Signal Progression Impacts on Transit Buses as Travel Time Probes

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Abstract

With the deployment Automatic Vehicle Location systems to monitor transit vehicles (and other fleet vehicles), there have been several efforts in recent years that seek to leverage these data to also obtain arterial travel times for the private vehicle population. The fleet vehicle data capture the traffic conditions, but they also capture behavior unique to the fleet, e.g., servicing passengers at a bus stop. There are several strategies used in conventional practice to eliminate the biases that occur in the vicinity of the bus stop. While investigating the benefits of using a perception sensor to identify ambient traffic conditions around the bus and correct for transit operations, the work revealed that even a perfect correction for local conditions resulted in large deviation between the travel time measured from the bus and the actual travel time experienced by the surrounding private vehicles.

This research uncovered a fundamental issue affecting almost all systems that use buses as arterial travel time probes: the fact that transit operations inevitably pull the bus out of the traffic signal progression no matter what corrections are made locally at the bus stop. The impact at subsequent traffic signals far downstream of a bus stop can be much larger than the local effects at the bus stop itself. This point is an important finding for any system that seeks to use transit vehicle probes to estimate the private vehicle travel times. To date the literature has made little consideration of the signal progression biases relative to the private vehicles that occur far beyond the bus stop. Finally, though the focus the present work is buses, the basic findings should apply to other fleets used as travel time probes as well if the given fleet behavior differs from the private automobiles.

Keywords

travel time, traffic probes, transit buses, signal progression

Introduction

Probe vehicles are often used as an effective means for obtaining arterial travel times (Omrani et al., 2013; Remias et al., 2013). The probe vehicle data typically come from vehicles already traveling the network, and either employ on-board devices broadcasting the probe vehicle's positioning information for fleet management, e.g., automatic vehicle location, (AVL) (Bertini and Tantiyanugulchai, 2003; Cathey and Dailey, 2002; Hall and Vyas, 2000); cell phone tracking for location based applications (Bar-Gera, 2007; Herrera et al., 2010; Liu et al., 2008)*;* or wayside sensors tracking the vehicle through the network, e.g., Bluetooth ID (Saeedi et al., 2013; Wasson et al., 2008), automatic number plate recognition (ANPR) (Hasan et al., 2011; Takaba et al., 1991), and magnetic signature based vehicle re-identification (Kwong et al., 2009). In addition to travel time estimation, arterial probe vehicles can assist in functions critical to improving signal operation such as the identification of signal timing (Hao et al., 2012) and queue length estimation (Ban et al., 2011)

This paper focuses on the growing use of fleet vehicles in general and specifically transit buses as traffic probes for traveler information and traffic control (Bertini and Tantiyanugulchai, 2003; Cathey and Dailey, 2002; Hall and Vyas, 2000). Such fleet vehicles inherently behave differently than the private vehicle population. The drivers are professionals who are on the road more hours of the day than most private vehicle drivers and many fleet vehicles travel predefined routes at regular intervals.

The fleet vehicle data capture the traffic conditions, but they also capture behavior unique to the fleet, e.g., servicing passengers at a bus stop. The unique fleet behavior can undermine accuracy under the common practice of assuming the fleet vehicles are typical of the surrounding traffic stream, e.g., Yoo et al. (2005) found that the travel time from taxis as probes exhibited a

dependency on the presence of a paying fare. When using buses as traffic probes there have been various efforts to remove the dwell time at bus stops. Bertini and Tantiyanugulchai (2003) used two techniques to remove bus stop dwell time: a *hypothetical bus* that removes the bus stop dwell time estimated via a geo-fence stop-circle combined with a door sensor, and a *pseudo bus* that only uses the maximum speed between road segments to estimate the travel time. Bertini et al. (2005) extended the dwell time estimation techniques to evaluate the effect of coordinated signal timing changes on travel times. Cathey and Dailey (2002) took a different approach by creating virtual point detectors along the bus route and used filters to determine if congestion exists at a given virtual detector. Some works attempt to predict arrival times by estimating the boarding time for passengers, e.g., (Bae and Kachroo, 1995), but Meng and Qu (2013) found that this dwell time estimation problem has proven to possess "a high degree of uncertainty." Others seek to use bus data to detect congestion via the reported travel times, travel distance, and bus stop dwell time, but Hall and Vyas (2000) found, "little correlation between speed estimates determined by the transit probe algorithm and recorded automobile speeds." None of these techniques are perfect. Those employing a door sensor may falsely attribute idling at time points to traffic congestion if the door remains closed. Stop-circles may erroneously exclude time when the bus is actually stopped due to traffic conditions if it is within the circle and may fail altogether if the boarding/alighting occurs away from the pre-assigned bus stop location. Finally, the maximum speed methodologies eliminate the ability to measure signal delay altogether. To date little consideration has been made in the literature of any biases beyond the bus stop duration in the use of transit buses as traffic probes.

While investigating the benefits of using a perception sensor to monitor ambient vehicles near the bus and correct for the impacts of transit operations, the work revealed that even a

perfect correction for local conditions resulted in large deviation between the travel time measured from the bus and the actual travel time experienced by the surrounding private vehicles. This research uncovered a fundamental issue impacting almost all systems that use buses as arterial travel time probes: even when the transit operation times are completely accounted for at the bus stops, large biases relative to the private vehicles remain. Transit operations inevitably pull the bus out of the traffic signal progression no matter what corrections are made locally at the bus stop, which can impact the bus's travel time long after it leaves the stop and reentered the traffic stream. This point is an important finding for any system that seeks to use transit vehicle probes to estimate the private vehicle travel times. We are not aware of any literature that considers these progression impacts far from the bus stops and have only found a single, brief comment in the literature related to this problem, "buses can also tend to lose the ability to take advantage of traffic signal timing progression strategies on arterials," (Berkow et al., 2008). Although the focus of the present work is on buses, the basic approach should apply to other fleets used as travel time probes as well, e.g., taxis (Liu et al., 2009; Zhan et al., 2013) or municipal vehicles if the given fleet behavior differs from the private automobiles.

The remainder of this paper is organized as follows: First we briefly introduce transit buses as travel time probes and illustrate the progression impacts and other errors that transit operations can induce when interacting with queues. Second, we present the dataset used in this analysis. Third, we discuss the simulation methodology. Fourth, we present the results. Finally, we close with a discussion and conclusions.

Transit buses as probe vehicles

AVL equipped transit buses are attractive for use as traffic probes because they are already traveling the network, reporting their status in real time. Transit buses typically operate

on major arterials at regular time intervals along fixed routes that cover many kilometers a day. As noted above, the unique behavior of buses means they do not behave like the surrounding traffic stream of private vehicles. Several approaches to using transit vehicles as travel time probes attempt to segregate the transit operations from traffic operations, using one or more of the three techniques discussed in the introduction. A commonality among these techniques is that each one only uses information regarding the bus's own trajectory to make travel time estimates. None of these techniques provide insight into the biases that arise when using a transit bus to estimate travel times for the private vehicles away from the bus stops, e.g., the impacts on signal progression.

Transit buses experience travel times that are inherently different from those experienced by the private vehicles due to a number of factors associated with servicing passengers at bus stops and we refer to these factors as *bus biases*. The bus stop creates a bias at the bus stop location in three ways: the time spent at the bus stop, the time gained *decelerating to* and *accelerating from* the stop, and any merging delay while the bus is waiting for an acceptable gap to reenter the traffic stream (of course the bus only incurs merging delay if the stop is outside the stream of traffic, such as a bus bay, merging delay will not be incurred curbside). While this paper considers the impacts on the signal progression, other potential bus biases include travel time differences across lanes, time point idling, and the different vehicle dynamics of cars and buses.

Whenever a bus stop is located immediately upstream of a signalized intersection the interactions with the queue can impact a bus's travel time in several ways. These influences can both increase and decrease the signal delay experienced by the bus, depending upon the nature of the interaction. Figure 1a-b illustrate two typical situations, in each case showing a time space

diagram containing private vehicle trajectories (light curves) and a single bus trajectory (bold curve). Traffic flows upwards in this figure with a signalized intersection stop bar at 110 m and a bus stop at 91 m. The bus stop dwell time, signal delay, and the signal red phase are delineated by horizontal bars at the bottom of each subplot. Figure 1a shows a bus experiencing signal delay that it would have avoided had the bus not stopped to service passengers. While servicing passengers during the *Bus Stop Dwell Time*, the signal changes from green to red (shown by the *Red Phase* bar) and the queue grows back to the bus. In this case, after removing the bus stop dwell time the adjusted bus travel time still includes an extra delay roughly equal to the duration of the red phase that a private vehicle arriving at the same instant as the bus would not experience. Figure 1b shows the opposite case, where the bus stop reduces the bus's signal delay relative to a private vehicle. Here the bus reaches the stop before the red phase's queue and soon after the bus finishes servicing passengers the signal has changed to green. So after removing the bus stop dwell time the adjusted bus travel time would be shorter than that of a private vehicle arriving at the same instant. Thus, when a bus stop interacts with a queue for a signalized intersection, relative to a private vehicle arriving at the same time, a bus may experience an increase (Figure 1a) or decrease in signal delay (Figure 1b) due to transit operations with impacts that can be as large as the red phase duration. The conventional stop-circles and door sensors used to subtract transit operations off the travel time would not be able to catch these errors and they would remove the signal delay too. Hence our original motivation to use a perception sensor to monitor the ambient vehicles near the bus, it should be possible to catch these two situations and preserve any signal delay beyond the time necessary for transit operations.

Unfortunately, as this work discovered, similar biases can also occur even when the bus stop is far from the signalized intersection. Consider Figure 1c-d, and the different signal delays

experienced by a bus (dark bold curve) and a private vehicle (gray bold curve) that enter at the same time. As before, the thin gray curves represent the remaining private vehicles. The bus stop can pull the bus out of progression (or the lack thereof), either decreasing the signal delay (Figure 1c) or increasing it (Figure 1d) far away from the bus stop. In this case even using a perception sensor to monitor the ambient vehicles will not be able to catch these two situations, because the change in delay is never evident in the ambient vehicles, it occurs far from the bus stop. For the remainder of this paper we will investigate the magnitude of these biases, in particular, progression due to signal coordination and how these biases might degrade the efficacy of transit buses as travel time probes.

Progression in NGSIM Lankershim dataset

Because pure simulation is always subject to the underlying models and calibration, this research used empirical data to the maximum extent possible. To this end, the work used the Next Generation SIMulation (NGSIM) Lankershim dataset (FHWA, n.d.) to provide vehicle trajectories traversing a signalized arterial roadway. The data contains actual vehicle trajectories measured at 10 Hz over a 488 m long arterial segment on Lankershim Blvd. between the US-101 freeway and James Stewart Ave. in Los Angeles, California. These real world trajectories consist of private vehicles behaving naturally, and thus, minimizing the number of assumptions that must be made when compared to strictly model based simulations.

Two 15 minute observation periods were collected on the morning of June 16, 2005, the first beginning at 0830 and the second at 0845. The traffic signals operate on a common cycle in a semi-actuated manner. The road travels along a roughly north-south path and contains four intersections, numbered sequentially beginning with the southernmost. For both directions of travel on Lankershim Blvd. the queue (and thus arrivals) at the most upstream intersection are

not recorded in the data, limiting the analysis to only three intersections for each direction of travel. Figure 2 shows the study area schematically. The linear reference system provided with the NGSIM data is used to locate the intersections and vehicles, with the origin at the southernmost boundary.

To judge the quality of progression within the analysis area we generated queuing diagrams and calculated the progression factor (PF). Queuing diagrams were constructed for each approach using virtual arrival curves and a classical point queue model, where a *virtual arrival* is the time when a vehicle would have arrived at the head of the queue (i.e., the stop bar) had it not encountered any delay upstream of the stop bar. The actual arrivals are measured at some location upstream of the physical queue and then shifted by a free flow travel time to the stop bar to yield the virtual arrival curve. The area between the two curves gives the total delay in vehicle-hours. Given first in, first out arrivals, the horizontal distance between the departure curve and virtual arrival curve shows the actual delay experienced by each successive vehicle on the segment. When the two curves fall (predominantly) on top of one another it indicates little delay, and thus, good progression on that approach.

This work defines each segment to span the distance from one intersection to the next. The virtual arrival times are calculated from the time a vehicle first enters the segment plus the distance of the segment divided by the vehicle's maximum speed while in the segment, via Equation 1, where x_2 is the location of the stop bar, x_1 is the entry location onto the segment, s is the maximum observed speed, t_0 is the time of entry onto the segment and t_a is the virtual arrival time. Taking the time and location of a vehicle's arrival in this fashion allows for the vehicle to enter anywhere on the segment, e.g., from mid-block entrances, and not just a fixed location at the upstream intersection; while also allowing arrivals to be calculated so long as the

queue does not overrun the entire segment. The maximum speed obtained was used instead of a nominal speed (e.g., free flow speed) in order to capture the effects of acceleration and congestion, where vehicles may not be able to achieve free flow speeds (similar to the pseudo bus in Bertini and Tantiyanugulchai, 2003). The departure time, t_d is recorded as the time when the vehicle crosses the stop bar. In the rare case that the calculated $t_a > t_d$ then t_a is set equal to t_d for that vehice.

$$t_a = \frac{(x_2 - x_1)}{s} + t_0 \tag{1}$$

In Figure 3 the queuing diagram for each intersection in each direction for the two time periods is shown separately. The arrivals in each subplot are shown with a grey curve, while the departures are shown with a black curve. The area between the arrival and departure curves is shaded light gray, denoting the point queue length. The northbound arrival rate at intersection 2 appears to be nearly constant due to the heavy right turning traffic coming from the freeway at intersection 1. Also apparent is a drop in volume past intersection 2 (an entrance to a large parking lot), and it is most pronounced in the southbound subplots. Qualitatively, most of the approaches appear to have good progression (i.e., the majority of vehicles arrive during the green phase) with the exception that occasionally the signal changes before a platoon has completely cleared, most pronounced in the northbound intersection 4 queuing diagrams.

The *PF* was calculated for each approach using the Highway Capacity Manual method (Transportation Research Board, 2010), repeated here in Equation 2, where *P* is the *proportion of vehicles arriving during the green phase*, and λ is the *green phase to cycle ratio* for the given approach, as follows. First P was calculated by determining the number of vehicles that stop anytime while on the approach, divided by the total volume served by that approach. Of note with this method it does not matter what the cause of a stop is (i.e., both signal and non-signal

related) all of the stops are attributed to signal phase. One such non-signal cause that was evident in this dataset is the queue for a turning movement overrunning its storage bay and blocking the through traffic. Next, λ was found by using the signal timing sheets provided with the NGSIM dataset for the period of analysis, and the average green phase was divided by the average cycle length for each 15 minute period. The resulting progression factors are given in Table 1.

$$PF = \frac{(1-P)}{(1-\lambda)} \tag{2}$$

These data show that a broad range of progression factors exist within the analysis area, ranging from 0.31 for southbound intersection 3 to 1.50 for southbound intersection 1. Only one approach, northbound intersection 4, exhibits a PF that is delay reducing (PF below unity) for one analysis period and delay increasing (PF above unity) for the other. The northbound intersection 2 progression factor is poor, due to the low fraction of green arrivals. Such a result is interesting, in that the nearly constant arrival rate on that approach should drive the progression factor to unity. Southbound intersection 1 shows a poor progression factor even though the green phase to cycle ratio is high. In the second period λ was 82%, but the fraction of green arrivals was only 73%, indicating that a portion of the green time was wasted. With the wide-ranging progression factors, the NGSIM Lankershim trajectories provide a rich dataset for evaluating the effect of progression on a transit bus as a travel time probe.

Simulation methodology

One of the challenges of this evaluation is the difficulty in collecting actual arterial travel times. Rather than simulating all of the vehicles, we chose to use actual vehicle trajectories from NGSIM and simulate the bus. While our simulated bus is simplistic, it encompasses more than enough details to clearly demonstrate the primary objective of this paper: that servicing passengers at a bus stop will pull the bus out of progression experienced by the private vehicles.

All of the NGSIM trajectories were taken as true. Simulated transit bus trajectories were then superimposed upon the NGSIM trajectories in the outside lane by modeling the characteristics of a bus's operation on the roadway. The simulated bus obeys traffic laws, maintains a safe following distance, decelerates to bus stops and accelerates from bus stops in a realistic manner. Since our focus is what the bus does and sees in the adjacent lanes, we make no attempt to simulate the impact of the bus on vehicles behind it. Each bus trajectory was calculated based on a set of input parameters: travel direction, entry time, bus stop dwell time, and bus stop location. The bus simulation starts at a predefined entry location (the extremities of the NGSIM data) traveling at free flow speed. The bus maintains free flow speed until the presence of a downstream vehicle, a red light, or a bus stop causes the bus to decelerate. Vehicle awareness for car following is realized by calculating the distance to the downstream vehicle as well as the closing speed. If the bus is about to violate a minimum following distance, the bus decelerates at an appropriate rate to meet the prescribed following distance. Thus, a bus will realistically queue behind slow or stopped traffic, and travel at a slow speed whenever it is within a queue. Bus stop awareness is realized by decelerating at a constant rate starting at the location necessary to reach zero km/h at the stop location, and then remain stationary for the prescribed bus stop dwell time. For this study we assume the bus pulls into a turnout, and thus, has to re-enter the traffic stream after servicing passengers. The bus will merge back in to the outside lane when an acceptable gap is present. Any time the bus is traveling below free flow speed, and there is no downstream constraint, it will accelerate at a constant rate of 2 m/s^2. Since the real vehicles do not see the simulated bus, we have to account for the possibility that they may overtake the bus's location. If a real vehicle overtakes the simulated bus in its lane of travel, the bus ignores the overtaking vehicle until it reaches a distance that exceeds the minimum

following distance per the car following model, to prevent the bus from decelerating in response to a physically impossible event that is an artifact of the simulation. These overtaking events occur primarily when the bus is slowing for a bus stop that the private vehicle population does not slow for.

To create a rich dataset, several bus stop locations and dwell times were simulated. Three bus stop locations A, B, and C were set at 91 m, 213 m, and 366 m, respectively, as shown in Figure 2. These locations were chosen so that stop A would be within the queue for intersection 2 for a northbound bus and in the discharge of intersection 2 for a southbound bus; while B and C would be outside the queue for any intersection in both directions. These bus stop locations capture various conditions that are expected in the real world, including when a bus stop interacts directly with a queue (as per Figure 1a-b). At each bus stop location, 25 different stop dwell times were simulated, from 0 to 120 seconds, with a five second increment between steps. A zero second bus stop includes decelerating to a stop and then immediately accelerating, which has a meaningful impact on travel time. The longest dwell time was chosen so that the stop duration exceeded the common signal cycle length of 100 seconds. For each of the bus stop locations and dwell time steps, bus trajectories were simulated entering the area of observation every 10 seconds over the usable NGSIM data time frame (i.e., care was taken so that the reported NGSIM trajectories were present for the entire bus trip). By doing so, a constant arrival rate was simulated, which mimics well the northbound private vehicles. The southbound private vehicles are already platooned upon their arrival into the study area, so in this case the use of a constant arrival rate for the southbound intersection 3 buses presupposes that the bus is already out of progression due to transit maneuvers. A minimum of 78 trajectories for each combination of: a single bus stop location, dwell time, observation period and direction were created. Additionally

a set of non-stop simulated trajectories was generated to represent the same vehicle arrivals in the absence of bus stops (i.e., the simulated vehicle performs no transit maneuvers, does not decelerate for a bus stop, and operates using only its car following model). The complete simulation of all bus stop locations, dwell times, and entry frame permutations consists of 110,448 unique bus trajectories.

The current state of the practice relating bus travel time to arterial time is to estimate and then subtract the time consumed by a transit maneuver, and frequently this process is simplified to only subtract off the dwell time. To quantify how un-modeled bus biases may elicit travel time estimation errors, four dwell time detection methods were simulated. Method 1 was perfect information, i.e., the exact dwell time was known. Method 2 is the hypothetical bus as proposed by Tantiyanugulchai and Bertini (2003), where the stop-circle and door sensor is used. Here the stop-circle is a 30.5 m radius around the bus stop where the entry time into, and the departure time out of the circle is recorded. It is assumed that the door opens the instant the bus comes to a complete stop (even for the zero second stop case) and this time is recorded. The dwell time is calculated as the difference between the departure time from the stop circle and the door opening time. Method 3 is a simplification of method two, where the door sensor is omitted and the difference in the arrival and departure times from the stop circle are used to estimate the transit maneuver time. Method 3 was intended capture the time lost due to deceleration to the bus stop.

Method 4 uses a perception sensor to monitor the speeds of nearby vehicles traveling in the same direction so that transit maneuvers can be identified with no a priori map or link information. The perception sensor could be LIDAR, video, or in the simulated case: radar records the movement of traffic around the bus. From the movements, one can separate a queuing movement, where the private vehicles begin to slow along with the bus, and a transit

maneuver where the private vehicles maintain speed when the bus decelerates. A rudimentary algorithm was employed in this simulation that uses radar observing the adjacent lane's traffic over a narrow field of view. When the bus comes to a stop, the radar observations are processed for the duration of the stop and a small window around it. If any observed radar speed during this time exceeds a threshold or no radar targets are seen at all then the stop is considered to be due to a transit maneuver, otherwise the stop is considered to be due to queuing.

Simulation Results

The results of travel time estimates using the four methods above were compared first to each other and then to those of the private vehicles. The results were segregated by method, direction, observation period, and bus stop location. Each of these segregated results consists of the average of the travel time estimated from the permutations of the bus stop dwell time and entry time.

The first analysis compares Methods 2, 3 and 4 against the perfect information case: Method 1. The objective was to determine which method best achieved the goal of estimating the dwell time of the bus. The results of this analysis are presented in Table 2 where the first four data columns present the average travel time (in seconds) after subtracting the estimated dwell time for the given method from the actual travel time through the study area, averaged across all of the simulated bus stop dwell times and entry times for the given condition. The final three data columns present the difference between the given estimation method and the perfect information case. Here Method 4 with the perception sensor shows the smallest difference from the perfect information case under all simulated scenarios. In all cases, there exists a negative bias in the travel time estimation (i.e., each method's travel time estimate was less than the perfect information case), signifying an over estimation of the bus stop dwell time. The cause of this

negative bias is the inclusion of other transit maneuver artifacts within the estimation methods, specifically: merging delay and acceleration. While the perfect information case subtracts off just the dwell-time, the resulting estimated time still includes the merging delay. Methods 2 and 3 incorporating stop-circles will discard all time from the termination of servicing passengers until the departure from the stop-circle region (including the merging delay), while Method 4 using perception sensors will also exclude the merging delay as long as the bus does not move. The results for northbound bus stop A show a larger bias than the other intersections. This result was due to the inadvertent removal of signal delay, when the bus queues within the limits of the stop-circle, exacerbated by the nearly constant arrival rate. Method 4 with the perception sensor did a better job segregating the dwell time from the signal delay compared to Methods 2 and 3.

The second analysis compares the efficacy of using transit bus travel times to estimate private vehicle travel time given non-unity progression factors. To this end the series of non-stop trajectories were simulated which had no transit maneuvers to capture the travel time of private vehicles under the simulated bus's lane choice. These mean travel time of vehicles traveling the entire length of the arterial without turning are recorded by the direction and 15 minute observation period in the first data column of Table 3, *Private Vehicles- Bus Lane*. The non-stop simulated vehicles are used for reference instead of the actual vehicle trajectories to control for the uniform entry times already used in the simulation rather than the non-uniform entry times of the actual vehicles. Nonetheless, for comparison, the NGSIM analysis report (Cambridge Systematics, 2006) provides aggregate travel time values for all vehicles across all lanes and these are presented in the *Private Vehicles- All Lanes* column. As in Table 2, the third through sixth data columns report the average travel time estimate across all of the simulated bus stop dwell times and entry times for the given method after subtracting off the measured dwell time.

Now, however, the seventh through tenth data columns present the error in seconds for the given method when compared to the corresponding private vehicle times in the same lane as the bus, i.e., data column one. The final column reports the progression factor at the first intersection downstream of the bus stop.

From these data one can conclude that none of the methods provide a consistently unbiased travel time estimate, and that all four of the methods (including the perfect information of Method 1) experienced over 30% error under some conditions. Depending upon the relationship of the bus stop location with the signalized intersection and progression, a given method may yield a positive or negative bias in the travel time estimate. The relationship is complex because the travel time depends upon the bus stop's interference with progression on all subsequent signals. The complexity of the progression's effect far downstream of the bus stop is shown by the lack of consistency in Method 4's results even though the perception sensors did a good job controlling for bus delays in the vicinity of the bus stop. The inconsistency of the magnitude and direction of the bias as it relates to the progression factor can be observed using the southbound 0830 bus stop A and B results. Both of these biases have the same direction (positive) even though the bus stop A case has a beneficial progression factor, and the southbound 0830 bus stop B case has a detrimental progression factor.

Table 3 shows that Method 4 is generally the best for northbound but Method 3 is the best for southbound. The mean absolute percent error under Method 1, perfect information, is 9.6% for the northbound estimates and 34.5% for southbound. Similar results are found for Method 4, the perception sensor case, with 7.6% and 26.6% error for the northbound and southbound estimates, respectively. The southbound progression factors (final column of Table 3) deviate further from unity than the northbound, suggesting that a portion of the errors in

estimating the private vehicle travel times from a transit bus are due to the effects of signal progression. There may be other factors contributing to the differences in error between travel directions, such as storage bay overruns, differing volumes and running speeds.

The effects of progression on the bus travel time can be further demonstrated by seeing how the average bus travel time fluctuates as a function of dwell time. Figure 4 shows the bus's average travel time as a function of stop duration at stop B after subtracting off the known dwell time via Method 1. Note that while the tables show the results averaged across all entry times, this figure shows typical results for a single specific entry time. If there were no signal progression impacts the curves should be flat, yet the northbound runs exhibit a 25 sec range and the relatively quicker southbound trips exhibit more than a 10 sec range. Here one can see that travel time is dependent on the bus stop duration, even though the original bus arrival rate is constant, and that dependency is cyclical with the 100 sec signal cycle length, shown most dramatically by the northbound data for both time periods, peaking at 15 sec and 115 sec bus stop durations. Also of note is that travel times are observed above and below the time experienced with a zero second bus stop (the leftmost point in each curve), signifying that the interaction with progression can result in both reduced and increased travel time, even if the progression factor is already significantly different than unity. Thus great care should be taken when attempting to correct for this progression bias, as one cannot presume that the effect will simply aid a poor progression or harm a good progression.

Discussion and Conclusions

This research uncovered a fundamental issue impacting almost all systems that use buses as arterial travel time probes: even when the transit operation times are completely accounted for at the bus stops, large biases relative to the private vehicles remain. Even after removing the

transit related delays of servicing passengers at a stop, the delay will knock the bus out of progression and thus, it will encounter different delays than the private vehicles when reaching signals downstream. The progression errors at subsequent traffic signals far downstream of the bus stop can be much larger than the local impacts at the bus stop. The net impact could be positive or negative. In short, using data from a single run, the transit buses as probes cannot correct for the progression errors that occur far away from the bus stop location. The work was limited to the fairly short corridor in the NGSIM dataset and this paper simulated a single bus stop. In a corridor with many bus stops the impacts could be much larger as the different stops interact with the signalized intersections. Across successive intersections the combined transit operations and progression impacts could compound in to large biases or they may cancel out. Thus, while it is clear the interaction is an important factor that must be accounted for, one cannot determine a priori how this factor will impact the travel time estimates without studying the interactions unique to the given corridor.

This caution should not be limited to the use of transit buses as probes, but instead, extend to the use of any fleet of vehicles as probes if the given fleet behavior differs from the private automobiles, e.g., taxis and public service vehicles may exhibit biases against the private vehicle population. Furthermore, while this paper considers the impacts of servicing bus stops on the signal progression experienced by a bus, other potential bus biases include travel time differences across lanes, time point idling, and the different vehicle dynamics of cars and buses.

The simulation process sought to minimize the number of assumptions. All of the private vehicles followed the real world trajectories collected in NGSIM. We use NGSIM to create a flow of private vehicles for a single simulated bus to travel in and respond to, and the only simulated vehicle in a given run was the bus. Meanwhile, since we are only studying the impacts

upon the bus, we do not need to consider the impact of the simulated bus on the vehicles behind the bus. The simulation did not capture all of the possible dynamics, e.g., a real bus might exhibit a different acceleration profile than simulated or cruse at a speed slightly slower than the surrounding automobiles. These omitted dynamics would shift the arrival time of all of the simulated buses, redistributing the impacts of signal delay, with little change in the average impact. More precise modeling might make the specific measurements more accurate, but it will not change the fact that the bus is knocked out of progression. However, the exact value of the bias is inconsequential since there is so much variance due to the specific time the bus arrives in the cycle that it would be impossible to derive a correction factor based strictly on the data from the bus, i.e., the bias should vary from corridor to corridor and from day to day.

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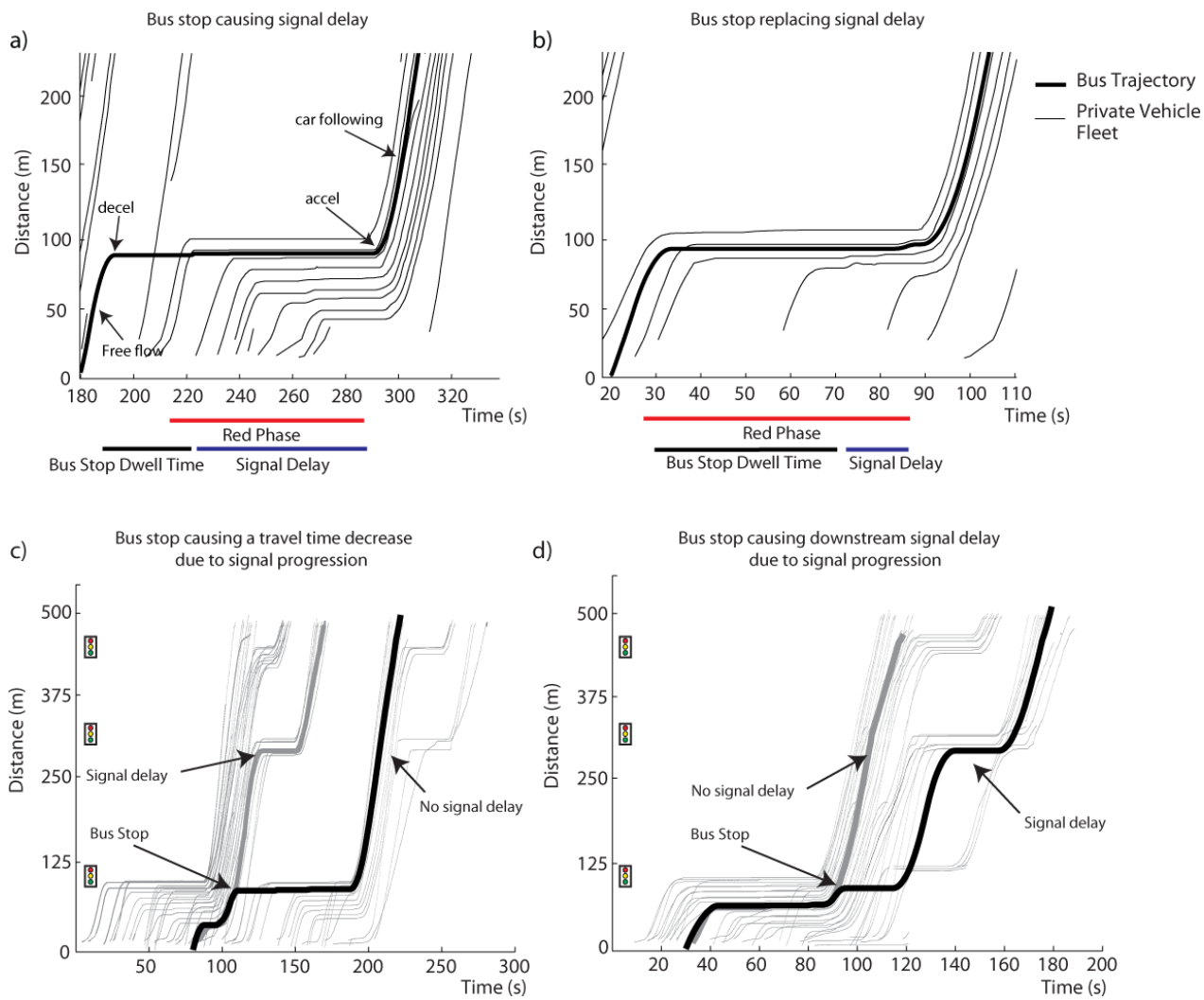

Figure 1, Time space diagrams showing a bus experiencing (a) additional signal delay and (b) reduced signal delay while simultaneously serving passengers at a bus stop within a queue. As well as experiencing (c) reduced signal delay and (d) additional signal delay far downstream of a bus stop due to the dwell time pulling the bus out of signal progression (for reference a second, lighter trajectory shows what the bus would have experienced had it not stopped to serve passengers).

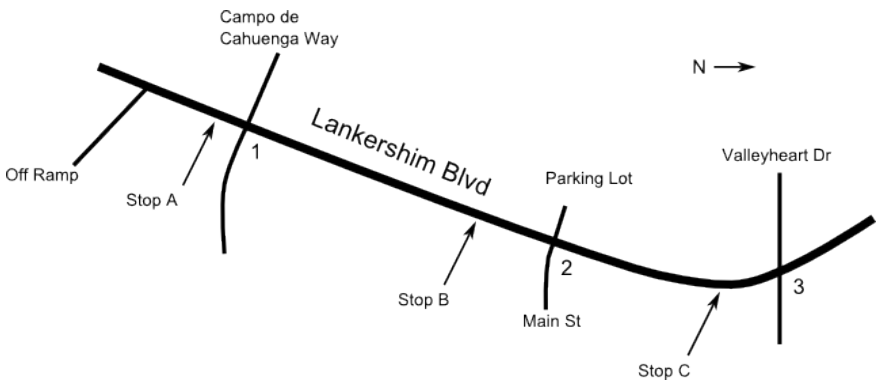

Figure 2, Schematic of the NGSIM Lankershim study area, intersections are labeled with numerals, bus stop locations labeled alphabetically

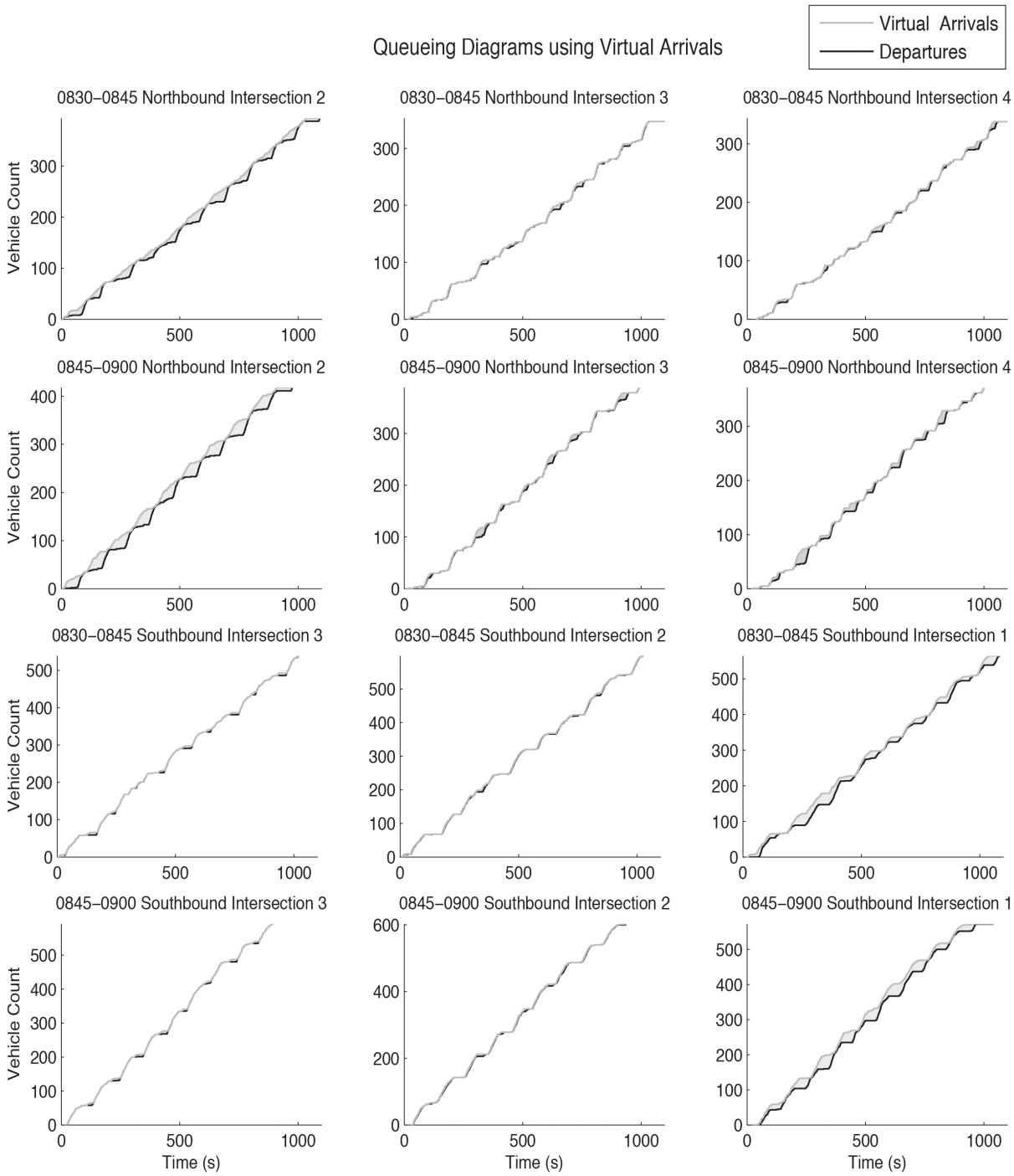

Figure 3, Queuing diagrams for all available northbound and southbound approaches in the NGSIM Lankershim dataset.

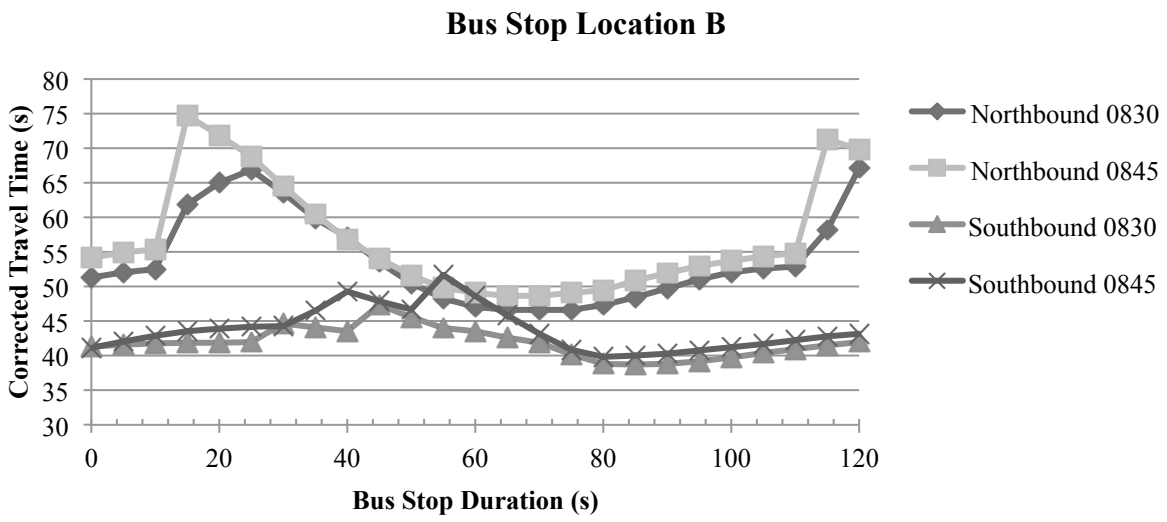

Figure 4, Dependency of the estimated travel time with bus stop duration removed as a function of the duration of the bus stop. Note the cyclical nature about the signal cycle length, 100 s.

Table 1, Green arrival fraction and progression factor for the intersections and observation periods of the NGSIM Lankershim dataset. Only northbound and southbound approaches are presented.

Approach	Northbound 2	Northbound 3	Northbound 4	Southbound 3	Southbound 2	Southbound 1
Green Arrivals, P 0830-0845	0.31	0.91	0.83	0.95	0.63	0.79
Green Phase to Cycle, λ 0830-0845	0.40	0.83	0.76	0.85	0.46	0.83
Progression Factor, PF 0830-0845	1.15	0.54	0.71	0.33	0.69	1.24
Green Arrivals, P 0845-0900	0.18	0.82	0.68	0.93	0.75	0.73
Green Phase to Cycle, λ 0845-0900	0.41	0.79	0.71	0.77	0.55	0.82
Progression Factor, PF 0845-0900	1.40	0.86	1.09	0.31	0.56	1.50

Table 2, Comparison of bus stop dwell time estimation methods. The first column presents the perfect information case to which the other estimation methods are compared. All units are in seconds except for the time of day, which is in hhmm format.

Direction	Time and Bus Stop Location	1) Perfect Information	2) Hypothetical Bus	3) Stop-Circle	4) Perception Sensor	2) Hypothetical Difference	3) Stop-Circle Difference	4) Perception Sensor Difference
Northbound	0830, A	103	71.0	60.9	96.6	-31.6	-41.7	-6.0
	0830, B	94.7	82.0	77.9	86.2	-12.7	-16.8	-8.5
	0830, C	98.9	91.6	87.4	97.1	-7.3	-11.5	-1.8
	0845, A	135	87.3	81.1	124	-47.3	-53.5	-10.6
	0845, B	113	93.6	89.4	96.3	-19.5	-23.7	-16.8
	0845, C	118	110	106	113	-7.5	-11.6	-4.6
Southbound	0830, A	80.1	70.7	65.8	76.3	-9.4	-14.3	-3.8
	0830, B	80.6	68.8	64.4	76.2	-11.8	-16.2	-4.4
	0830, C	83.4	71.7	67.7	78.3	-11.7	-15.7	-5.1
	0845, A	89.7	77.1	72.5	86.4	-12.6	-17.2	-3.3
	0845, B	93.8	75.7	71.4	85.5	-18.1	-22.4	-8.3
	0845, C	90.5	77.8	73.7	84.6	-12.7	-16.8	-5.9

Table 3, Comparison of the various dwell time estimation methods against the travel time of the private vehicle average. All units are in seconds except for the time of day, which is in hhmm format.

Direction	Time and Bus Stop Location	Private Vehicles – Bus Lane	Private Vehicles – All Lanes	1) Perfect Information	2) Hypothetical Bus	3) Stop-Circle	4) Perception Sensor	1) Perfect Information error	2) Hypothetical bus error	3) Stop-Circle error	4) Perception Sensor error	Progression Factor
Northbound	0830, A	88.9	67.3	103	71.0	60.9	96.6	14.1	-17.9	-28.0	7.7	1.15
	0830, B	88.9	67.3	94.7	82.0	77.9	86.2	5.8	-6.9	-11.0	-2.7	0.54
	0830, C	88.9	67.3	98.9	91.6	87.4	97.1	10	2.7	-1.5	8.2	0.71
	0845, A	113	98.2	135	87.3	81.1	124.0	22	-25.7	-31.9	11	1.40
	0845, B	113	98.2	113	93.6	89.4	96.3	0	-19.4	-23.6	-16.7	0.86
	0845, C	113	98.2	118	110.1	106.0	113.0	-5	-2.9	-7.0	0	1.09
Southbound	0830, A	62.8	60.3	80.1	70.7	65.8	76.3	17.3	7.9	3.0	13.5	1.24
	0830, B	62.8	60.3	80.6	68.8	64.4	76.2	17.8	6.0	1.6	13.4	0.69
	0830, C	62.8	60.3	83.4	71.7	67.7	78.3	20.6	8.9	4.9	15.6	0.33
	0845, A	65.5	63.4	89.7	77.1	72.5	86.4	24.2	11.6	7.0	20.9	1.50
	0845, B	65.5	63.4	93.8	75.7	71.4	85.5	28.3	10.2	5.9	20.0	0.56
	0845, C	65.5	63.4	90.5	77.8	73.7	84.6	25	12.3	8.2	19.2	0.31