lane) were used to convert bus flows to car equivalent flows: 1550/920 = 1.7 (cars/bus). Of further interest, the intersection signal's effective green times (thereafter EGTs) for the approach were different in each cycle. This is because traffic (including cross-traffic) commonly entered the intersection even after its green times had ended. To make comparisons, vehicle counts in each estimated EGT were proportionally adjusted using the signal's nominal EGT of 50 seconds.

Outcomes from this natural experiment were favorable, as revealed in Figure 7.5. Its o-shaped data points are the adjusted counts per cycle for the combination of: buses and right-turning cars in lane 3, and through-moving cars in both lanes 2 and 3; i.e., the counts constrained by binding Equation 7.5b. The x-shaped data points are the same counts after subtracting the through-moving cars in lane 3 (which are only legal with the pre-signal). These counts should be constrained by binding Equation 7.4a. The o's and x's that correspond to the same cycle are connected by the lightly-drawn vertical lines.

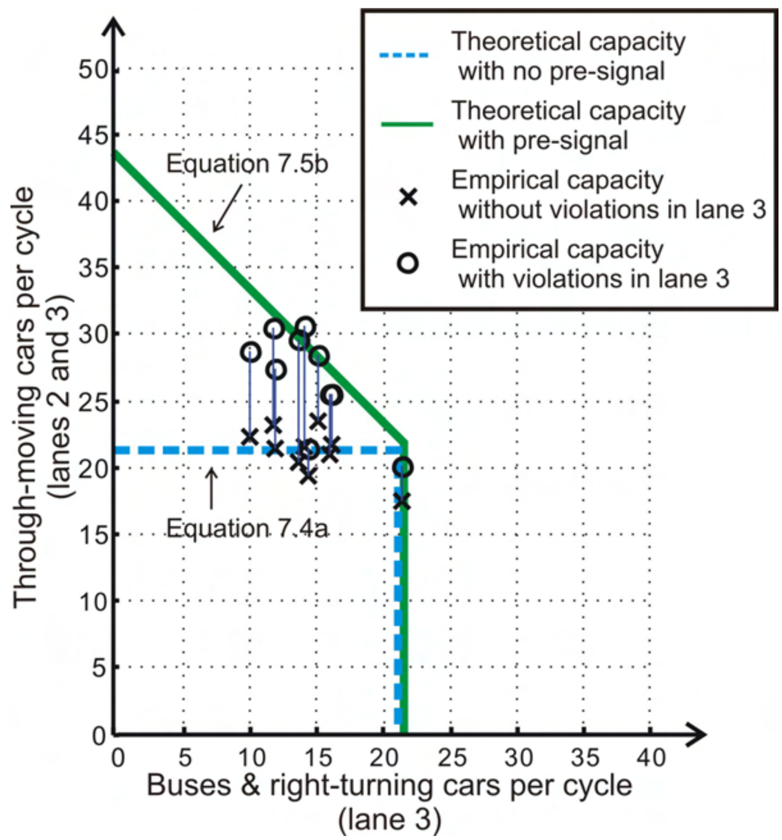


Figure 7.5. Comparison of the natural experiment result versus theoretical capacity constraints.

Note that the x's cluster closely around the horizontal dashed line segment in Figure 7.5 (corresponding to Equation 7.4a), indicating that the theoretical capacity constraints in the absence of a pre-signal are reasonable descriptions of real-world conditions.

Table 7.2. Comparison of capacity among the status quo, bus lane enforcement alone, bus lane enforcement as well as tandem sorting, and tandem sorting of both cars and buses

Capacity (vehicles/hour)	Status quo (100% as baseline)	Bus lane enforcement alone	Bus lane enforcement and tandem design (with 1 tandem lane)	Tandem sorting of both cars and buses
Morning peak	1586 (100%)	1405 (89%)	1568 (99%)	1708 (108%)
Evening peak	1145 (100%)	1019 (89%)	1249 (109%)	1389 (121%)

Further note how the o's fall either near or below the slanted solid line in the figure (corresponding to equation Equation 7.5b). This demonstrates that the theoretical capacity constraint Equation 7.5b is nearly reached by a real traffic stream despite the lack of suitable laws and organization. The two outliers well below the slanted line (cycles 3 and 5) are explained by some drivers' reluctance to use the bus lane illegally. Videos clearly show that lane 3 (the bus lane) was vacant toward the end of the green phase in those cycles despite an abundance of through-moving cars on lane 2. This suggests that the use of a pre-signal would reduce the lane 3 vacancies, producing a more perfect fit and supporting the linear superposition assumption.

The amount of capacity increase resulting from this proposal depends on how underutilized the bus lane is. Figure 7.5 shows that only about 2/3 of the green time for the bus lane (lane 3) is used in our natural experiment. That translates into an capacity increase of about 140 vehicles/hour. This capacity increase is in addition to what can be achieved in Chapter 6, because it comes from the bus lane. Table 7.2 shows the capacity that can be achieved, if the proposed design in Chapter 6 also allow through-moving cars into the bus lane through the pre-signal (termed "tandem sorting of both cars and buses" in the table).

Empirical evidence shows that with proper lane designations in the sorting area, the capacity of a studied intersection could be significantly increased with the use of either a mid-block yield sign or a pre-signal. The pre-signal would provide additional benefits over the yield sign in at least two ways. First, signal control could bring safety benefits compared with yield signs, because the chance for drivers to run red lights might be smaller than the chance that drivers fail to yield. Second, when congestion is heavy, left-turning buses have difficulty weaving through car traffic toward the approach's left turn pocket.

Of further note, the traffic demand of distinct vehicle classes in this case study is relatively stable, and thus justifies a fixed lane designation. If traffic demand were to be more volatile, dynamic lane designations could be considered.

Chapter 8

Conclusion and Future Work

8.1 Conclusion

The dissertation proposes a new "tandem design" to organize traffic and increase flow capacity at signalized intersections. In the tandem design, a mid-block pre-signal is used to sort left-turning vehicles (LVs) and through-moving vehicles (TVs) in tandem, rather than side by side in the conventional design. For intersections with separate through and left-turn phases, the tandem design outperforms a conventional system because more lanes can be used to discharge traffic during at least one of the phases.

The extra capacity that can be achieved by the tandem design is evaluated. If the saturation headway is deterministic, the capacity can be as large as if there were no left turns. Even when saturation headway is modeled stochastically, the tandem design can still increase capacity by 10% to 20%, even if only one lane is rearranged in tandem. The dissertation also examines the spatial requirements for the proposed design. It is found that to fully realize the capacity benefit, the block length would have to be very long. However, modifications to the tandem design (e.g., swapping phases at the intersection signal) can reduce the length requirement and make the design more feasible. After discussing some operational issues, a case study conducted at a signalized intersection in the city of Chengdu, China, is presented. The case study shows that the tandem design, together with bus lane enforcement, can be used to benefit both cars and buses.

The idea of tandem sorting with pre-signals is then used to increase the capacity of intersections with multimodal traffic. One critical assumption of the capacity formulation is that the time it takes to discharge a mixture of vehicle classes equals the sum of the times that it would take to discharge the vehicle classes separately. A natural experiment is conducted to verify this assumption. The natural experiment confirms the validity of the assumption and it also illustrates the effectiveness of tandem sorting with pre-signals to increase intersection capacity.

8.2 Future Work

The ideas of using pre-signals to increase intersection capacity deserves further study. Possible directions for future research are:

(a) For any new design like the tandem design proposed in this dissertation, the most challenging question is to confirm how drivers would react to it. The question is challenging because human drivers are too complicated to model. This issue is partially addressed in Sections 5.2 and 5.3, but the discussion is far from enough from an application point of view. More analysis and field experiments are needed.

(b) The study in this dissertation is limited to a single signalized intersection. Although this is a necessary first step, further study to extend the ideas to the network level seems worthwhile.

(c) The dissertation only briefly illustrates how the idea of tandem sorting with pre-signals can be applied to increase the capacity of intersections with cars and buses. However, the situation with cars and buses have not been thoroughly studied yet; e.g., it is unclear what is the best thing to do with cars and buses when intersections have two separate green phases. Furthermore, there are generally more modes of transport at intersections, like bicycles and pedestrians. The effect of pre-signals on these modes should also be studied.

From the policy point of view, safety is usually the first priority with intersection design/redesign. Therefore, some measure of safety of the proposed tandem design needs to be studied before idea is tested in the field. The tandem design will induce more lane changes so that vehicles get sorted. But also, there will be less interaction between buses and cars. Whether there will be safety problems in this situation needs to be studied.

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