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One Light, Two Light, Red Light, Green Light: An Analysis of Signal Priority on the Metro G Line

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One Light, Two Light, Red Light, Green Light:

An Analysis of Signal Priority on the Metro G Line

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16. Abstract Los Angeles County Metropolitan Transportation Authority (LA Metro) planning staff, working alongside engineers from the Los Angeles Department of Transportation (LADOT) seek to make improvements to the Metro G Line (Orange) busway to address a number of operational problems with the popular line. The Metro G Line is the backbone of transit in the San Fernando Valley, serving more than 22,000 pre-COVID-19 pandemic weekday boardings. Part of the problem for public transit in a chronically traffic congested place like Los Angeles is that buses typically have to compete for road space with private automobiles. As a result, buses get stuck in traffic. Light rail vehicles, when travelling on surface streets with cars, get stuck in traffic as well. The G line busway thus has a significant advantage, as it runs on its own dedicated route. Efforts to further separate the G line from nearby traffic, such as grade separated over- and under-passes or railroad-style gate arms at street crossings, will require complex planning and take considerable time and resources to implement. However, speeding up the G line with current infrastructure is possible by improving transit signal priority (TSP). TSP prioritizes a direction along a roadway by extending green time at signals so priority vehicles (in this case buses) can pass through an intersection without stopping. This report explores the current signal regime along the G line alignment, some of the history of the TSP system, and draws on case studies to develop applicable lessons to the Metro G line.		
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Disclaimer

One Light, Two Light, Red Light, Green Light

An Analysis of G Line Signal Priority

UCLA Institute of Transportation Studies

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Executive Summary

Los Angeles County Metropolitan Transportation Authority (LA Metro) planning staff seek to make improvements to the Metro G Line (Orange) busway to address a number of operational problems with the popular line. The Metro G Line is the backbone of transit in the San Fernando Valley, serving more than 22,000 pre-COVID-19 pandemic weekday boardings.

One option is to improve signal timing along the busway. Metro staff, in partnership with engineering staff at the Los Angeles (City) Department of Transportation (LADOT), are looking to strengthen the transit signal priority (TSP) system in place along the G line, whereby green time for the prioritized phase is extended so that more G line buses can pass through an intersection without stopping.

This report begins by introducing TSP, then reviews the relevant literature to assess the experience of TSP as implemented in cities throughout the United States and Europe, and then examines the history and challenges of how TSP has been implemented in Los Angeles, with a brief explanation of how it ties into the Automated Traffic Surveillance and Control (ATSAC) system used by the City.

In this analysis, I draw on signal timing charts, time-space plots, and other information provided by LADOT for the G line, as well as G line improvement reports created for LA Metro. I find that because of the long-standing “slow order” requiring buses to slow to 15 mph in intersections, as well as other technical limitations, the current signal timing regime for the G line does not reflect on-the-ground conditions. I conclude by recommending potential improvements to improve the operation of this marquis bus rapid transit alignment.

The report considers some elements that might make the TSP system in the San Fernando Valley more effective:

In examining the evidence of successful TSP systems from around the country, I find that the success of a TSP system hinges on political alignment from key stakeholders. LA Metro and LADOT should be clear about their agency objectives, and find compromise where they do not agree.

Evidence I reviewed indicates that LADOT’s traffic control systems have highly optimistic estimates of bus speeds and do not account for dwell times. This leads to buses waiting unnecessarily at signals, as buses miss the “green wave” of traffic signals. A spate of early crashes caused a “temporary” slow order to be passed in 2005. The slow order requires G line buses to slow to 15 mph in intersections. While rescinding the slow order may be politically fraught, it is one of the reasons that the G line is not performing as intended. Updating the traffic control system to better reflect on-the-ground conditions would benefit the G line immensely.

Any changes made to signal timing or sections speeds should be evaluated for safety and to ensure that speed benefits are materializing as expected. However, given the evidence presented, I am certain that the G line can be further improved to offer an even better transit experience.

Introduction

As transit agencies across the country ponder how to “build back better” from the pandemic, the Los Angeles County Metropolitan Transportation Authority (LA Metro) has been continuing its bus network redesign and overhaul - the NextGen bus plan. As part of that effort, bus stops are to be relocated, lines merged, and service frequency increased. This redesign is part of a holistic plan for transit in the Los Angeles region, including ambitious elements to speed up buses and light rail vehicles (LRV).

One key line of interest is the LA Metro G line (Orange). The Metro G line is the backbone of transit in the San Fernando Valley and the agency’s marquis bus rapid transit line. Serving more than 22,000 pre-pandemic weekday boardings, the G line is one of the most utilized routes in the LA Metro network, and the agency is interested in making further improvements to it (Chiland, 2019).

Part of the problem for public transit in a chronically traffic congested place like Los Angeles is that buses typically have to compete for road space with private automobiles. As a result, buses get stuck in traffic. Light rail vehicles, when travelling on surface streets with cars, get stuck in traffic as well. The G line busway thus has a significant advantage, as it runs on its own dedicated route. Efforts to further separate the G line from nearby traffic, such as grade separated over- and under-passes or railroad-style gate arms at street crossings, will require complex planning and take considerable time and resources to implement. However, speeding up the G line with current infrastructure is possible by improving transit signal priority (TSP). TSP facilitates the flow of transit vehicles through signalized intersections, increasing travel speeds and travel time reliability and improving the quality of transit service (Baker et al., 2002).

This introduction will cover the basics of high-quality transit service broadly, and transit priority and preemption in particular, in order to provide context for the current Los Angeles TSP systems. The material for this analysis comes primarily from published and internal reports and documents, with background information drawn from the Federal Highway Administration (FHWA), the National Association of City Transportation Officials (NACTO), and the Intelligent Transportation Society of America (ITS America), among others. This introduction also provides a high level overview of how TSP is implemented in the City of Los Angeles by its Department of Transportation (LADOT); the material for this part of the analysis comes from contemporary press coverage and reports from LA Metro and LADOT.

These data and information help inform possible improvements to the G line busway. Current signal timing reflects speed assumptions made when the G line was first opened. I find that because of the long-standing “slow order” requiring buses to slow to 15 mph in intersections, as well as other technical limitations, the current signal timing regime for the G line does not reflect the on-the-ground conditions. As a result, improvements are needed to improve the operation of this marquis bus rapid transit alignment.

Research Design

Staff at LA Metro had already gathered most of the LA Metro documents relevant to this study. The initial data I analyzed included prior reports on TSP on various parts of the LA Metro system, prior analyses of the G line alignment by consulting firms, and signal timing charts for intersections along the G line. Cooperation with staff at LADOT allowed me to access the time-space plots created by ATSAC for a significant portion of the G line alignment.

Information about ATSAC and other cities was gathered from LADOT reports, research literature on TSP, and interviews I conducted with engineering staff from various city departments across the country with active TSP systems. In particular, the information ultimately included for Santa Monica and Houston draw heavily from interviews I conducted with engineering staff in these cities. Many resources about ATSAC and its capabilities came from conversations and interviews with current and former LADOT staff, and my project supervisor at LA Metro was particularly helpful in clarifying details of LA Metro's and LADOT's traffic control systems.

The Benefits of Transit Speed Improvements

Frequent transit riders often lack access to a private vehicle, are disproportionately lower-income and people of color (Manville et al., 2018). Any improvement to transit speed and reliability is key to producing a more equitable transportation system, allowing easier access to jobs and essential services for those most reliant on transit. Moreover, for those who can access alternate travel modes, such as privately owned motor vehicles, faster and more reliable transit makes it a more attractive choice, potentially encouraging its use (Kittelson & Associates, Inc. et al., 2013).

But improving bus and light rail service in mixed traffic - having transit compete with automobiles and trucks for the same space - is easier said than done. Many factors can affect transit vehicle speeds, like how long it takes passengers to board and alight vehicles, how closely spaced stops are, how easy it is to rejoin the traffic stream, and general congestion levels (Boyle et al., 2014). Many options already exist for speeding up transit, including dedicating exclusive rights-of-way for buses, limiting people from driving in congested areas (e.g. through congestion charging), or redesigning transit networks to reduce the number of stops. Many of these options may be politically fraught or have long time horizons. Engineering solutions such as TSP may be the closest to a "silver bullet" or a "one-step solution" to improve G line operations (Chung, 2014). Accordingly, this report focuses on TSP, the LA Metro G line (Orange), and the potential of the former to increase travel time reliability and make transit a more robust option on the latter.

What is transit signal priority?

Before discussing transit signal priority, some terms need to be defined. A movement describes how a vehicle crosses an intersection (as in left turn, through, or right turn). Vehicles are described by their direction of travel when approaching an intersection. An eastbound left, for instance, describes a car initially travelling towards the east that makes a left turn in the intersection. A traffic signal phase is the timing interval that shows a green light to a given movement.[1] A basic overview of signal phasing is provided at the end of this document as Appendix A.

Preemption vs. Priority

With respect to signalization, it is important to note the difference between preemption and priority. The FHWA defines preemption as interrupting a traffic signal cycle in order to offer a green indication to an approaching vehicle (Koonce et al., 2008). Preemption is more often granted to rail vehicles with gate-separated rights of way and emergency response vehicles. Priority is less invasive than preemption in that it does not interrupt signal phasing wholesale to serve the priority vehicle. Instead, signal priority helps the priority vehicle move through an intersection, typically by showing the priority vehicle's phase an early green to shorten the time a transit vehicle is stopped at an intersection, or by extending the green to enable an approaching transit vehicle to clear the intersection without having to stop at all.

There are two types of signal priority: active and passive. Passive signal priority is based on pre-timed and pre-programmed signal phasing using existing knowledge of transit patterns along a corridor; signals are then timed accordingly to increase the probability that a priority vehicle, such as a bus, will "catch" a green pattern, limiting the amount of time spent stopped at a signal. In passive signal priority, these timing and priority rules do not change in response to fluctuating traffic conditions. Active TSP, in contrast, alters traffic signal phase timing to show more green time where a priority vehicle is detected. This helps the priority vehicle clear the intersection more readily (Koonce et al., 2008). There are many variations to this general schema, depending on local context. For instance, for a bus with a passenger stop on the far side of the intersection, signal priority may show a red shortly after the bus has cleared the intersection. This interrupts the traffic stream, allowing the bus to merge from the stop back into the travel lanes and continue its route. See **Figure 1** (starts next page, continues onto following page) for a diagram illustrating the various types of transit signal priority (NACTO, 2016).

[1] Traffic engineers often also refer to phase sets as simply phases; phase sets are any unique combination of movements that can happen simultaneously, for instance a northbound and a southbound through movement.(Buckholz, n.d.)

GREEN EXTENSION provides extra time for a detected transit vehicle to clear an intersection. Green extension is most applicable when transit runs at the back of the vehicle queue, as is common at the first signal after a far-side stop. Green extension may be the easiest form of TSP to implement on urban streets since it does not require unexpectedly truncating a pedestrian phase.

GREEN REALLOCATION shifts when in the signal cycle the green phase occurs—if the transit vehicle is on pace to arrive late, the green phase begins and ends late to accommodate transit. Phase reallocation provides similar benefits to phase extension, but with less impact to cross street traffic since the total green time per cycle does not change. This strategy requires AVL technology.

RED TRUNCATION provides a green phase earlier than otherwise programmed, clearing an intersection approach with a waiting transit vehicle sooner than otherwise. Red truncation requires the detection of the transit vehicle far enough away that the crossing pedestrian phase can clear. It is easiest to implement on long blocks or on transitways with predictable travel times.

UPSTREAM GREEN TRUNCATION, also known as a reverse queue jump, stops traffic behind a bus as boarding is completed, allowing the bus to re-enter the lane after a pull-out stop. Upstream green truncation can also be used to stop traffic at an intersection where transit makes a far-side in-lane stop, preventing queuing in the intersection. Green truncation is most effective on moderate frequency transit routes where delay upon reentry due to congestion is common. It can also benefit passengers alighting and crossing the street behind the bus.

PHASE INSERTIONS and **PHASE SEQUENCE CHANGES** describe the special bus-only phases or prioritization of turn phases used for shared turn/queue jump lanes, and are also helpful when buses make left turns.

PHASE RESERVICING provides the same phase twice in a given signal cycle, such as a left-turn phase or a queue jump. Reservicing a phase can significantly reduce bus delay, particularly when the phase in question is relatively short.

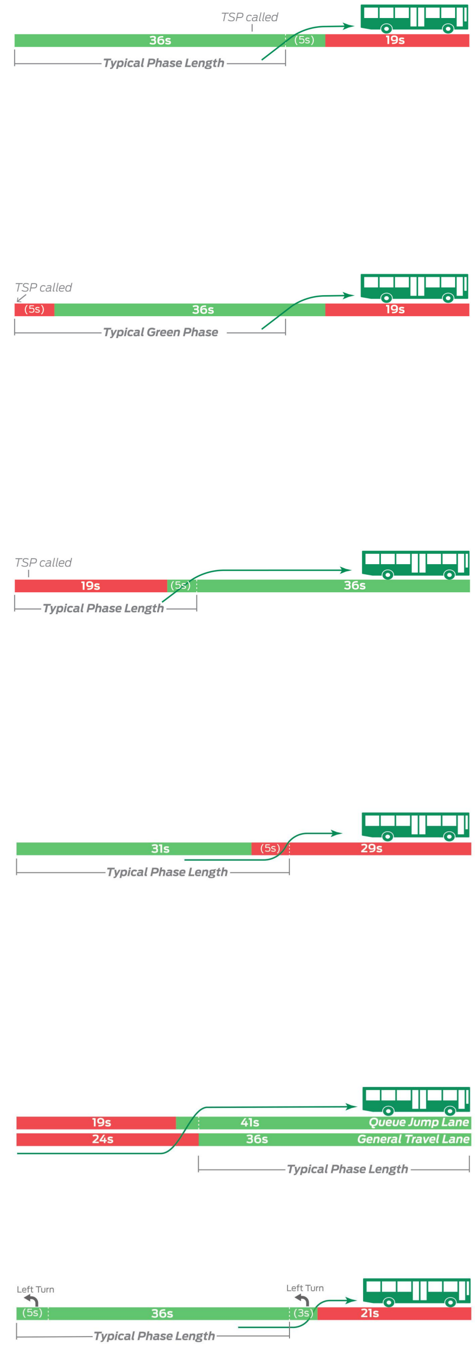


Figure 1. Transit priority treatments (NACTO, 2016)

In order to offer priority, the phase length may need to be adjusted. To do so, the priority phase may need to “borrow” some time from another phase (shortening the green for the conflicting phases), or from future cycles (shortening the priority phase for the next few cycles). For systemwide signal timing, this could affect how signals are coordinated along a corridor.

The limits to preemption and priority and guidance for their deployment are offered in the California Manual on Uniform Traffic Control Devices (CAMUTCD).[2] For instance, the CAMUTCD also mandates that a pedestrian interval (the combination of the walk and flashing don’t walk phases) in effect when priority is initiated shall not have its timing affected (Baker et al., 2002; State of California et al., 2020).[3] The CAMUTCD also provides other defined standards for preemption and priority, such as disallowing the shortening of yellow change interval (the yellow light) and the infrastructure requirements for transmitters that communicate between the signal and the prioritized or preempted vehicle.[4]

While by-and-large this report focuses on signal priority, there are some references to preemption, particularly with reference to light rail.

Benefits and Challenges of Transit Signal Priority

Several transit signal priority (TSP) benefits are commonly cited. These include better on-time performance for transit vehicles, decreased emissions, reduced transit vehicle maintenance from less frequent acceleration and deceleration, and faster average speeds for buses (Baker et al., 2002; Li et al., 2008). Increased bus speeds and reduced travel times lead to higher mobility, and signal priority as an intervention is generally less disruptive to other system users (Urbanik et al., 2015).

Time Savings and Travel Time Reliability

A theoretical model (**Figure 2**, below) describes the relative time savings of TSP at a modelled intersection given a 90 second cycle (Rodriguez & Danaher, 2014).

[2] Note that there is a different national MUTCD.
[3] A pedestrian interval is defined as the walk and flashing don’t walk timings. With respect to preemption, this means that the pedestrian countdown cannot be affected. However, walk timings longer than the MUTCD prescribed minimum can still be shortened to the minimum remaining walk time.
[4] Preemption and priority are specifically referenced in CAMUTCD Section 4D.27.

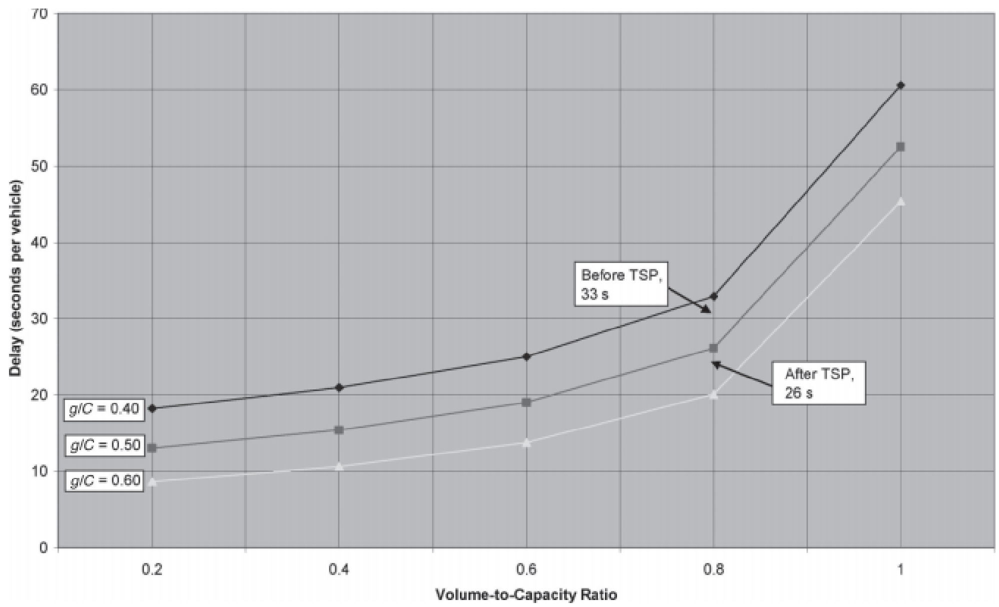


Figure 2. Possible time savings for TSP. The y-axis shows delay for seconds per vehicle. The g/C figure represents the green time per cycle length of a given intersection. Note that the arrows are slightly misaligned, they should be pointing at the black and gray dots at 0.8 Volume-to-Capacity ratio (Rodriguez & Danaher, 2014).

This model, developed by consultants at Parsons Brinckerhoff, uses a 90 second cycle. The x-axis shows the volume-to-capacity (VC) ratio, a common congestion measure. The y-axis shows delay for seconds per vehicle. The g/C figure represents the green time per cycle length of a given intersection. To clarify what this graph means, a 90 second cycle with a 0.40 g/C (for the priority phase phase) with a volume-to-capacity ratio of 0.8 would give the priority phase 36 seconds of green time. The model estimates that the per-vehicle delay for all vehicles would be 33 seconds. Adding an additional nine seconds of green to the priority phase would increase the g/C ratio by 0.10, and, per the estimations of the model, decrease the per vehicle delay by seven seconds. Adding yet another nine seconds of green would shave off another six seconds of delay. (The arrows in the diagram do point at slightly incorrect positions.) This model is germane to how the the City of Los Angeles traffic engineers currently program the TSP system--during a cycle when priority is requested, the system extends green windows with an additional 10 percent of cycle time.[5]

Saving time at intersections can also improve travel time reliability. Travel time reliability (measured in proxy by on-time performance) is used by metropolitan planning organizations (MPOs) in the larger goal of increasing ridership (Lyman & Bertini, 2008). High travel time reliability does encourage travelers to take transit; a commute mode choice simulation in Texas

[5] If available or applicable. Not all cycles are able to give the full 10%, due to the need to keep coordination with other signals, process high traffic volumes, or other intersection-specific timing factors. Likewise, if priority was granted a cycle, the one cycle lockout means that the signal uses one cycle to “catch up” and will not provide priority during the subsequent cycle.

found that well-designed, highly reliable transit (in the study modelled as a commuter rail line) could shift drivers to taking transit (though its full effects depended on the utility it afforded commuters) (Bhat & Sardesai, 2006). TSP was shown to increase on-time performance in Toronto (Danaher, 2010). Models have shown that TSP works in increasing transit service quality; a model of buses in the Washington, DC metropolitan area found that conditional priority increased bus reliability by 3.2 percent and reduced bus running times by 0.9 percent, while having only minor impacts (which the model found to be around 1% of increased delay) on other traffic (Chang et al., 2003).

Well-implemented TSP systems can create significant time savings for transit, on the magnitude of 15 percent or more. However, the model presented earlier, which suggests potential time savings of just over 20 percent in fairly busy conditions may be optimistic. Studies in North America and Europe have found that, due to other compounding factors, the time savings may not be as much as the model's estimated seven seconds per intersection at a volume-to-capacity ratio of 0.8 (Smith et al., 2005). Travel time savings have generally ranged from 2 percent to 18 percent, depending on the corridor length, with 8 percent to 12 percent reductions being typical. Reduction in bus delay at signals ranges more widely from 15 percent to 80 percent (Danaher, 2010). An early model found that unconditional priority could reduce bus delay as much as 20 or 30 percent, though unconditional priority with no constraints has been found to have negative impacts on buses' schedule reliability (Anderson et al., 2020).[6]

Implementing TSP is not without its possible downsides. The Transit Capacity and Quality of Service Manual published by the national Transit Cooperative Research Program cites possible risks including interrupting coordinated traffic signal operation, lowering intersection level of service, requiring heavy cooperation among jurisdictions, and impeding other transit vehicles on perpendicular streets (Kittelson & Associates, Inc. et al., 2013). Most of these risks share a common root: by prioritizing one signal phase, there is risk that the cross street or incompatible phases will see excessive delay. This effect is context-specific; research has found that well-implemented TSP designs have little to no delay on cross streets (Baker et al., 2002; Ludwick, Jr., 1975). I found only one study that estimated delay improvements of 20 to 30 percent were possible without significant cross street impacts (Hounsell et al., 1996).

In addition, for exactly what percentage of time reduction TSP is responsible in a given transit line or system overhaul is not easily untangled from other concurrent improvements. Transit signal priority is just one tool in the agency toolbox to increase transit travel speed and travel time reliability. Other factors, such as increased transit stop spacing, easing the ability of stopped transit vehicles to rejoin the traffic stream, and optimized transit service schedules may also play important roles in determining on-time performance (Anderson et al., 2020). And while agencies and organizations across the country have expressed interest in TSP for several decades, documentation on implementation remains sparse, with no clear evaluation

[6] Unconditional priority grants priority to all buses, and can lead to buses getting ahead of schedule and increased bus bunching (buses on different scheduled runs form a convoy).

framework. The wide variety of local context-specific implementation challenges has thus resulted in differing priority parameters, making direct apples-to-oranges comparisons difficult.

Evaluation of TSP

A May 2008 Caltrans report provides a host of possible TSP evaluation metrics, with foci on three primary criteria:

> Technology - Is the selected technology working as expected? Is it acceptable based on the specifications developed as a part of the system engineering process? Does TSP increase maintenance costs?
>
> Transit Performance - Is TSP providing measurable benefits for buses and passengers? What are the effects on service reliability?
>
> Arterial Performance - What are the impacts of TSP on other roadway users (network delay, safety, etc.)? (Li et al., 2008)

Data required to evaluate these criteria include ridership forecasts and actual ridership, traffic analyses, crash data, and delay analyses.

Common metrics for benefit evaluation include travel times, intersection delay, on-time performance, headway adherence, and travel time and headway variability. However, different agencies may differ in their goals for TSP and how much TSP they want or need to provide, and their context-specific parameters may differ as a result. These variations mean that there is no standardized information on best practices for TSP operations, maintenance, and optimization (Anderson et al., 2020). Given the apparent success of TSP deployments in reducing transit travel times and increasing reliability, however, it should be no surprise that agencies around the country have deployed TSP.

North American TSP Deployment

A 2017 survey by the Texas Transportation Institute at Texas A&M on behalf of the Transit Cooperative Research Program (TCRP) found 28 agencies using active TSP on their bus systems, ranging in size from Cities Area Transit (CAT) (Grand Forks, ND-MN) to King County Metro (Seattle, WA). Priority rules varied across the systems: most did not check if buses were behind in their scheduled run when requesting priority (18/31 systems responding), most had check-out detection to see if a bus had cleared an intersection (20/30), and the most common type of TSP deployment was extended green (28/31 systems used this, some in combination with other methods). Possible green extension lengths ranged from one to 30 seconds. The median minimum green extension was 7.5 seconds, and the average maximum green extension was 10 seconds. A slim majority of systems (16/31) employed lockout (preventing the intersection from implementing priority again for some specified period). Lockout parameters were time-based, ranging from two to five minutes, or cycle based, generally one to three cycles. The agencies selected for the survey are shown in **Figure 3**, below.

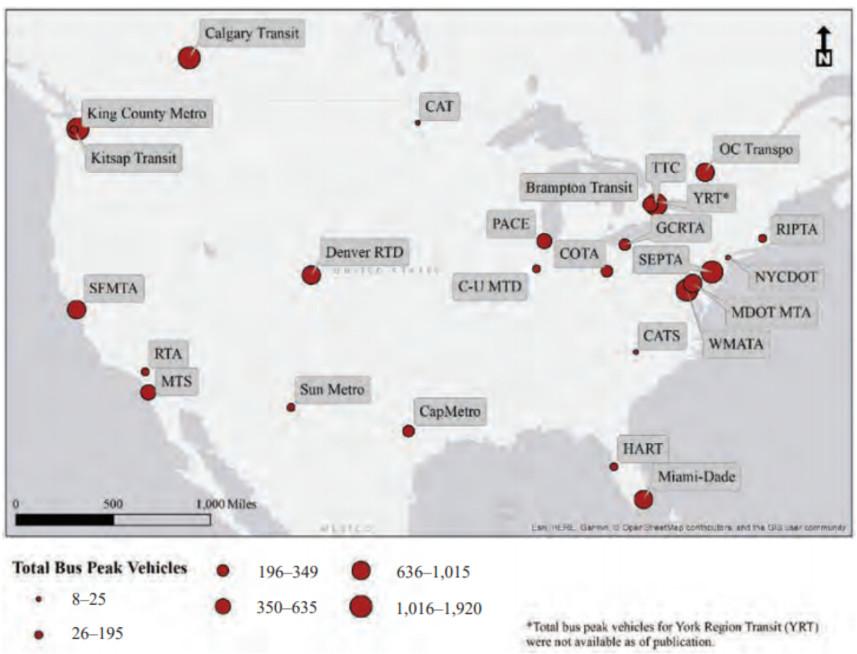


Figure 3. A map showing U.S. transit systems that use active bus TSP. Notably, LA Metro, which does use active bus TSP, is not included (Anderson et al., 2020).

San Francisco

Other than requiring that the doors be closed, the San Francisco Municipal Transportation Agency (SFMTA) grants unconditional priority for its buses (with some exceptions along express routes that serve only rapid buses). In many cases, not granting priority to buses is due to bus stop design. Along some lines, stops are located on the near side of intersections; that is to say, the bus does not clear the intersection before stopping. As the time spent picking up or dropping off passengers is variable, and while at the stop the bus has no intention of continuing through the intersection, this helps prevent the signal from giving priority unnecessarily.

The San Francisco TSP experience offers two lessons: the need to do rigorous testing to ensure that the TSP system is performing to expectation, and the need to be technology-flexible in order to include the majority of buses. Because rigorous before-and-after testing was not conducted in San Francisco, the full systemwide impact of the TSP, and its effects on non-bus users, was not evaluated. As a result, evaluation of the TSP system has been largely qualitative, though some quantitative benefits have been measured. Travel time was reduced about seven percent and approach delay, the delay experienced before entering an intersection, was significantly reduced with magnitudes of delay reductions on certain segments of up to roughly 50 percent. A report released in 2020 noted that SFMTA was planning a trial where TSP would be switched off for one month to allow before-and-after analysis of the TSP system (Anderson et al., 2020). This is being done because the TSP was rolled out alongside some other improvements, which made it hard to evaluate the independent effects of the TSP.

SFMTA was an early adopter of TSP, installing a base system in 1998 that used detectors on the city's overhead wires. This approach was limited, however, to the trolleybuses, and the system was expanded to use an infrared-based system, where receivers on the traffic signal poles and heads (the physical lights) received an infrared signal from buses. In 2013, a systemwide overhaul upgraded the SFMTA's priority system to be a global positioning system (GPS) based system. While each deployment faced technical challenges, the GPS based system currently has problems receiving signals in Downtown San Francisco, where tall buildings obstruct GPS signals. This has disabled the TSP system at ten intersections in the downtown core (Anderson et al., 2020). This latest problem notwithstanding, the technology-agnostic approach of San Francisco has helped it adapt to newer technologies as they have become available, and has helped it deploy a system that now spans 450 intersections and 900 buses and trolleybuses.

King County, Washington

King County Metro Transit Department (King County Metro) serves King County, Washington, which includes Washington State's largest city, Seattle. It is another early adopter of TSP, creating an initial system in 2000. A 2002 report noted that the system had a variety of goals:

To improve their ability to transport people

To improve transit performance (to provide incentives to switch mode)

To not cause undue delay to non-transit vehicles and not disrupt the flow of traffic (Chada & Newland, 2002)

The system was designed to be flexible, and have many options in order to not skip any phases and not break coordination if priority was invoked. Buses carried radio frequency tags that are detected by a device installed in roadside signal infrastructure, though a later upgrade moved to a roadside Wi-Fi network that communicated between the signal and buses, and between buses (Anderson et al., 2020).

Results during the AM peak period indicated a 13 percent reduction in average intersection delay in the TSP enabled direction (and a 3% reduction delay in perpendicular street and protected left turns), with a 24 to 34 percent decrease in intersection delay time for TSP-enabled buses at TSP-enabled intersections (Chada & Newland, 2002; Daniel et al., 2004). While midday did see increases in delay for cars along the perpendicular street and within the priority-enabled street's protected left turn, overall level of service did not degrade (Chada & Newland, 2002). King County Metro has also continually worked to optimize the priority system--the TSP system is regularly updated, and tests with TSP on and off have been conducted periodically to ensure that the system is in fact speeding up transit (Anderson et al., 2020).

Unlike in San Francisco, where SFMTA owns and operates the bus and signal infrastructure, deployment of TSP across King County Transit's service area is complex, requiring interfacing with several different controller types across various municipalities. In implementing the system, Washington State's Department of Transportation, King County Metro, and the City of Seattle worked together with a common goal of implementing a TSP that did not cause significant delays to non-transit users. Underscoring the need for flexibility, the City of Bellevue uses different controllers from that of the City of Seattle, requiring extensive local government stakeholder communication to create a comprehensive system (Anderson et al., 2020).

Houston

Houston Metro's experience with signal preemption is particularly relevant to the LA Metro G Line. Downtown Houston consists of a series of parallel and perpendicular one-way streets. These one-way streets cross the light rail alignment and Main Street, which is parallel to the light rail tracks. The light rail does not employ any gate arms. Following an experiment with priority and finding that to gain the level of time savings desired required priority so aggressive that it bordered on preemption, Houston Metro implemented a preemption system. The preemption system, called SmartSync, implemented what Houston Metro called Preempt Service Delay, which requests greens in sequence between stations and generates a green wave, allowing light rail vehicles to travel along between stations without stopping (Houston Metro Engineers, 2019). The prior system requested greens from all signals in parallel between light rail stations. As the signals were at different parts of their cycles, some would immediately serve the transit phases, and others would wait, creating uneven journeys across downtown. In the worst case scenarios, a series of signals some intersections away would be ready to serve the light rail while the intersections directly in front of the light rail vehicles were not. By the time the light rail vehicle approached the signals that were ready some minutes ago, the maximum green time had been reached and those signals were now serving automobile traffic. This system would lead to halting and inconsistent trips across downtown as light rail vehicles waited for upcoming signals that, under the best circumstances, would provide a coordinated green wave to allow them to pass, but had no guarantee the signals would do so.

The new system gives the train a green when possible but offers a coordinated series of green signals for trains. If trains miss this coordinated window (because a higher-than-expected number of passengers were boarding and alighting, for instance), the signals would go back to serving auto traffic. Trains would then be served another green window, albeit one that was shorter, so as to not cause undue delay to auto traffic. This incentivizes operators to take the initial window, but does not penalize them unduly for missing it, and maintains traffic service in the Downtown area. The implementation of this system increased smoothed train travel across the central business district, allowing Houston Metro to maintain the same headways (one train every six minutes) using one fewer train (Houston Metro, 2019). In addition, as part of this new system, Houston Metro also implemented a dynamic exit system, detecting which cross streets had been red the longest and allowing those private vehicle drivers to cross the intersection, decreasing the amount of red light running by impatient drivers. (The entire system won an American Public Transit Association (APTA) public transit award, with crash rates expected to normalize at 15 to 20 percent below pre-TSP rates) (American Public Transportation Association, 2019; Frederick Mills, personal communication, December 17, 2020).

Santa Monica

Closer to home, Santa Monica has implemented an aggressive priority system for use with the E Line (Expo). A memorandum signed between the City of Santa Monica and LA Metro agreed that signal treatments necessary to maintain a previously agreed-upon five minute peak period headway would be implemented (Martin, 2014). To do so, during conflicting phases, Santa Monica's signal system skips phases to serve the light rail train immediately but will not end a current conflicting phase early (i.e. the system will preserve minimum greens and pedestrian times). If a light rail train approaches during a compatible phase, the light rail train will be served.

The system verges on light rail preemption, and has proven successful in moving the E line rapidly through Santa Monica. This aggressive priority, however, ends at the city boundaries. LADOT engineers continue to have significant reservations about such aggressive prioritization for light rail vehicles, particularly as they may impact street traffic in congested downtown LA. Santa Monica's intersection volumes are much lower than in the congested downtown LA core, meaning that the installed priority system affects fewer vehicles in Santa Monica, creating less delay on the beach city's street system as a whole. In addition, engineers from LADOT have expressed concern that changing phase sequencing may subvert driver expectation; drivers familiar with the intersection may unwittingly enter the intersection when they are used to being shown a green, creating an unsafe situation (A. Maximous, personal communication, December 28, 2020).

Lessons learned from case studies of TSP in other cities

Case studies in San Francisco, Seattle, Houston, and Santa Monica have shown the importance of being technologically flexible and working with local stakeholders, as well as the benefits of “smarter” TSP and the possibility of implementing “more aggressive” TSP. Los Angeles is locked into its ATSAC system, a system that offers incredible granularity but has its limits, particularly for programming new transit priority functions (J. Shahamiri, personal communication, April 2021). Any updates to signal timing along the G line alignment must be made jointly between LA Metro, the transit operator, and LADOT, the controller of the roadside infrastructure. The two agencies must work closely together for any improvement to signal priority, not just with the G line, but across the entire city of LA.

Metro is taking action to ensure that the TSP systems its vehicles use are working as expected, and looking to further improve regional TSP technologies. Metro contractors and engineers have an established policy to collect ample “before” comparison data for any new TSP deployment. LA Metro is also considering more flexible priority logic for the E line outside of Santa Monica and the G line by experimenting with more aggressive forms of transit priority throughout Los Angeles.

Transit Priority in the City of Los Angeles

Transit priority for buses was implemented as part of a pilot project in 1999 with the Metro Rapid service (the 720 Wilshire/Whittier and 750 Ventura) in response to a consent decree requiring better quality bus service (Los Angeles Metro, 2002). To handle priority, LADOT developed an in-house transit priority system (TPS) that works with the Automated Traffic Surveillance and Control (ATSAC) system that is the “brain” of traffic control in the city.[7] Engineering studies conducted at the time found major improvements to operating speed and service quality, with a 20-27 percent reduction in travel time, and benefits due to signal priority were estimated by LADOT engineers in a 2005 report to account for 30-40 percent of this reduction, with minimal adverse impacts on cross street traffic, an impact of roughly 6-10.8 percent (Daniel et al., 2004; Los Angeles Metro, 2002). (A later report issued in 2008 estimated a more modest 1.7 percent to 2.8 percent decrease in travel time for buses, though signalized intersection delay was decreased by 34-39 percent (Li et al., 2008). Over time, the system was expanded to include rapid bus routes, the G Line, J line (formerly Silver), and light rail lines.

There are two primary detection types for transit signal priority for use within the City of LA. The first, used by light rail and G line bus rapid transit (BRT) involves detector loops, which detect the transit vehicle when it is a certain distance away from the intersection (see **Figure 4**, below). This “upstream” detector loop puts in a request for priority, which activates the priority phasing. The system predicts when the bus will arrive at the intersection based on known operating speeds, and will attempt to show a green based on the predicted arrival time. A downstream checkout loop ensures that the light rail or BRT vehicle has cleared the intersection.

[7] The generic term used to this point is transit signal priority, TSP. TPS is the LA-specific system designed to handle transit priority within ATSAC.

Figure 4. An upstream loop detector (bottom right) (Google, 2014).

Rapid and priority route buses, such as the Rapid 720 along Wilshire Boulevard and Whittier Avenue, are equipped with transponders that communicate with the signal system. If a rapid bus is behind schedule, and no other bus has recently requested priority, the signal will move to serve priority phasing for that rapid bus. The system then makes sure that the bus has passed the intersection using a “check-out” detector. All priority requests are handled by a central transit priority manager located in the ATSAC command center, which determines whether or not to grant priority and distributes traffic across the network. The TPS system is capable of handling transit priority requests only on the main street or coordinated phase, and will not handle any further requests from that bus until the bus hits the check-out detector. TPS will also not grant requests for priority on a subsequent cycle after priority has been granted. These limitations may pose a potential problem at high-volume intersections (Los Angeles Metro, 2002).

A particular operational issue is that buses are assigned fixed transponders that track their schedule and route to ensure they are on time. (i.e. A 720 bus is assigned a trip and schedule along Wilshire/Whittier, and the system tracks that schedule. If that bus is sent along Vermont, then TPS will neither recognize the route nor give priority, since it is not behind schedule for its route along Wilshire.) An illustration of this system is included below as **Figure 7**. With the upcoming NextGen bus route system overhaul, Rapid buses, which receive priority, are being combined with their local lines, which do not. The plan increases service frequency and consolidates stops, and may move away from a schedule-based system to a headway-based system (buses arrive every X minutes). The ability to provide priority to all buses will be vital to implementing the full vision of the NextGen plan, especially as buses arrive within a given number of minutes from one another, rather than at scheduled times. Other potential policies being reexamined include a policy inhibiting priority from being served on consecutive phases (put in place to preserve signal coordination), and moving towards a more preemption-like system for light rail. Stronger priority for the Expo Line, discussed above in the Santa Monica case study, has also been pushed by the City Council (Chiland, 2020; Fonseca, 2019; Linton, 2019; Neal Broverman, 2019; Sharp, 2019).

ATSAC

One major component to consider during the implementation of signal priority in LA is ATSAC, the city's networked traffic control system. Installed in advance of the 1984 LA Olympics to smooth traffic, ATSAC was cutting edge in the 20th century, with a 1993 report from the Center for Urban Transportation Research at the University of South Florida's "industry sources" calling it "[maybe] the most technologically advanced traffic management system currently operating in the U.S." (Center for Urban Transportation Research, 1993). (A picture of ATSAC from shortly after the Olympics in 1984 is available as **Figure 5**.) A major overhaul of the system was completed in 2013, improving and modernizing the control room and helping to install newer software (Bliss, 2014; LADOT, 2012). ATSAC can receive up to one signal per second from the thousands of loops buried around LA's city streets and can automatically adjust signal timing plans to keep traffic flow smooth across Los Angeles. ATSAC now controls more than 4500 intersections in the LA region (Kang Hu, personal communication, December 9, 2020).

ATSAC offers incredible granularity of data for LADOT engineers. Much of the decision-making is handled by the ATSAC system under the City Hall Annex, rather than individual controllers. In the client, which LADOT engineers use to control ATSAC, bus positions, the status of the upcoming signal (and whether it has granted a bus priority at a particular intersection), how late a bus is, and the estimated time of arrival to a given intersection are all visible. A view of the ATSAC client is included as **Figure 6**. However, ATSAC does have its limitations. The traffic phase configurations it can hold in memory are limited to a certain template, creating more complex logic problems when dealing with complex intersections or transit priority. The nature of ATSAC is also that it optimizes regional vehicle flows, which can constrain options when deciding to prioritize passenger flows in a single heavily used transit corridor in the region. That ATSAC was developed in-house (the system was developed before many commercial off-the-shelf TSP systems were available) is also a double-edged sword. When programming, ATSAC engineers use the in-house standard described by LADOT's traffic signal control program (TSCP) within the adaptive traffic control system (ATCS). While this means LADOT has great control over ATSAC and its function, it also means that creating new functionalities and programs must rely considerably on institutional memory. A rough overview of the logic of TPS is included as **Figure 7**.

Figure 5. ATSAC, ca. 1984 (Unknown, 1984).

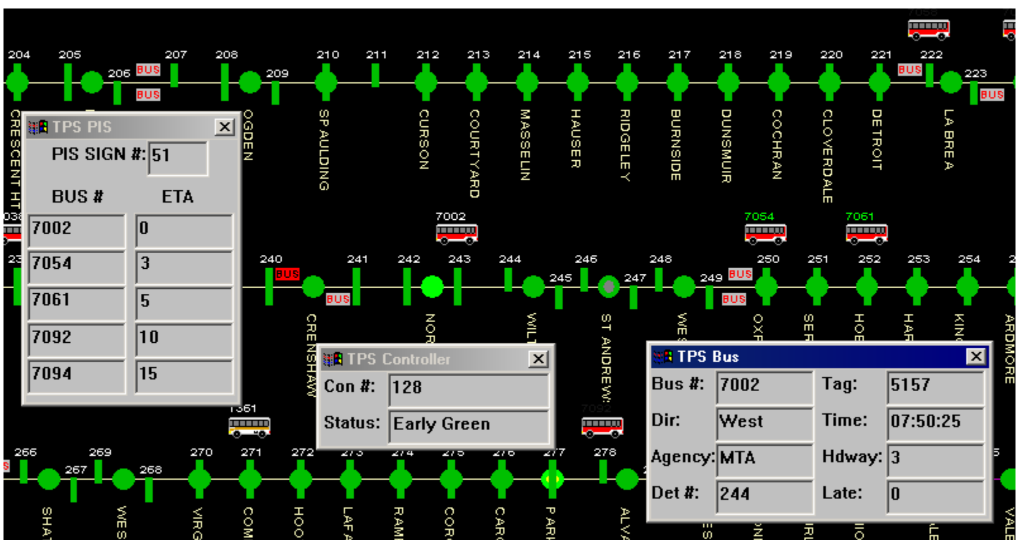


Figure 6. View of the ATSAC client, ca. 2007, with bus statuses (Hu, 2007).

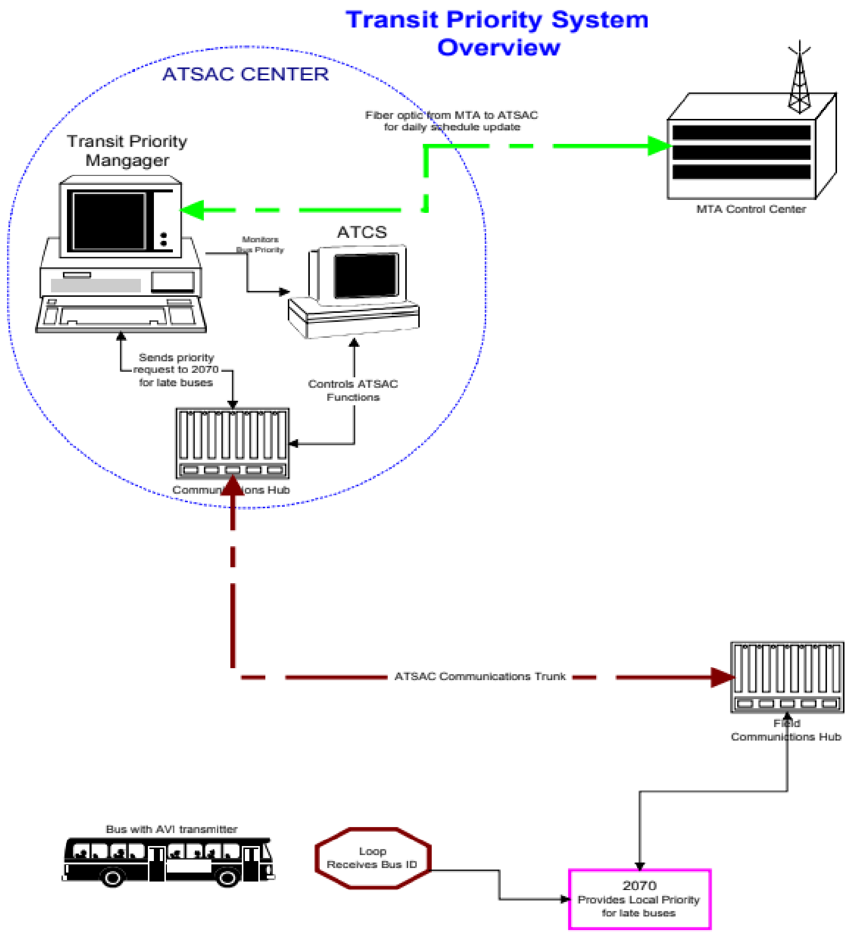


Figure 7. TPS system overview from 2001. A loop receives bus information, which is communicated to ATSAC. ATSAC communicates with the traffic controller, the 2070, if it should allow priority for the bus (LA Metro was previously branded the MTA), which communicates schedules to ATSAC, allowing the system to determine which buses were behind schedule. (Hu et al., 2001) Current plans for NextGen involve abolishing the schedule requirement and providing priority for all buses.

The Metro G Line

The G (formerly Orange) line is LA Metro's marquis bus rapid transit line, which travels 18 miles along 18 stations in the San Fernando Valley (LA Metro, n.d.-a). Starting from where the B (Red) line terminates at North Hollywood, the G line follows Chandler Boulevard on a dedicated median right of way until cutting north, running north parallel to Oxnard Street. The busway follows Interstate 405 north until running just south of and parallel to Victory Boulevard, before curving south and rejoining Oxnard Street at the west end of the Sepulveda Basin Recreation Area. The busway then follows Topham Street and Victory Boulevard west, where a short run loop terminates at the Warner Center district. The busway otherwise follows Canoga Avenue north until it terminates in Chatsworth. Construction was done in two phases, with phase one to Canoga Park completed in 2005 and the extension to the present Chatsworth terminus completed in 2009 (Sotero, 2020). The route map is included as **Figure 8**, below.

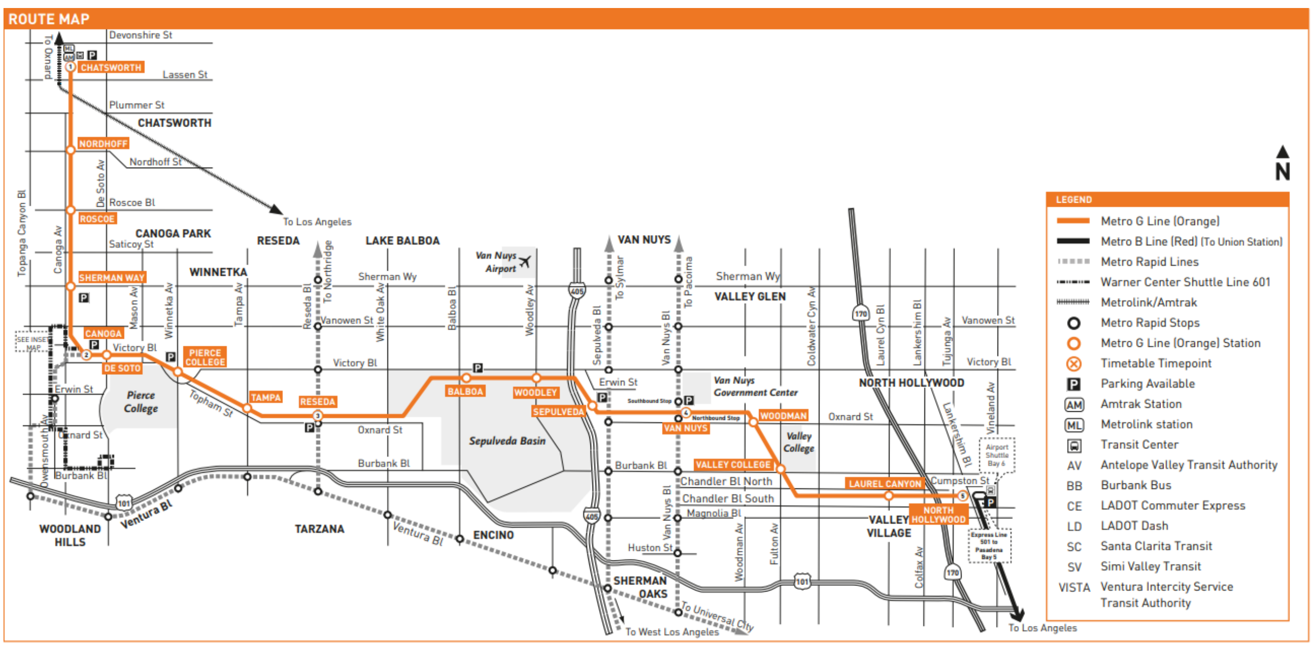


Figure 8. Metro G line route map (LA Metro, 2020).

In international standards, as set by the Institute for Transportation & Development Policy, a bus rapid transit (BRT) system must be at least 3km in length with dedicated lanes, have certain dedicated right-of-way and busway alignments, and have certain design elements, such as payment before boarding, dedicated stations, and elevated platforms. The Metro G Line meets the standard to be classified as a “bronze” BRT classification (The Bus Rapid Transit Standard, n.d.).

The G line is a vital link between the San Fernando Valley and the LA Basin, connecting to the B line (Red) and other bus connections at the North Hollywood terminus. The system served more than 22,000 weekday boardings pre-pandemic (LA Metro, n.d.-b). Speeding up this vital transit link would benefit the residents and workers of the San Fernando Valley who ride the G line.

Metro has a current contract with the Turner Engineering Company (Tenco) to collect and provide data on the G line. Upcoming improvements to the data collection and processing will increase data collected from bus-mounted GPS receivers to once per second. These data will be used to measure various standard key performance indicators (KPIs), from delay, to run time variability, to delay at red or percent of buses arriving at green.

As part of an ongoing G line improvement project, Tenco provided six possible solutions to improve traffic signal operations on the G line. They are:

1) Corridor synchronization: Consecutive intersections are not currently synchronized, so buses are left waiting unnecessarily at signals between stations.

2) Minor intersections: Using extant volume information, certain low-volume intersections imposed higher levels of red light delay on G line buses than is warranted by their volumes.

3) Rush hour precedence: Signal timing could better prioritize the eastbound (EB) rush hour traffic in the AM period and WB rush hour traffic in the PM period.

4) Transit Signal Priority: The G line's implementation of transit signal priority operates on the ATSAC TPS system, which adjusts the phase timing of the busway such that buses get greens as often as possible. Further improvements are possible to the current system; possibilities include creating a passive priority system with better corridor-wide synchronization of signals between stations.

5) Busway recall: Signals along the G line busway could be set to allow the busway to automatically show green for the bus when parallel streets show green and when no conflicting requests, either by automobile loop detectors or pedestrian buttons, have been detected. Cooperation between LA Metro and LADOT has improved busway recall programming along the G line, with some intersections currently in testing. Tenco also noted that where pedestrian routes and the busway are parallel,

6) Don't Walk Indicator: Tenco engineers believe that a better Don't Walk indicator can be used to more accurately predict upcoming green phases and have the green phase predictions be integrated with onboard display units provided to bus operators (Turner Engineering Corporation, 2020b).

Tenco has already deployed a proof-of-concept machine learning and neural network prediction system, which showed increased prediction accuracy for green along the busway. As shown on the mockup of a new connected bus display system in **Figure 9** below; this system communicates with the LADOT signal system and predicts the upcoming green for the signal. These predictions use operator and bus location and speed to inform the operator when the upcoming signal is going to show green.

Figure 9. Proposed connected bus display system at work (Turner Engineering Corporation, 2020c).

Of these six recommendations, engineers at LA Metro and LADOT are already working on #5, improving busway recall. Using signal timing data along the corridor, I take a closer look at recommendation #4, transit signal priority, and by extension, recommendation #1, corridor synchronization.

A Closer Look at Signal Timing Data

The document that lays out signal timing at a given intersection is known as a timing chart. Since the focus of this report is on signal timing, a brief introduction of the signal timing charts is in order. The example used for this report is the intersection of Ethel and Busway, a satellite image of which is shown as **Figure 10**.

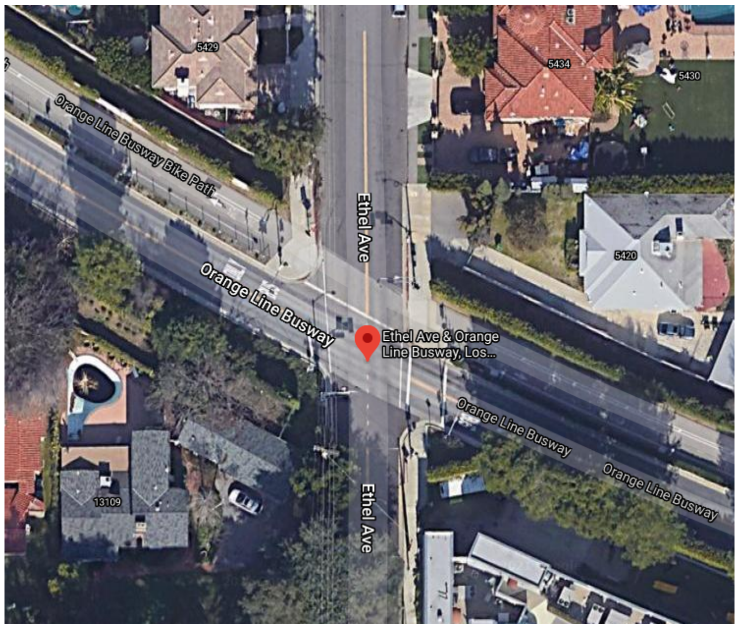


Figure 10. Ethel Avenue and Busway Satellite View, Google Maps

Ethel and Busway is one of the simplest phase diagrams along the G Line busway, but the timing is still fairly unusual in comparison with a typical signalized intersection. (Refer to appendix A for more information about the ring and barrier structure.) In **Figure 11**, below, we see that phases 2 and 6 are marked as overlap phases. Overlap phases will only run when their parent phases, in this instance marked as phases 2,4,6, and 8, are green (i.e. the overlaps are able to go during any time). In general, BRT phases are not assigned individual phases, but are operated as overlap phases. In this case, the BRT is also assigned only to show during overlap A, which is compatible with all phases.

Particularly for more complex phase diagrams, it is important to remember that this is the chart and not the phase order. For instance, there is no guarantee that phase 1 is shown after phase 2. For a given signal diagram, it is entirely possible that the phase order for the ring is 2, 1, 4, 3. (See **Figure 13** for a more complex chart.)

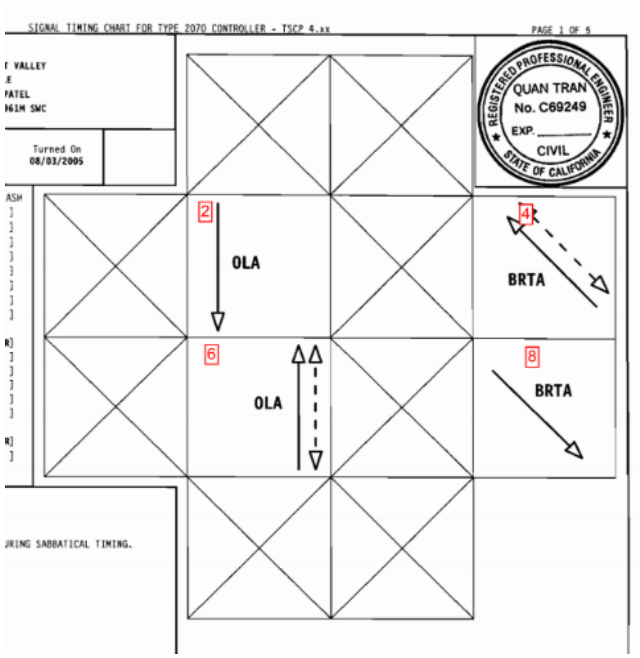


Figure 11. Ethel Avenue and Busway phase diagram (Tran, 2006)

While overlap A is compatible with all phases, we see that the pedestrian phases (on the south and east sides of the intersection) are assigned only to certain phases. The minimum and maximum timings for these are listed in **Figure 12**. When operating along a preprogrammed timing plan, green factors determine the maximum time allocation for each phase. Phases two and six are the sync phases, from where the “zero” of the cycle is referenced. In this particular timing chart, phases four and eight are programmed to show simultaneously.

Part of the challenge of BRT priority timing is that the current signal timing software employed by Los Angeles DOT is capable of handling only an eight-phase, two-ring structure, necessitating heavy use of overlaps. An example phase diagram showing heavy use of overlaps (to accommodate an odd intersection control geometry) is included as **Figure 13**.

TIMING

Phase (2-2)	ϕ1	ϕ2	ϕ3	ϕ4	ϕ5	ϕ6	ϕ7	ϕ8
Walk 1	0	0	0	0	0	7	0	0
Walk 2	0	0	0	0	0	0	0	0
Delay Walk	0	0	0	0	0	0	0	0
Flash Don't Walk	0	0	0	0	0	5	0	0
Solid Don't Walk	0	0	0	0	0	0	0	0
Minimum Green	0	10	0	7	0	10	0	7
Bike Green	0	0	0	0	0	0	0	0
Det Limit	0	0	0	0	0	0	0	0
Max Initial	0	18	0	0	0	12	0	0
Max Green 1	0	20	0	35	0	20	0	35
Max Green 2	0	0	0	0	0	0	0	0
Max Green 3	0	0	0	0	0	0	0	0
Extension	0.0	4.0	0.0	1.0	0.0	3.0	0.0	1.0
Maximum Gap	0.0	3.0	0.0	1.0	0.0	3.0	0.0	1.0
Minimum Gap	0.0	3.0	0.0	1.0	0.0	3.0	0.0	1.0
Add Per Vehicle	0.0	2.2	0.0	0.0	0.0	2.2	0.0	0.0
Reduce Gap By	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reduce Every	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Yellow	0.0	3.6	0.0	3.9	0.0	3.6	0.0	3.9
All-Red	0.0	1.4	0.0	2.1	0.0	1.4	0.0	2.1
Bike All-Red	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Overlaps (2-3)	A	B	C	D	E	F
Min Green	10.0	0.0	0.0	0.0	0.0	0.0
Green Ext	0.0	0.0	0.0	0.0	0.0	0.0
Yellow	3.6	0.0	0.0	0.0	0.0	0.0
All-Red	1.4	0.0	0.0	0.0	0.0	0.0

Red Revert (2-8) Time 2.0

COORDINATION

Press [F] key to select Green Factors or Force-Off

Local Plan (7-1..9)		Cycle	Offset	Perm	ϕ1	ϕ2	ϕ3	ϕ4	ϕ5	ϕ6	ϕ7
Plan 1	Green Factor	60	26	10	0	17	0	32	0	17	
Plan 2	Green Factor	60	26	10	0	17	0	32	0	17	
Plan 3	Green Factor	60	26	10	0	17	0	32	0	17	
Plan 4	Green Factor	60	26	10	0	17	0	32	0	17	
Plan 5	Green Factor	0	0	0	0	0	0	0	0	0	
Plan 6	Green Factor	0	0	0	0	0	0	0	0	0	
Plan 7	Green Factor	0	0	0	0	0	0	0	0	0	
Plan 8	Green Factor	0	0	0	0	0	0	0	0	0	
Plan 9	Green Factor	0	0	0	0	0	0	0	0	0	

ATSAC Plan

Figure 12. Signal timings for Ethel Avenue and Busway (Tran, 2006)

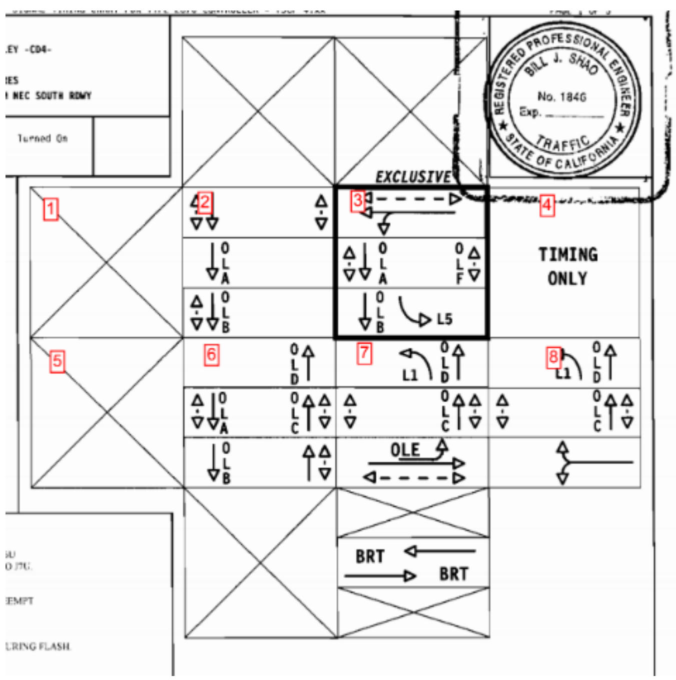
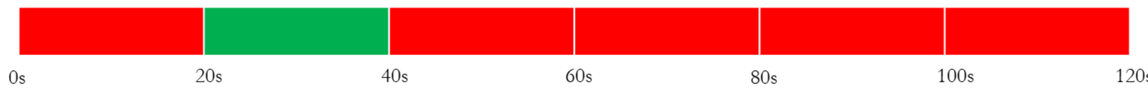


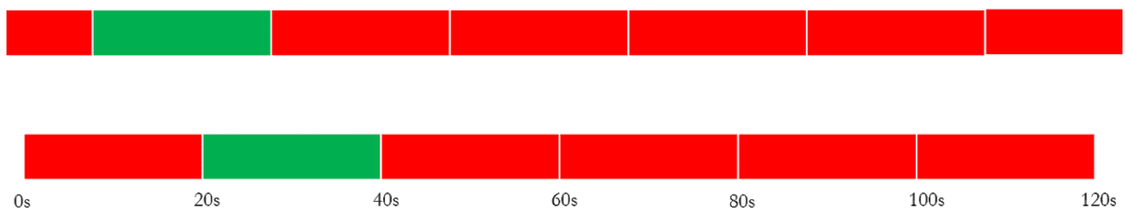
Figure 13. Timing chart at Tujunga Avenue, Busway, and Chandler Boulevard (Shao, 2012)

By understanding the timings at each intersection for a particular signal in a particular set of parallel and compatible directions, a new chart can be created to help us understand the progression along a given segment.

Imagine a signal with a 120 second cycle where buses are given 20 seconds to pass through the intersection. Treating the yellow time as green time when the bus is allowed to pass the intersection, we would end up with a band that over time looked something like this:



Layering two intersections may then look something like this:



A bus could then pass along the green band, and could be illustrated using a diagonal line. An example could look something like this:

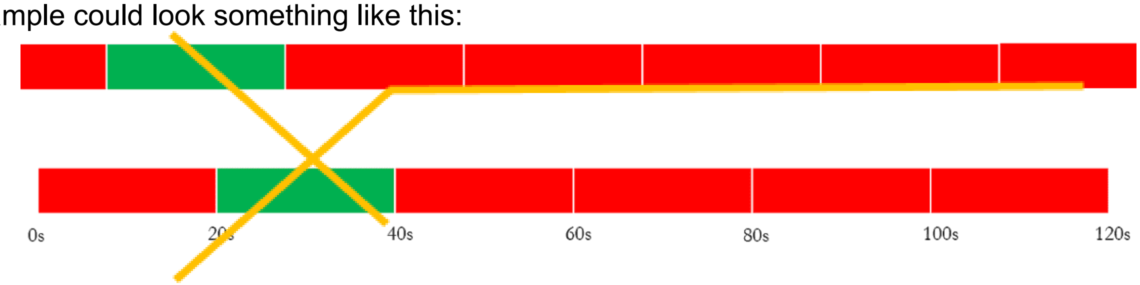
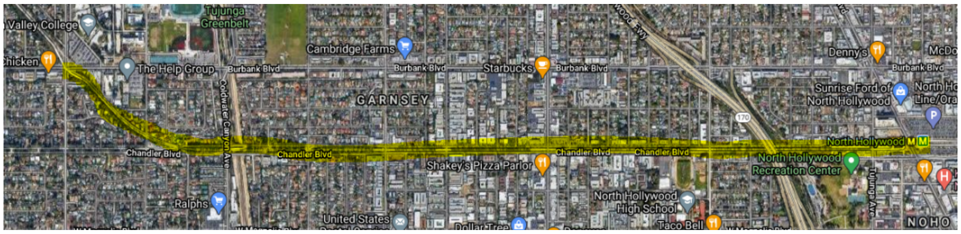


Figure 14. An example time-space plot with vehicle travel plots. In this example, one bus moves through the intersection. In the other, the bus becomes stuck at its second signal. Note that in this case, the buses would see green at the same time.

What we see here are two vehicles, travelling in parallel but opposite directions. One is able to clear two intersections without stopping, while the other gets caught at the second intersection, spending a long time at the signal. This is a highly simplified version of how a time-space (TS) plot works.

A full-fledged TS plot is included as **Figure 15**. This is generated by LADOT in ATSAC, allowing access to the busway signal statuses. The distances between intersections are to scale and shown on the y-axis. Time, in ticks of 20 seconds, is shown on the x-axis. Intersection names are shown on the right. The full size TS plots as provided by LADOT are included as Appendix B.



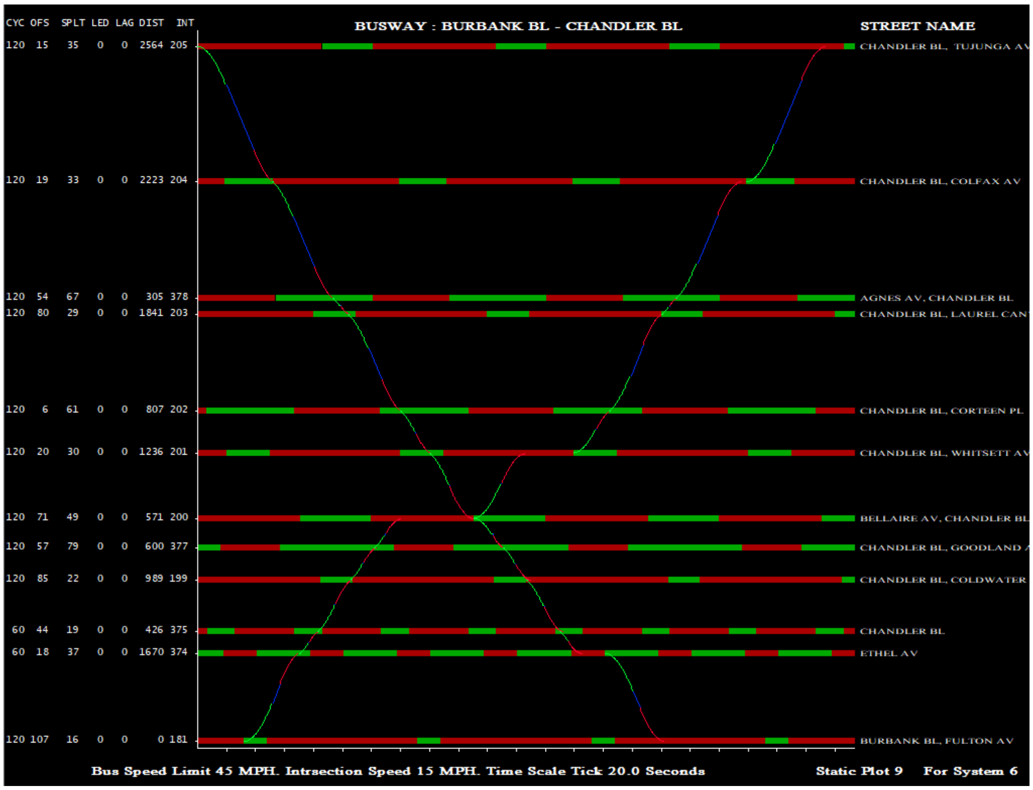


Figure 15. TS plot from Chandler Boulevard and Tujunga Avenue until Burbank Boulevard and Fulton Avenue. This tracks the busway signals' parent phases. These data were collected for the PM peak period on a weekday afternoon. The satellite view of the corresponding segment of the G line is highlighted in yellow below.

Analysis

This TS plot uses acceleration and deceleration curves (the red and green curves above along the diagonal lines) rather than more conventional straight-line speeds. (The blue lines are steady-state 45 mph speeds.) While knowing the curves would be ideal, there is no guarantee that future bus models will retain the same curve and I was unable to obtain the data used to generate the curves. Therefore, my work with these TS plots will use more conventional straight-line plotting.

In addition, an astute viewer may notice much smoother traffic service going westbound. This is normal: it is difficult, and in most cases impossible, to create "dual progression," that is, perfectly smooth traffic service in both directions.

There remains one major caveat. A slow-speed order, implemented in 2005 as a temporary measure to increase safety after two crashes along the G line alignment shortly after it opened, remains in place (Linton, 2014). G line buses continue to operate under the direction to slow to 10 mph in intersections—even slower than the 15 mph assumed by LADOT in the TS plot. As noted in a 2015 Iteris report, the slow order makes it impossible to evaluate the efficacy of current signal timing plans. The ultimate goal of this report is to make recommendations about increasing the G line's speed and reliability, and one primary slowdown for the G line is the continuation of the temporary slow order. A later section will explore the average speed of the G line.

Beyond the intersection at Reseda Boulevard and Bessemer Street, the vast majority of signals run "free," meaning that there is no fixed timing plan and the signal serves predicted phases. LADOT's systems in that region also were unable to generate a full TS plot for that area, however, the arguments presented for increasing the busway's speeds can be applied along its length.

From North Hollywood to Fulton Avenue

Along the section detailed in **Figures 16 and 17**, speeds along this section vary from 35 mph at the North Hollywood depot, then 35 mph after Colfax Avenue then up to 45 mph after Fulton. Already, then, at least for this segment, the steady-state assumption of 45 mph and the intersection low-speed assumptions of 15 mph are generally, but not completely correct.

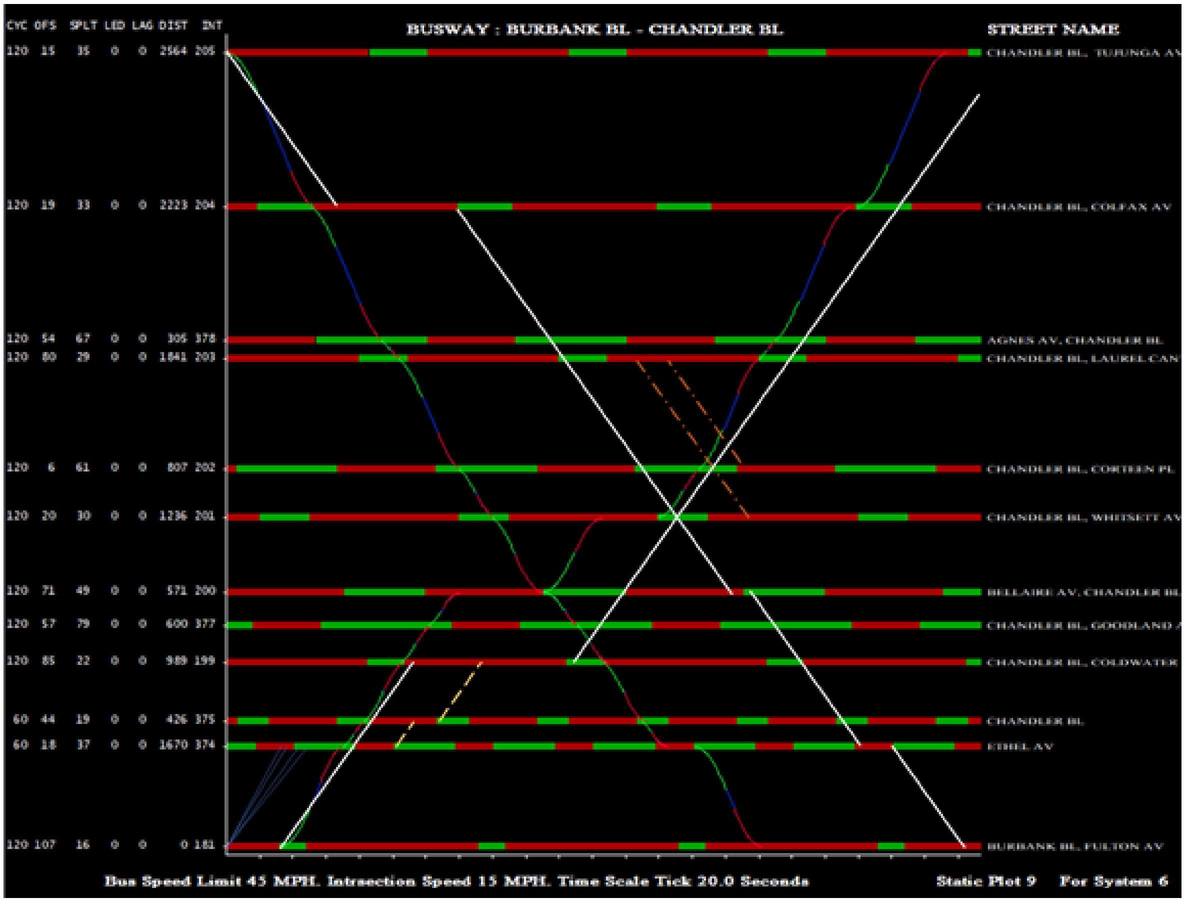


Figure 16. Projected bus speeds for each intersection by space, given the actual speed limit for each segment. The dotted lines in the lower left represent an operator who slowed to a stop at the intersection, rather than attempting to cross at the end of the green. The dash-dot line near the center of the chart illustrates a bus that dwells at the stop at Chandler Boulevard and Laurel Canyon Boulevard before advancing, hitting a red at subsequent signals.

The white lines indicate the expected TS plots. The plotted charts show that the eastbound direction appears to have no major progression issues until Ethel Ave. However, the vehicles are plotted without dwell time (time spent loading and unloading passengers at stops). At Laurel Canyon, for instance, which like most stops is on the far side of the intersection, if a bus is delayed 20 seconds, then it needs to wait for the entire cycle upon reaching Whitsett Avenue (illustrated by the longer orange dash-dot line). In the PM peak, the direction prioritized is the westbound run towards the Chatsworth terminus; considering the commute patterns along the G Line, this is sensible.

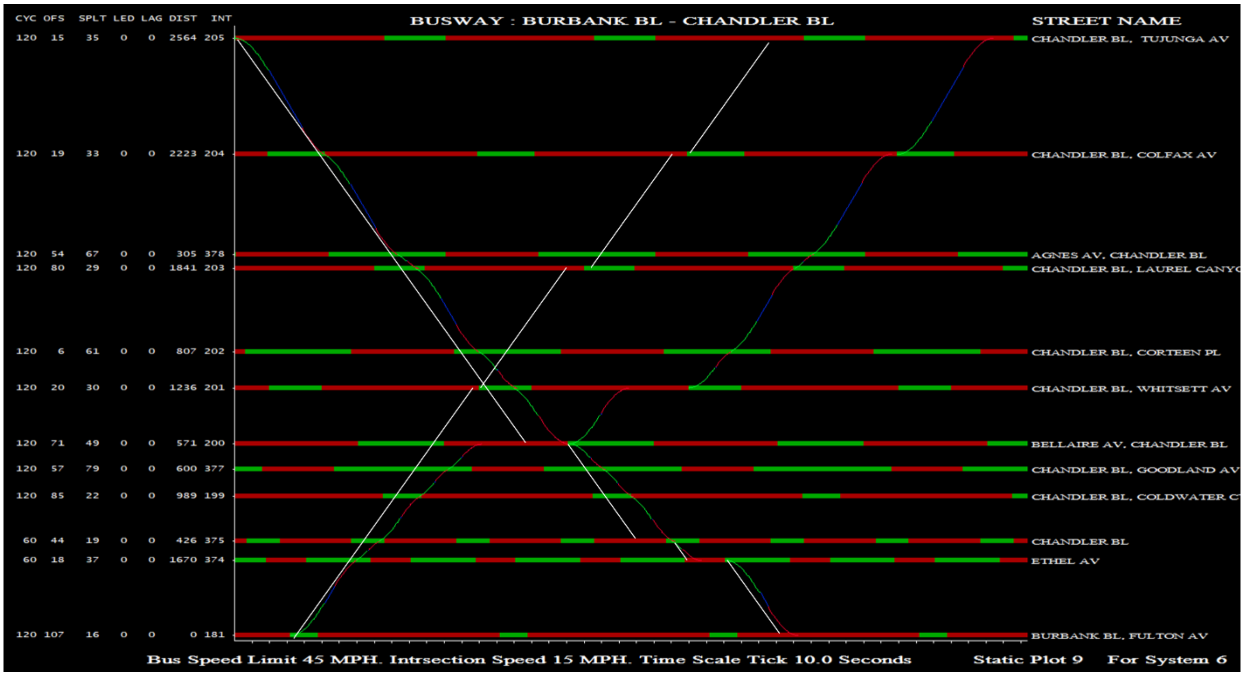


Figure 17. TS plot recorded during the AM peak hour. Note the differing x-axis tick marks between the PM and AM peak charts.

In the AM timing plot used by LADOT, as seen in **Figure 17**, the westbound direction still appears to be prioritized. However, plotted to 35 mph linear speeds, the TS plot appears more favorable to the eastbound traffic to North Hollywood. As commuters in the AM are assumed to go from residential San Fernando to connect with the Red Line towards the basin, this is as expected.

From Fulton Avenue to Reseda Boulevard

From Fulton Avenue to Van Nuys Boulevard, the speed limit is 35 mph before increasing to 45 mph. It is 45 mph until Sepulveda Boulevard, where it returns to being 35 mph with a 25 mph speed advisory sign before the bus enters an underpass. Here, the speed varies by direction. After Woodley Avenue, continuing in the westbound direction, the speed limit is 55 mph until the end of the G line segment shown on the TS plot in **Figures 18 and 19**. In the eastbound direction, the speed is 55 mph from Reseda until Woodley, when it slows to 35 mph (with the 25 mph speed advisory sign as noted above).

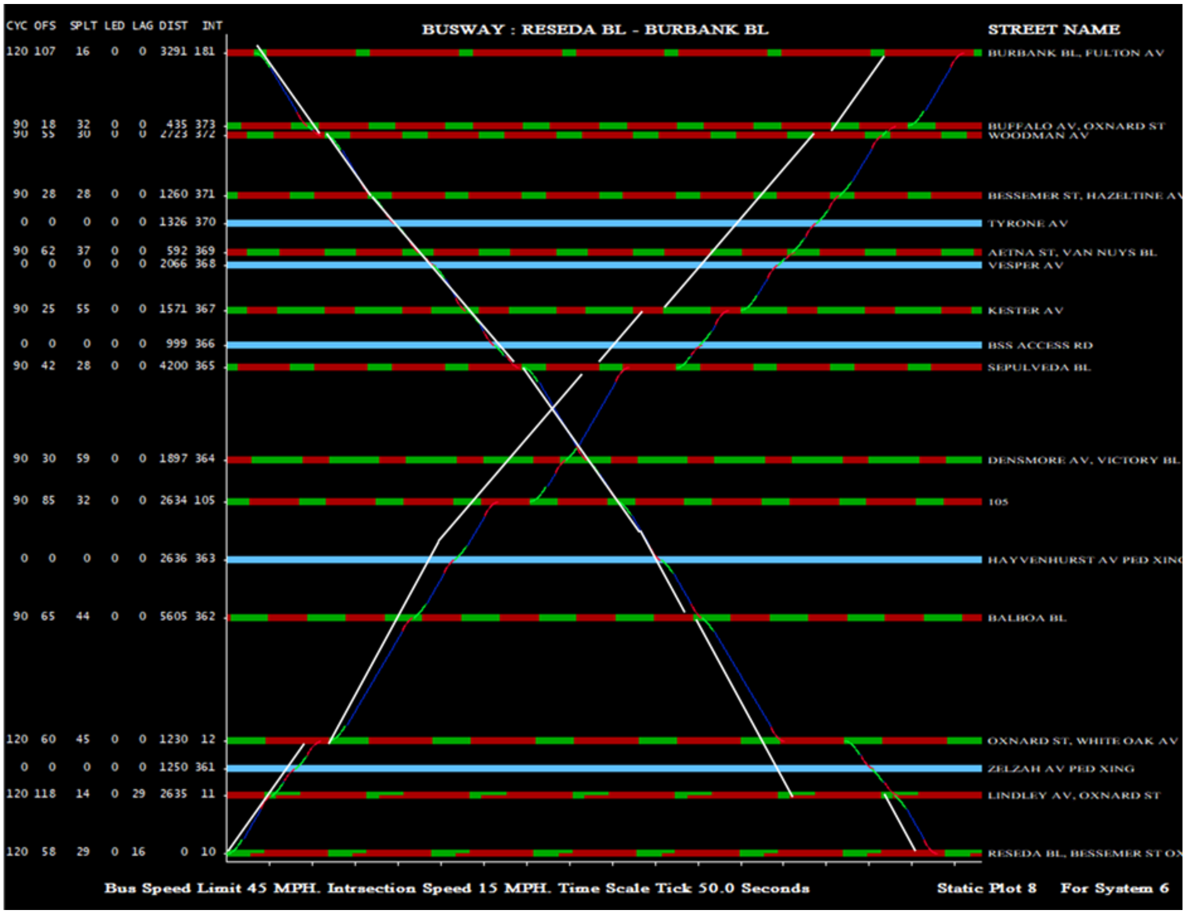


Figure 18. The TS plot between Burbank Boulevard/Fulton Avenue and Reseda Boulevard/Bessemer Street/Oxnard Street and Busway intersections. This plot is for the PM rush hour. The white lines represent bus travel with linear speed (no acceleration and deceleration curves) using the known speed limits. Chart furnished by LADOT.

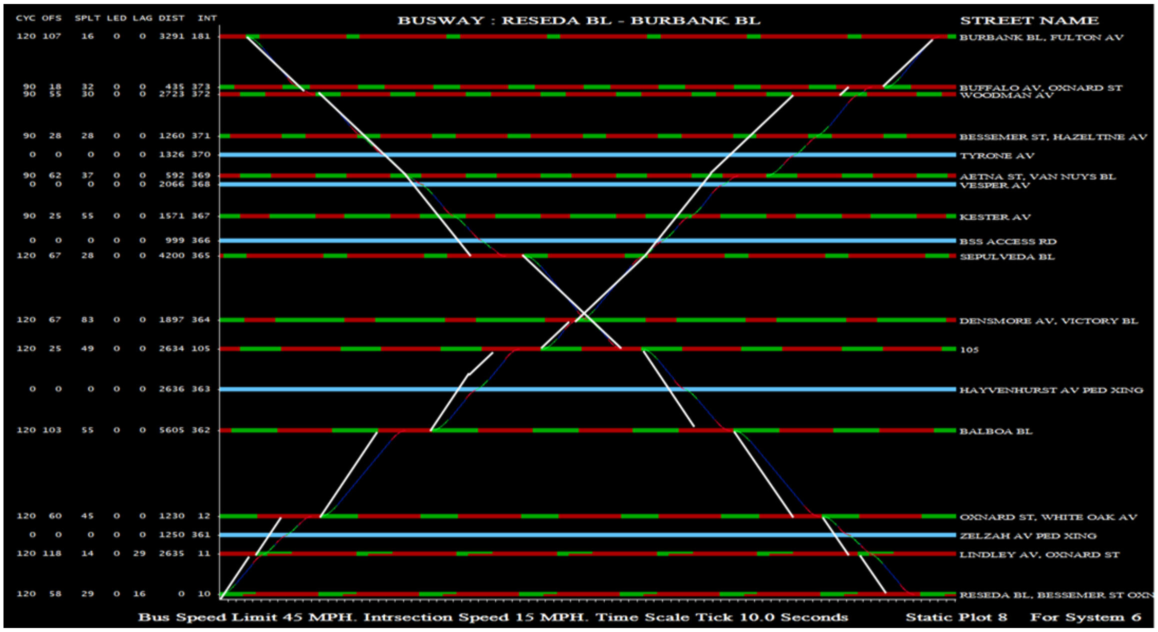


Figure 19. The TS plot between Burbank Boulevard/Fulton Avenue and Reseda Boulevard/Bessemer Street/Oxnard Street and Busway intersections. This plot is for the AM rush hour. The white lines represent bus travel with linear speed (no acceleration and deceleration curves) using the known speed limits. Chart furnished by LADOT.

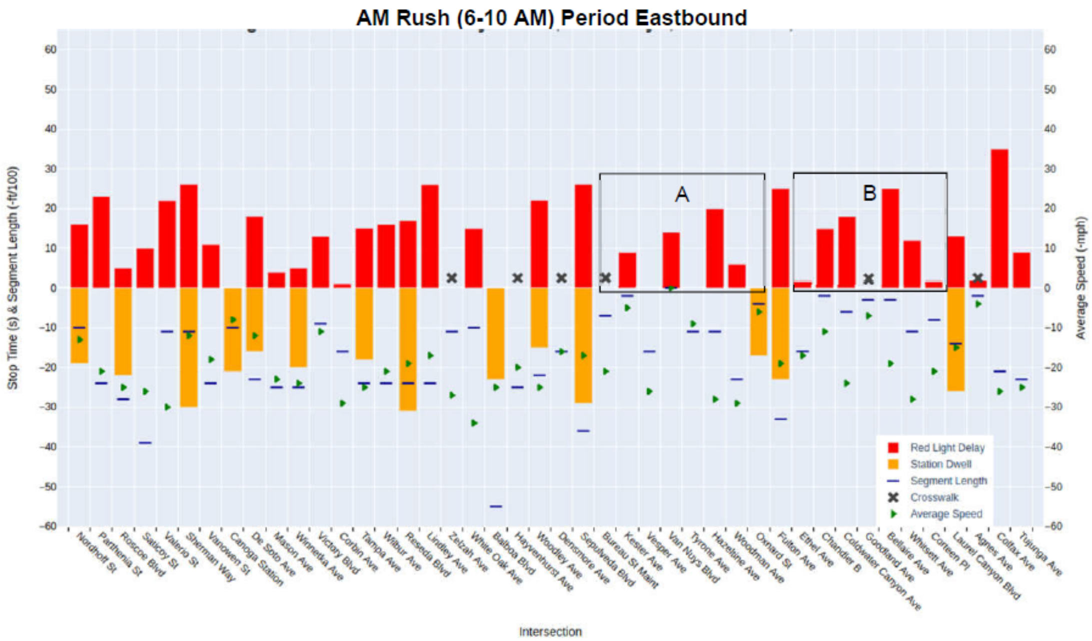
For many of these intersections, especially along the section of the G line laid out in **Figures 18 and 19**, it appears that progression along the busway is reasonable, with perhaps a few intersections where there is undue delay. In some cases, it looks as if changing the offset at a given intersection by 20 or 30 seconds will be enough to create progression between G line stations. And in whole, it appears that the 45 mph steady-state speed assumption with 15 mph intersection speeds as laid out by LADOT are reasonable assumptions.

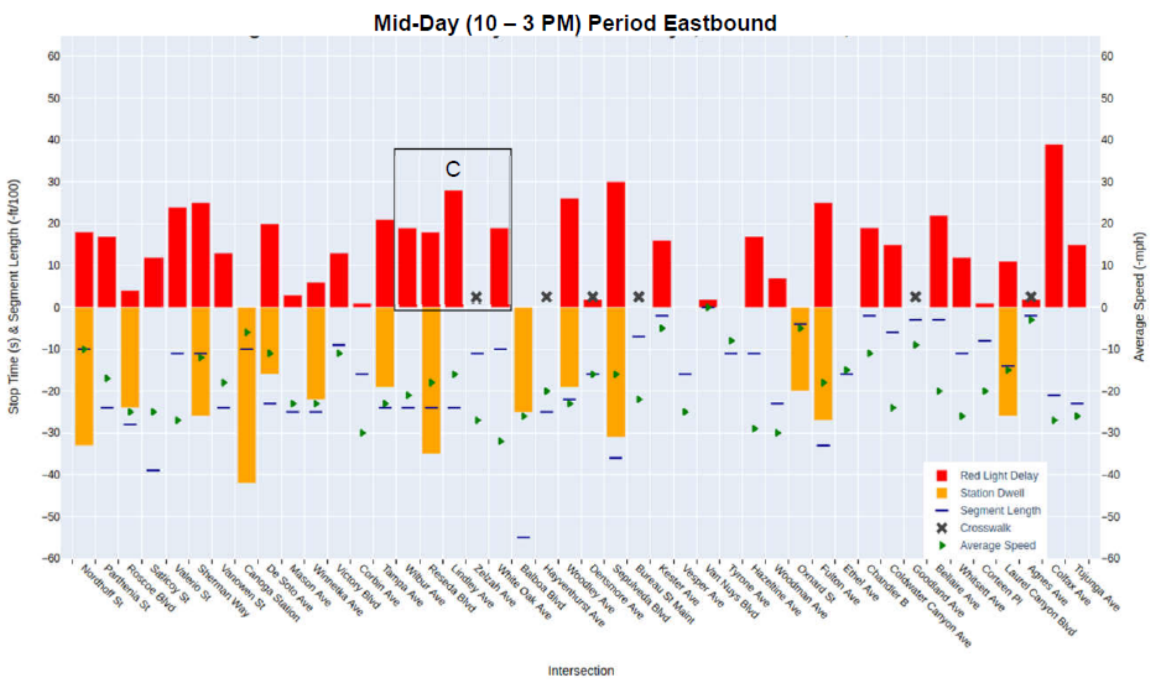
I will expand on some of the problems I alluded to in my discussion of these charts. As laid out after **Figure 16**, there are no representations of dwell times, which may shift the bus out of a green band created by ATSAC. And, as I noted earlier, there has been a slow order in place along the G line, which does not appear to have been reflected in these TS plots.

Dwell Times and Average Speed

Dwell time, the time a bus spends decelerating to a stop, picking up and dropping off passengers, and accelerating to cruising speed, can vary significantly from vehicle to vehicle, as demand changes or more mobility-impaired users seek to board or alight.

Tenco collected dwell time data along the G line to help develop its recommendations for improvement along the alignment. A select part of the data is shown below as **Figure 20**.


AM Rush (6-10 AM) Period Eastbound
A
B
Stop Time (s) & Segment Length (-ft/100)
Average Speed (-mph)
Red Light Delay
Station Dwell
Segment Length
Crosswalk
Average Speed
Nordhoff St
Parthenia St
Roscoe Blvd
Saticoy St
Valerio St
Sherman Way
Vanowen St
Canoga Station
De Soto Ave
Mason Ave
Winnetka Ave
Victory Blvd
Corbin Ave
Tampa Ave
Wilbur Ave
Reseda Blvd
Lindley Ave
Zelzah Ave
White Oak Ave
Balboa Blvd
Hayvenhurst Ave
Woodley Ave
Densmore Ave
Sepulveda Blvd
Bureau St Maint
Kester Ave
Vesper Ave
Van Nuys Blvd
Tyrone Ave
Hazeltine Ave
Woodman Ave
Oxnard St
Fulton Ave
Ethel Ave
Chandler B
Coldwater Canyon Ave
Goodland Ave
Bellaire Ave
Whitsett Ave
Corteen Pl
Laurel Canyon Blvd
Agnes Ave
Colfax Ave
Tujunga Ave
Intersection


Mid-Day (10 – 3 PM) Period Eastbound
C
Stop Time (s) & Segment Length (-ft/100)
Average Speed (-mph)
Red Light Delay
Station Dwell
Segment Length
Crosswalk
Average Speed
Intersection

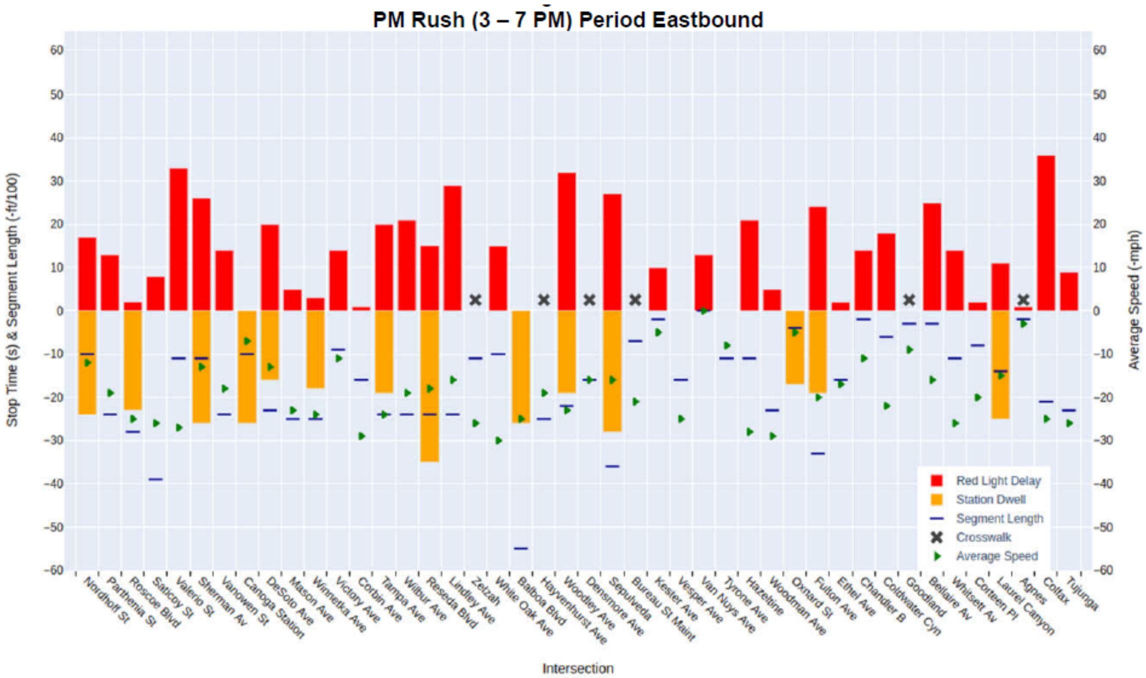


Figure 20. Eastbound dwell time illustration. Full sized versions of these graphics are included in Appendix B. The graph shows red light delay(red bars) station dwell (orange) segment length (black bars) where crosswalks are present (x's on the axis) and the average speed (green arrows). Intersection names are on the x-axis, the left side y-axis shows stop time in seconds and section length in hundreds of feet, and the right side y-axis is used for average speed (Turner Engineering Corporation, 2020a).

As **Figure 20** illustrates, dwell times vary by time of day at various stations. In the illustrations above, note how the leftmost orange (downward) bar, representing dwell time at Nordhoff street, varies in length throughout the day. While Metro keeps data on dwell times, ATSAC does not track dwell times and the TS plots generated by LADOT show no station dwell times.

Smooth progression along the G line is contingent on having accurate green time predictions to help transit buses catch a "green wave." An ideal system would help operators understand when to leave a station to catch an upcoming green wave. Is it possible to develop "smart" dwell time expectations and predictions for the G line? Tenco staff, who were contracted by LA Metro to install smart speed bus displays for operators onboard G line buses, claim that this is indeed the case. Tenco approached the next green prediction problem using a proof-of-concept artificial intelligence (AI) system to create more accurate predictions at each intersection. A similar project could be used to try and predict dwell times, but the development of improved dwell time expectations and upcoming greens using AI is beyond the scope of this report's analysis.

The other part of the assumptions question is average speed along the alignment. According to data captured by the consulting firm Iteris in 2015, the average travel times along the entirety of the G line were between 53 and 56 minutes (as shown in Table F1, below). In total, the amount of time lost at traffic signals along the G line was between 8 and 9 minutes. Iteris indicated in its report that the “ultimate result of [the slow order] was to slow the operation of the Orange Line buses across the Valley such that the average speed fell to 21 mph or less” (Iteris, 2015). **Figure 18** assumes a bus can travel 35,450 feet in roughly 850 seconds, which equals a speed of about 28.4 mph. The most optimistic average speed, the 21 mph offered by Iteris, is a full 25 percent lower than the average speed assumed by the TS plots from LADOT. (Measured end-to-end average speeds, as shown in Table F1 below, show that buses take 53 minutes or more to travel from end-to-end. 18 miles in 53 minutes equals an average speed of roughly 20.4 miles per hour--and that is at the best times along the route.) **Figure 20** breaks this down further, showing that while some sections of the alignment see speeds of 20 mph or more, many segments hover around or have average speeds well below 20 mph. The vast majority of these showed delay at intersections, many more intersections than is suggested by the TS plots furnished by LADOT. Whether it is because the slow order means buses are driving at lower speeds, or because the bus has moved out of a green wave offered by ATSAC, updating TSP to reflect on-the-ground speeds and conditions will be a key step in improving progression along the G line.

Eliminating signal delay and increasing bus speeds to existing posted speed limits, Iteris estimated, would reduce the travel time from North Hollywood to Canoga from 45 minutes to approximately 30 minutes or less. Fully realizing the benefits of signal timing and allowing maximum speed by buses would make the G line more than just competitive with the automobile; trips from Chatsworth to the B line station at North Hollywood would be faster by 10 or more minutes than cars making the same trip on nearby surface streets (Iteris, 2015).

Table 1: Measured travel times along the G-line (Iteris, 2015)

SEGMENT	WESTBOUND/NORTHBOUND TRAVEL TIME (MIN)				EASTBOUND/SOUTHBOUND TRAVEL TIME (MIN)			
	AM[1]	MID-DAY[1]	PM[1]	DAY[1]	AM[1]	MID-DAY[1]	PM[1]	DAY[1]
North Hollywood to Canoga Time between stations[2] (min)	39	40	42	40	38	42	39	39
Canoga to Chatsworth Time between stations[3] (min)	14	16	14	15	15	12	14	14
North Hollywood to Chatsworth Total travel time (min)[4]	53	56	56	55	53	54	53	53

Source: Iteris Travel Time Runs, August 2015
Notes:
[1] The travel times shown represent the average travel times of all line rides conducted during this time period. AM time period occurred from 7:00-10:00 AM, Mid-day occurred from 10:00 AM -3:00 PM, PM period occurred from 3:00-7:00 PM; DAY is the average for all three time periods.
[2] The distance between the North Hollywood station and the Canoga station is approximately 13.5 miles.
[3] The distance between the Canoga station and the Chatsworth station is approximately 4.5 miles.
[4] Total travel time results include dwell times for boarding/alighting at stations.

Improvement Effects on Automobile Traffic

When LA Metro implemented its original TPS system, LADOT engineers expressed concerns about additional delay for cars travelling on perpendicular routes. Tests at the time, however, found little impact on private vehicles, with an average increase of one second of delay per vehicle per cycle, with increases up to two seconds of delay (Los Angeles Metro, 2002). Thus, creation of a passive priority system to synchronize the bus corridor between stops should not introduce new delays for automobiles, as adjustments to cycle offsets to prioritize buses will not significantly affect timing on perpendicular routes. Given the time savings that improving signal priority could generate, as well as the minimal impact LA has had with implementing TSP in the past, the case for improving TSP along the G line alignment is strong.

Plans for the G Line

Some improvements are already being tested. LA Metro staff are preparing to generate more accurate average speed information, and plan on updating the LADOT with the average speeds of G line buses by the end of this calendar year. Doing so may help create more realistic green wave timings for buses, and could form the basis of an effective passive priority system. Eliminating signal delay and speeding up buses by removing the slow order could save 10 minutes or more per run (Iteris, 2015). In addition, LADOT's signal timing experts are already rolling out improvements to set more intersections in busway recall.

Another plan to create long-term improvements for the G line is now in the works. Metro plans to grade-separate (construct an underpass for) major roads, such as Sepulveda Boulevard and Van Nuys Boulevard, heavily prioritize the bus and/or restrict access across the busway at very low-volume intersections, improve signal priority technology and bus connectivity, and install railroad-style gate arms along the G line alignment (Chou, 2017; LA Metro, n.d.-c). These plans, however, will all have relatively long time horizons. Constructing the underpasses will take time, and gate arms will require that traffic crossing the G line alignment wait for longer than is currently required at signals. Details for how to maintain signal coordination and allow smooth flow for automobiles with gate arms along a busy transit corridor are still being developed.

In the long term, LADOT staff may also consider changes to the priority system itself. LADOT and LA Metro engineers could explore other technologies, such as a Wifi and GPS systems as used in Seattle or San Francisco, or moving to a control system that allows for easier programming of signal priority logic. However, based on the six recommendations laid out by Tenco, signal retiming and improvements provide ample ground for improvement to speed the G line further.

Case studies in other jurisdictions also indicated the importance of political and strategic alignment between agencies. LADOT and LA Metro may also engage in longer-term discussions about how best to ensure that both are optimizing metrics that prioritize the G line. A possible measure to consider is switching from vehicle-seconds of delay to person-seconds of delay in order to move the most people along the G line. An extremely crowded rush hour bus carrying 200 passengers would then be worth 200 times a car carrying a single commuter. On other measures, LADOT and LA Metro may simply need to agree to disagree, and find ways to compromise and ensure that both transit passengers and drivers are experiencing the best of LADOT's powerful traffic control system.

Conclusions and Recommendations

LA Metro is considering some long-term improvements for the Metro G Line, including grade separating major streets, and adding railroad-style gate arms. However, there are immediate steps that, in partnership with LADOT, would improve service considerably on the line. Present assumptions made by LADOT's ATSAC system do not correspond with actual conditions. As a result, the TSP system works less optimally than intended.

In the short-term, LA Metro should explore what can be done to lift the slow order along the G line alignment, pursuant to community concerns about (and real-world experience with) crash safety. The slow order significantly impacts average speed on the busway, creating conditions slower than the current signal timing plans anticipate. If the slow order cannot be rescinded, signal timing plans should be updated to reflect real on-the-ground conditions. In the course of updating timing charts, by obtaining more reliable travel speed and dwell time data, better coordination of signals between G line stops can be created. These data would significantly improve the current signal timing states along the G line.

Philosophically, LADOT and LA Metro can discuss moving to measuring delay of people rather than delay of vehicles. If average occupancy on the buses far outstrips the estimated number of drivers and passengers in cars, then using a per-person delay measure can bring political alignment between the parties on the goal of the signal system.

At least one change recommended in a previous report on G line improvement is already being tested on the busway: improved busway recall. But the data indicate that short term improvements are achievable and possible along the G line alignment. By ensuring buses pass quickly through intersections and eliminating signal delay, significant travel time savings could be realized for the G line, and greatly improve this vital transit link in the San Fernando Valley.

Appendix A: Signal Timing Basic Concepts

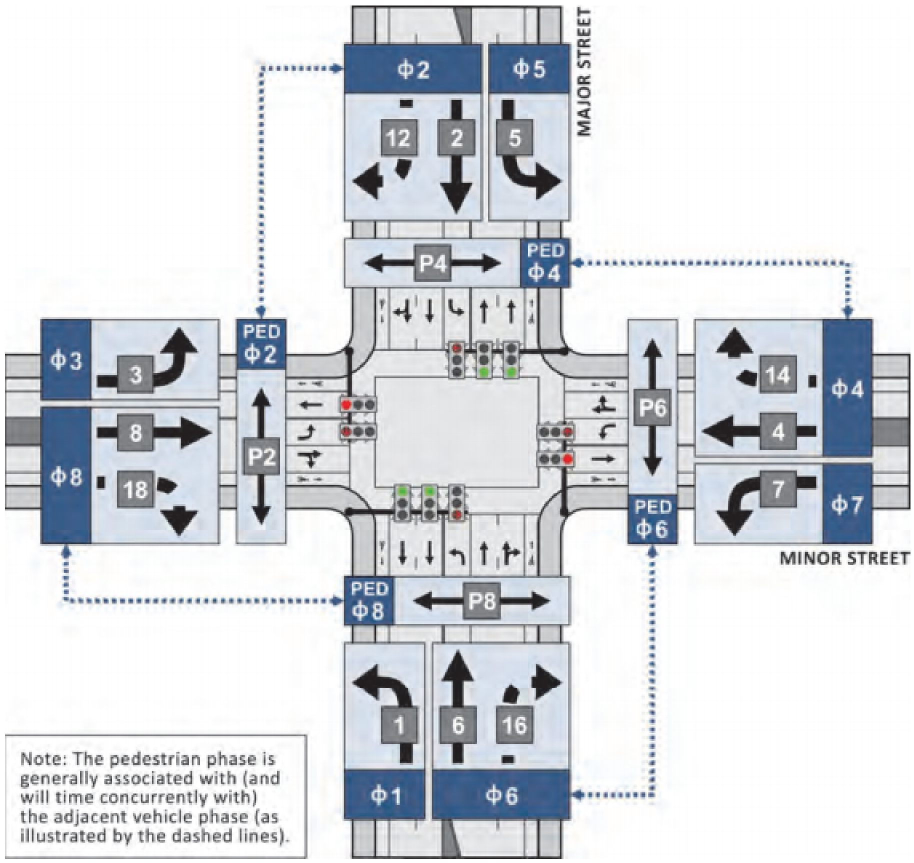


Figure A1. Phase and approach numbering for an intersection.(Urbanik et al., 2015)

First, some basic terminology. A movement is defined by the approach to the intersection and whether someone goes straight through, turns right, or turns left. For example, someone coming (or approaching) from the south and going straight is making a northbound thru movement (gray box 6 in the diagram above) (they are going north and straight). A vehicle approaching from the east and turning left is making a westbound left (gray box 7 in the diagram above). The blue boxes, marked by the capital Greek letter Phi, represent the signal phases. This style of phase notation is generally known as the National Electric Manufacturers Association Standard (NEMA) standard. (Urbanik et al., 2015)

What is a phase? Traffic engineers and signal technicians may be referencing slightly different things when referring to a phase. Traffic engineers may sometimes refer to a combination of phases being served, a phase set such as east and westbound “main street phases," as a phase. Signal technicians will refer to a singular movement, such as just the westbound thru, as a phase. To eliminate confusion, I use the signal technicians' definition of a phase. However, note that at a basic four-way intersection, right turns are allowed concurrently with through movements, and are frequently considered part of the same phase. This is illustrated by **Figure A2**.

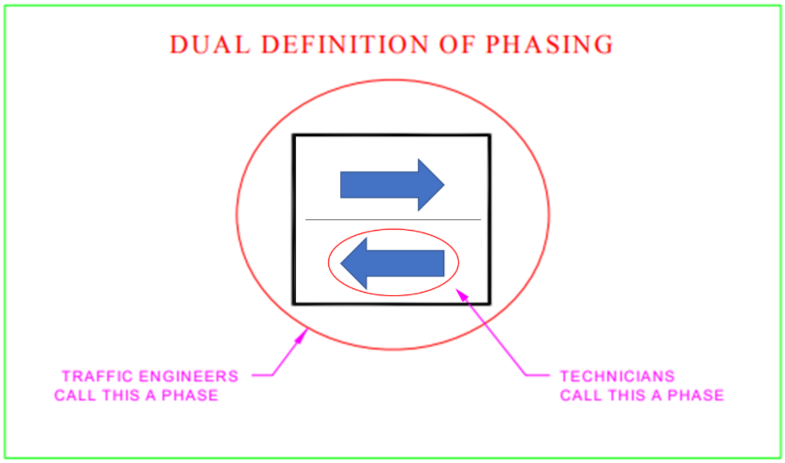


Figure A2. The Dual Definition of Phasing, illustrated. (Buckholz, n.d.)

Returning now to **Figure A1**. In normal signal operation, multiple phases are being served at once. For instance, cars going through both north and south are generally given a green signal. The NEMA phase notation can be represented using a ring-and-barrier diagram.

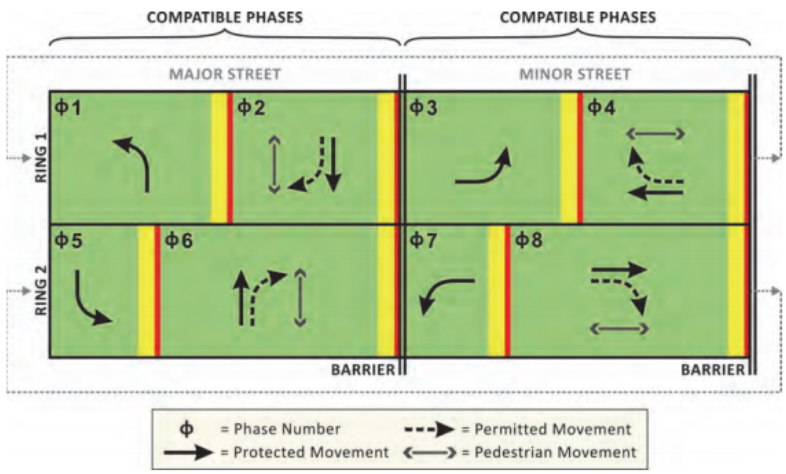


Figure A3. Ring-and-Barrier diagram. By convention, the main street phases are phases 2 and 6. In general, a phase diagram like this one would not also encode timing information (Urbanik et al., 2015).

In this diagram, a phase in ring 1 is compatible with all phases in ring two, as long as they are contained within the same barriers. For instance, phase 3 is compatible with both phases 7 and 8. Or phase 6 is compatible with both phases 1 and 2. However, phase 1 would NOT be compatible with phases 7 and 8. Or 2, 3, or 4 for that matter. (I would encourage any reader for whom this is new to take out a piece of paper and attempt to draw these phases. Figuring out which conflict and do not with a diagram of an intersection is much easier than reading the explanation.) There are an incredible number of possible diagrams; certain intersections can get particularly complex. In Los Angeles, ATSAC is fairly limited to two-ring eight-phase diagrams, which means that certain intersections require…creative programming. The time from one set of phases to be served until that set of phases is served again (traditionally the start of phases 2 and 6) is known as a phase cycle, and the time required to do so is the cycle length.

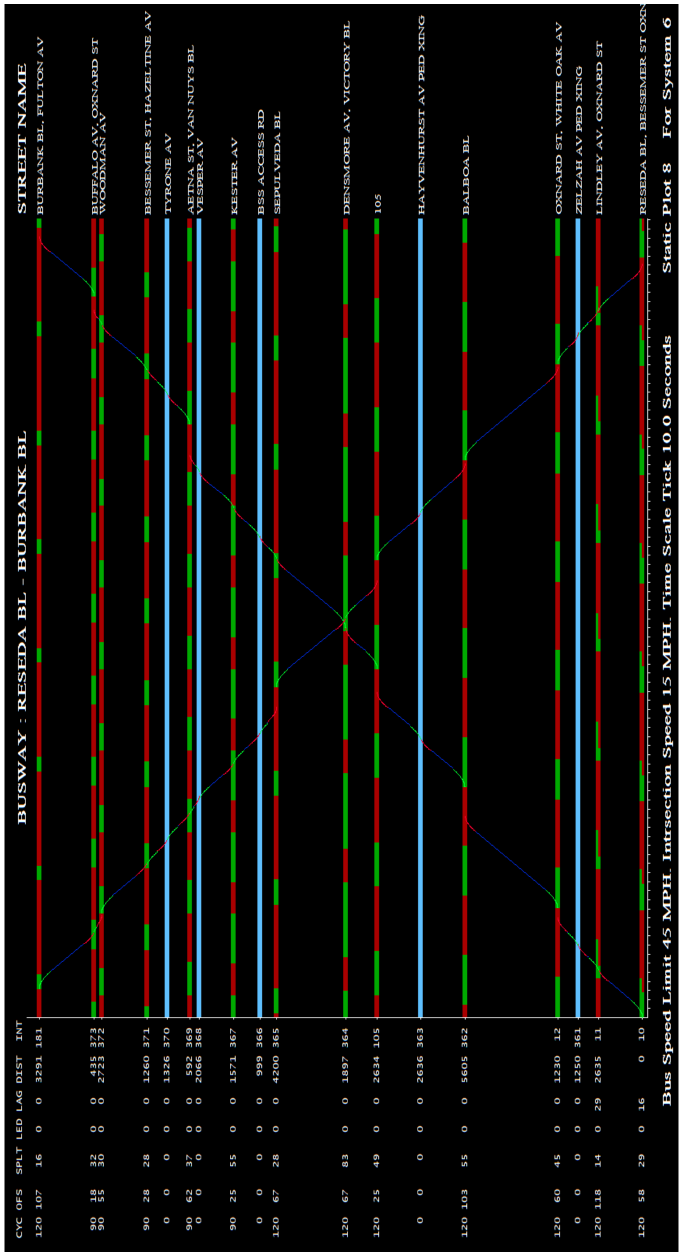
If a signal is set in recall, then a green indication is shown even when there is no vehicle present in that direction. Pedestrian recall means that the signal will show the pedestrian walk indication without the need for the pedestrian button to be pressed.

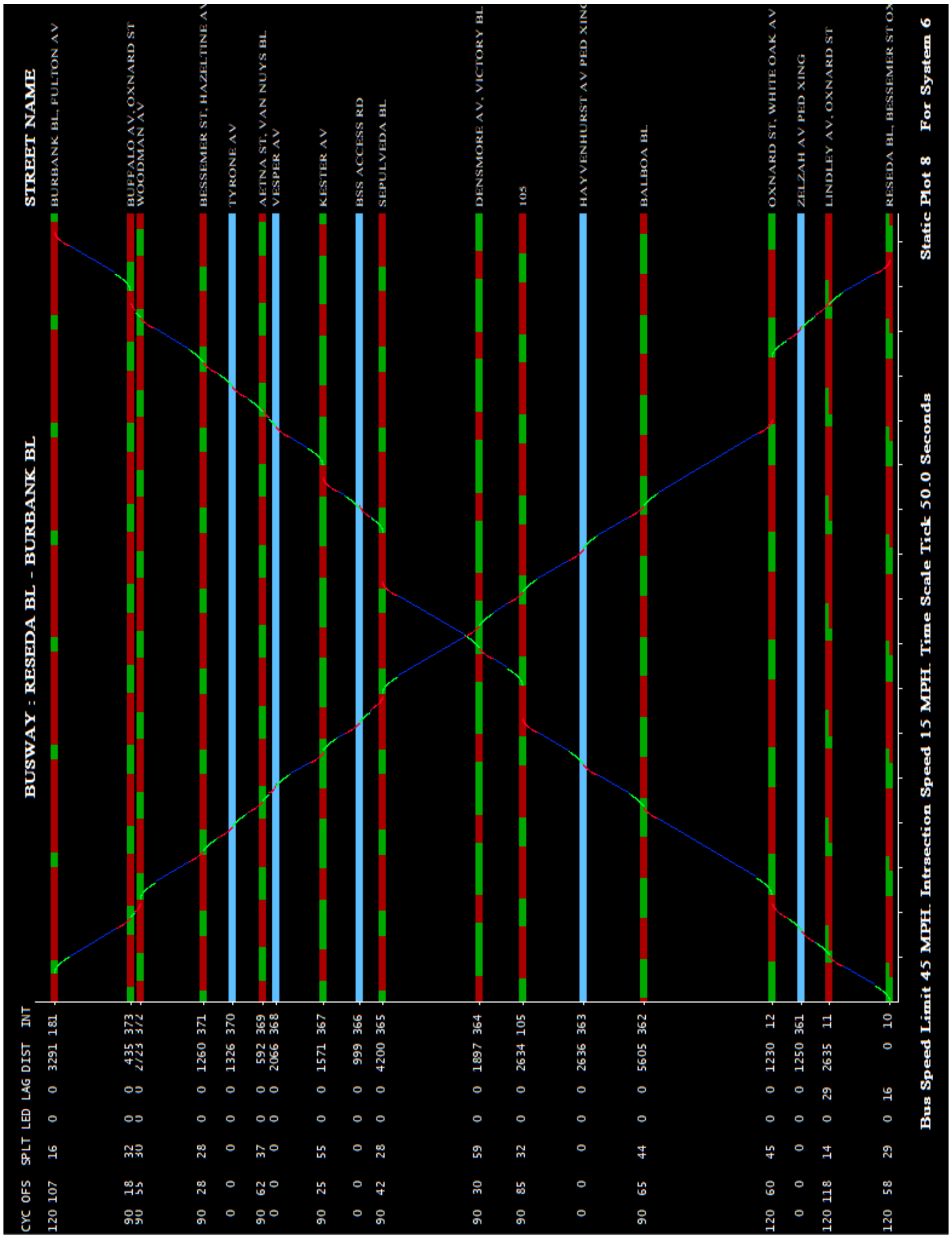
Appendix B: Full-size Graphics

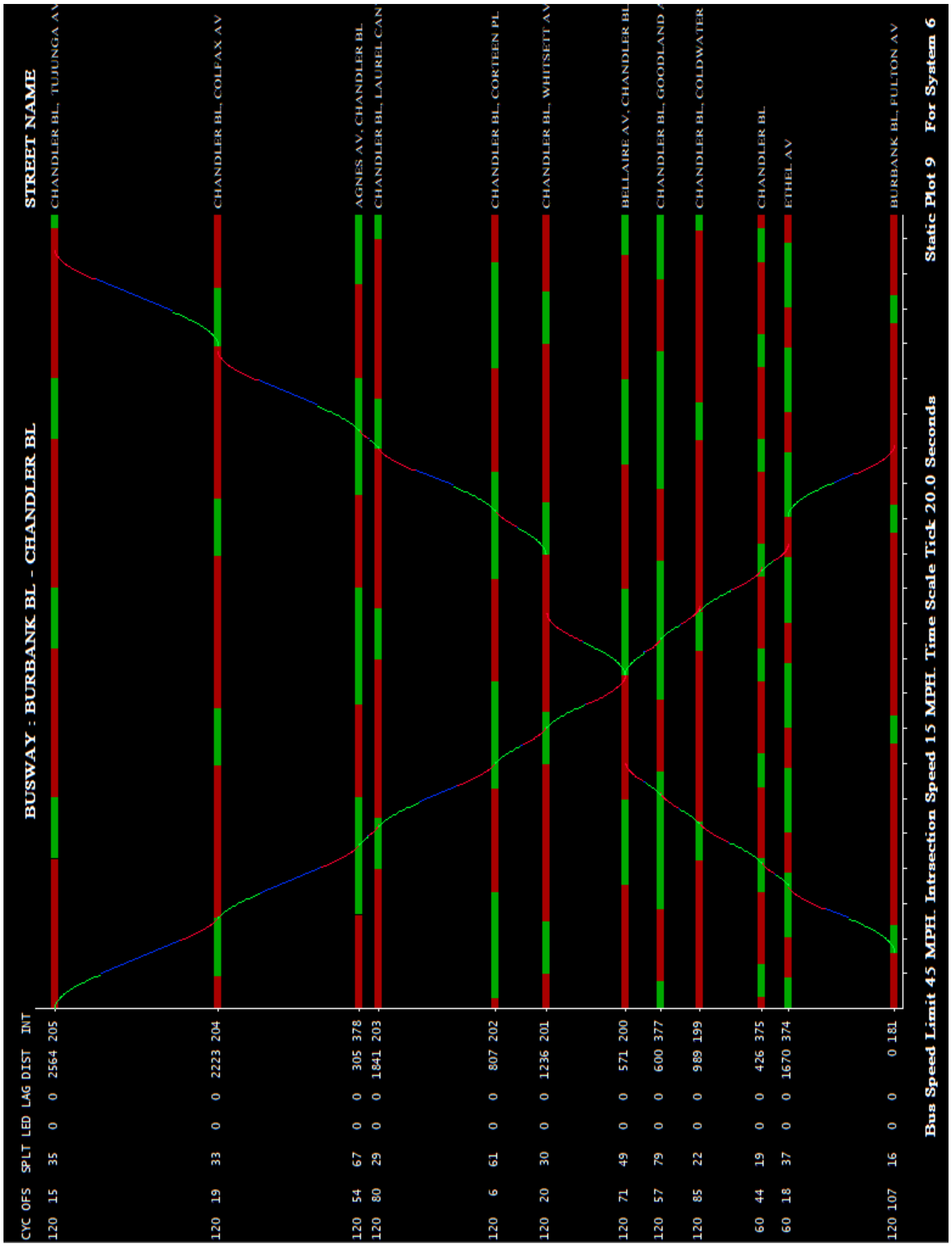
Two plot types are presented here, time-space plots and bus speed and dwell time plots.

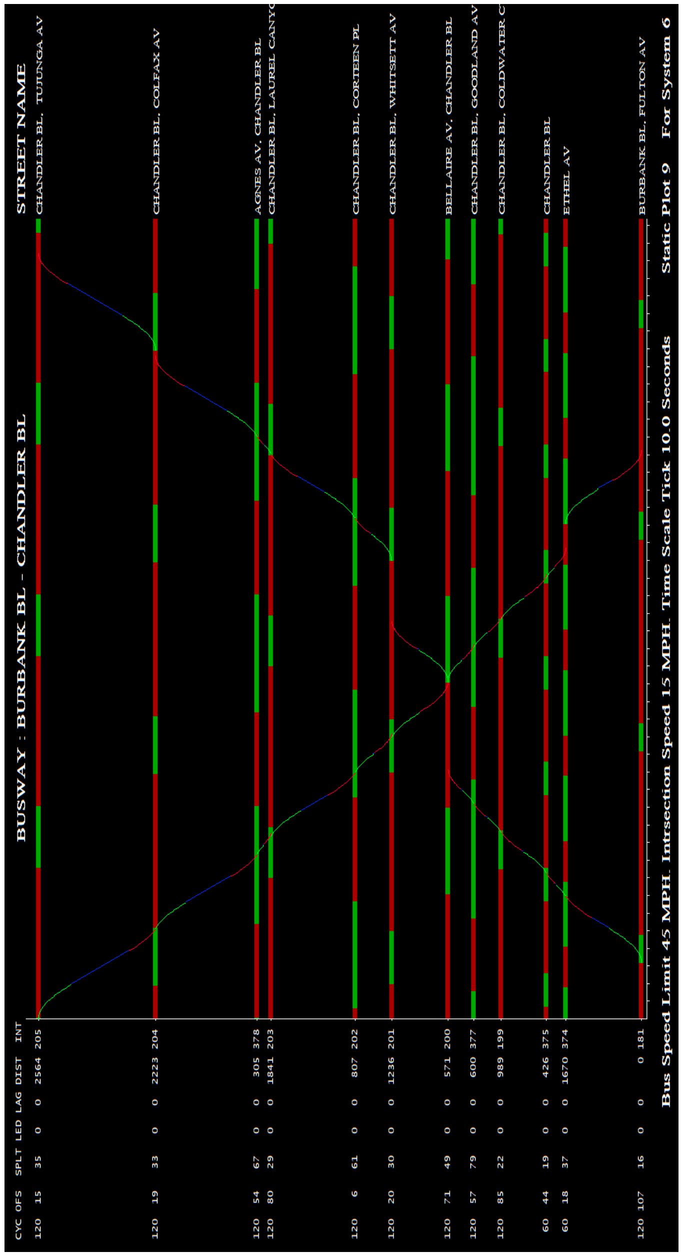
The time-space plots are courtesy of LADOT, and begin on the next page. The AM peak plots are presented first for each segment, followed by the PM peak plots.

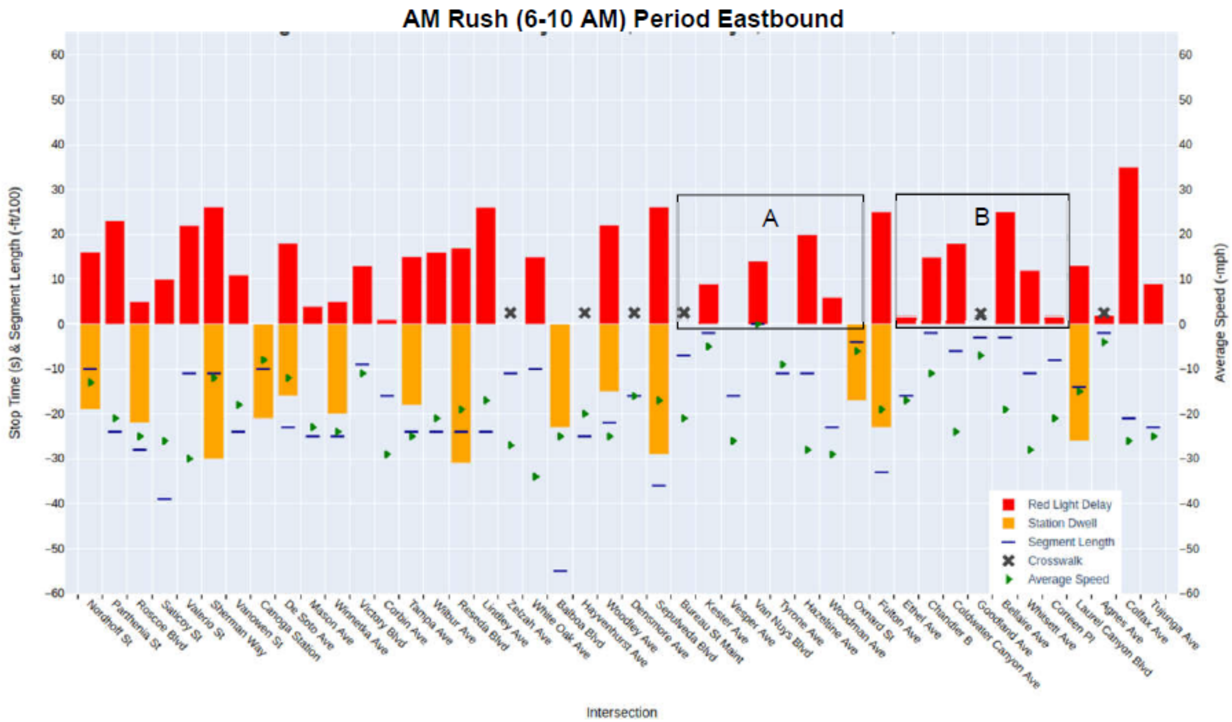
The bus speed and dwell time plots are from a report generated by the Turner Engineering Corporation (Tenco) (Turner Engineering Corporation, 2020a, p. 8).


BUSWAY : RESEDA BL - BURBANK BL
CYC OFS SPLT LED LAG DIST INT
STREET NAME
BURBANK BL, FULTON AV
BUFFALO AV, OXNARD ST
WOODMAN AV
BESSEMER ST, HAZELTINE AV
TYRONE AV
AETNA ST, VAN NUYS BL
VESPER AV
KESTER AV
BSS ACCESS RD
SEPULVEDA BL
DENSMORE AV, VICTORY BL
105
HAYVENHURST AV PED XING
BALBOA BL
OXNARD ST, WHITE OAK AV
ZELZAH AV PED XING
LINDLEY AV, OXNARD ST
RESEDA BL, BESSEMER ST OXN
Bus Speed Limit 45 MPH. Intrsection Speed 15 MPH. Time Scale Tick 10.0 Seconds
Static Plot 8
For System 6


BUSWAY : RESEDA BL - BURBANK BL
STREET NAME
BURBANK BL, FULTON AV
BUFFALO AV, OXNARD ST
WOODMAN AV
BESSEMER ST, HAZELTINE AV
TYRONE AV
AETNA ST, VAN NUYS BL
VESPER AV
KESTER AV
BSS ACCESS RD
SEPULVEDA BL
DENSMORE AV, VICTORY BL
405
HAYVENHURST AV PED XING
BALBOA BL
OXNARD ST, WHITE OAK AV
ZELZAH AV PED XING
LINDLEY AV, OXNARD ST
Bus Speed Limit 45 MPH, Intersection Speed 15 MPH, Time Scale Tick 50.0 Seconds
Static Plot 8 For System 6


BUSWAY : BURBANK BL - CHANDLER BL
STREET NAME
Bus Speed Limit 45 MPH, Intersection Speed 15 MPH, Time Scale Tick 20.0 Seconds
Static Plot 9 For System 6


BUSWAY : BURBANK BL - CHANDLER BL
STREET NAME
CHANDLER BL, TUJUNGA AV
CHANDLER BL, COLFAX AV
AGNES AV, CHANDLER BL
CHANDLER BL, CORTEEN PL
CHANDLER BL, WHITSETT AV
BELLAIRE AV, CHANDLER BL
CHANDLER BL, GOODLAND AV
CHANDLER BL
ETHEL AV
BURBANK BL, FULTON AV
CYC OFS SPLT LED LAG DIST INT
Bus Speed Limit 45 MPH. Intrsection Speed 15 MPH. Time Scale Tick 10.0 Seconds Static Plot 9 For System 6


AM Rush (6-10 AM) Period Eastbound
Stop Time (s) & Segment Length (-ft/100)
Average Speed (-mph)
A
B
Red Light Delay
Station Dwell
Segment Length
Crosswalk
Average Speed
Nordhoff St
Parthenia St
Roscoe Blvd
Saticoy St
Valerio St
Sherman Way
Vanowen St
Canoga Station
De Soto Ave
Mason Ave
Winnetka Ave
Victory Blvd
Corbin Ave
Tampa Ave
Wilbur Ave
Reseda Blvd
Lindley Ave
Zelzah Ave
White Oak Ave
Balboa Blvd
Hayvenhurst Ave
Woodley Ave
Densmore Ave
Sepulveda Blvd
Bureau St Maint
Kester Ave
Vesper Ave
Van Nuys Blvd
Tyrone Ave
Hazeltine Ave
Woodman Ave
Oxnard St
Fulton Ave
Ethel Ave
Chandler B
Coldwater Canyon Ave
Goodland Ave
Bellaire Ave
Whitsett Ave
Coreen Pl
Laurel Canyon Blvd
Agnes Ave
Colfax Ave
Tujunga Ave
Intersection

Mid-Day (10 – 3 PM) Period Eastbound

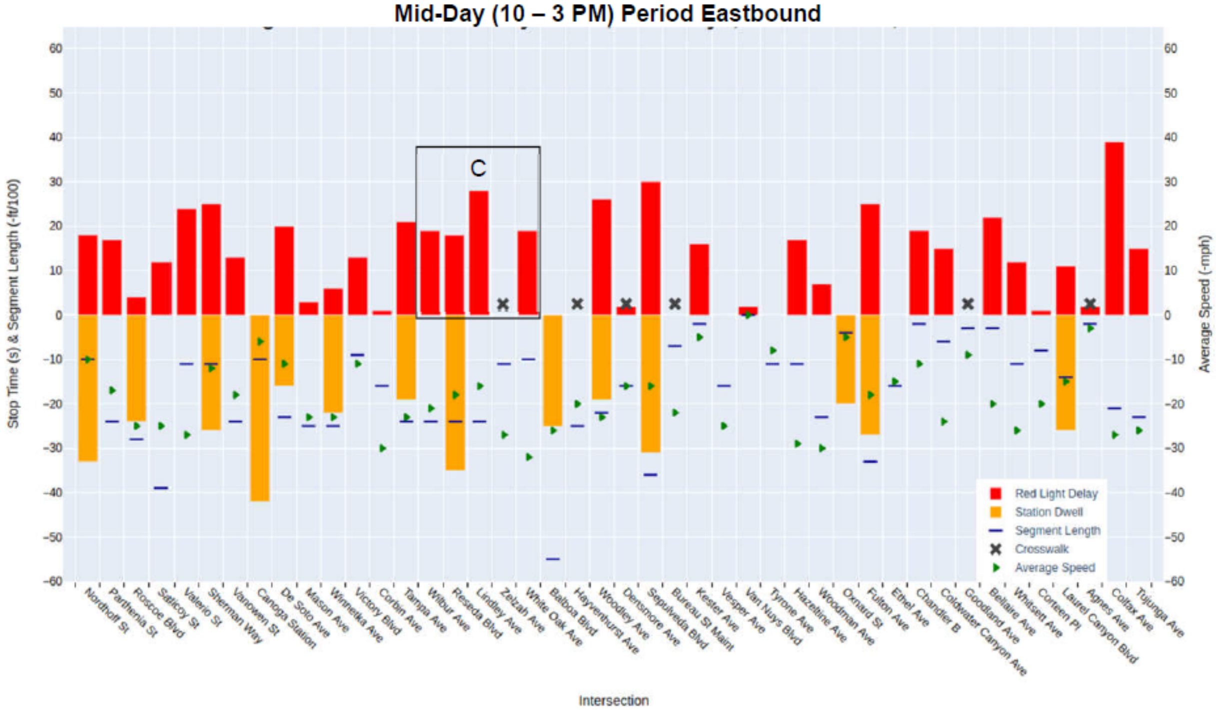
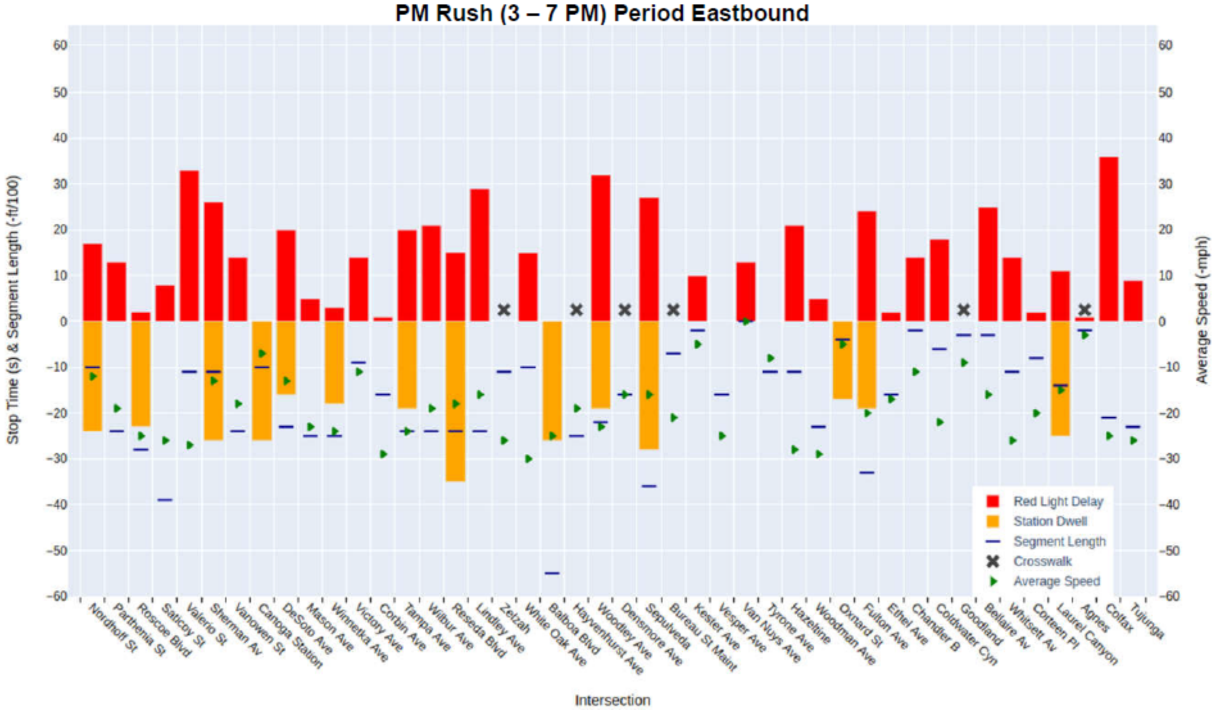


Figure 3-3

PM Rush (3 – 7 PM) Period Eastbound



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