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Planning Corridors for Transit Signal Priority While Considering Pedestrian Delay

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16. Abstract:

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TSPRT was applied to corridors in Charlottesville, Blacksburg, and Arlington. Microscopic simulation was used to address the impact of TSP implementation. Results indicated that among these three corridors, Columbia Pike in Arlington would be best suited for TSP implementation. Columbia Pike had a medium score for TSP where Blacksburg and Charlottesville had low scores for successful TSP implementation. The higher the TSPRT score, the more viable TSP is for implementation.

A higher TSPRT score does not necessarily imply higher reductions in delay due to the implementation of TSP. Instead, the impact of TSP depends on the target area's characteristics and can be measured through the use of microsimulation, which indicated substantial benefits for buses and traffic in the same direction as buses. However, a trade-off was evident between the TSP direction and the non-TSP direction in terms of overall delay. Nevertheless, from the perspective of delay for transit passengers, TSP could reduce overall passenger delay, because the number of passengers on a bus is generally higher than the number of passengers in a passenger vehicle. The simulated effect of TSP on crossing pedestrians was negligible. In order for TSP to have a meaningful impact on pedestrians, higher volumes of crossing pedestrians and more frequent TSP activations would be required. In smaller towns such as Blacksburg or Charlottesville, TSP would not impact pedestrians substantially.

The study recommends that 1) the Virginia Department of Rail and Public Transportation's Public Transportation Division should consider which of its business processes could benefit from the incorporation of the TSPRT and 2) the Virginia Department of Transportation's Transportation and Mobility Planning Division and/or the Department of Rail and Public Transportation's Public Transportation Division should disseminate information regarding the use of the TSPRT tool to Virginia metropolitan planning organizations and localities. The benefit of TSPRT may be more efficient budget allocation, by supporting programs such as project prioritization processes.

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FINAL REPORT

PLANNING CORRIDORS FOR TRANSIT SIGNAL PRIORITY WHILE CONSIDERING PEDESTRIAN DELAY

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ABSTRACT

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INTRODUCTION

A common inconvenience faced by Virginia travelers is delay during their journeys. Part of that delay can be attributed to traffic congestion in urban and suburban settings. The interactions of light-duty passenger vehicles, trucks, transit buses, rail, and pedestrians influence overall system delay as travel patterns and paths interact. Travelers choosing transit alternatives for daily transportation have a positive effect on overall system operations as they remove vehicles from the roadway and thus mitigate delay. Although delay may be unavoidable, transit agencies can improve access to destinations and make transit more attractive to potential users through the use of Transit Signal Priority (TSP).

TSP is an operational measure implemented at signalized intersections to improve transit performance by temporarily modifying signal timings to prioritize transit vehicle movement. TSP consists of communication between transit vehicles and traffic signal controllers to either extend the green time on the approach that the transit vehicle is traveling or reduce the red time on that approach. Additionally, since TSP is intended to provide benefits to transit riders who are pedestrians before boarding and who become pedestrians upon alighting, pedestrian facilities and operations should also be analyzed when considering TSP.

TSP uses technology to reduce transit vehicle dwell time at traffic signals and may be implemented at individual intersections or across corridors. TSP systems require four components: 1) a detection system aboard transit vehicles; 2) a priority request generator, which can be aboard the vehicle or at a centralized management location; 3) a strategy for prioritizing requests; and 4) an overall TSP management system (Smith et al., 2005). There are two types of TSP systems: centralized and distributed.

In a centralized TSP system, a system organizes and manages requests for priority from many transit vehicles. The priority request system may be located on the transit vehicle if that vehicle is equipped with a Global Positioning System (GPS) and can communicate directly with the traffic management center. Alternatively, the priority request system is based at the traffic management center and processes requests in real-time as vehicles approach intersections (Li et al., 2008). In a distributed TSP system, all priority decisions are made at the intersection level, rather than at a central location. This method requires less communication between traffic and transit management centers than centralized TSP, but one potential problem in this system is the possibility of granting priority to vehicles that are on-time or ahead of schedule (Li et al., 2008).

Based on previous research, this study created a tool that will help guide stakeholders on the applicability of TSP implementation on a corridor of interest. Virginia agencies are anticipated to benefit as the procedure emphasizes consideration of transit network characteristics and minimization of adverse effects to other road users, specifically pedestrians.

PURPOSE AND SCOPE

The purpose of this study was to develop a tool capable of guiding Virginia decision-making agencies considering both the implementation of a TSP system and pedestrian quality of service. This tool is a TSP viability index calculated from criteria variables derived from previous research. The procedure considers general transportation network characteristics, transit operation characteristics, and the effects of pedestrian interactions in the system.

The scope of the study was limited to developing the tool; demonstrating its use on three Virginia corridors considering their traffic composition, geometry, and demographics; and validating the tool by conducting microsimulation on those three corridors.

METHODS

Five main tasks were undertaken to complete the research for this study:

1. Review relevant literature
2. Develop a criteria table
3. Collect data
4. Apply the TSP recommendation tool on Virginia corridors
5. Conduct simulation and analysis of test corridors

Reviewing Relevant Literature

The process of collecting background information for the development of the criteria table consisted of a literature review that studied TSP reference guides, refereed journal articles, case studies, and government reports of TSP implementations. The main objective of the literature review was to identify criteria that relate to TSP performance or operations and reduce negative impacts on other modes, specifically pedestrians.

Developing a Criteria Table

The construction of a weighted criteria table was completed by utilizing findings from the literature review informed by the research team's engineering judgment to identify valid criteria. A list of the criteria categories that were explored is provided below.

- Geometric characteristics
- Transit characteristics
- Pedestrian characteristics
- Traffic characteristics
- Signal characteristics

The resulting table consisted of these five categories and 14 criteria, each with associated metrics. The number of criteria was reduced to as few as possible to allow for a relatively quick analysis of the viability of TSP on a selected corridor.

The criteria were given weights on a five-point scale as follows to show the relative influence of each on the viability of successful TSP implementation:

- A weight of five indicates a criterion is essential to successful TSP implementation.

- A weight of four indicates a criterion is very important to successful TSP implementation.

- A weight of three indicates a criterion is beneficial to successful TSP implementation.

- A weight of two indicates a criterion is somewhat important to successful TSP implementation.

- A weight of one indicates a criterion is least important to successful TSP implementation.

Other attributes of the area being analyzed that could either affect the ease of implementing TSP or that could be improved by TSP were assigned scores. These criteria weight scores were defined as follows.

- A score of 3 indicates an attribute that would either highly facilitate TSP or would be improved substantially from a TSP investment.

- A score of 2 indicates an attribute that would either facilitate TSP or would be improved from a TSP investment.

- A score of 1 indicates an attribute that would make the implementation of TSP difficult or would be not be improved substantially from a TSP investment.

- A score of 0 indicates that the attribute would not allow for TSP implementation or a TSP investment would not improve the attribute.

Equation 1 provides a general equation for the TSP Viability Index, a weighted sum of the weights and scores for the variables in the criteria table.

$$TSP_{VI} = \frac{\sum_{i=1}^{19} Weight_i \times Score_i}{50} \quad (1)$$

Where:
TSP_{VI} = the TSP Viability Index for the corridor/project in question, $Weight_i$ = the weight assigned for each criteria variable *i* (where 5 is the most viable TSP solution and 1 is least viable TSP solution), $Score_i$ = the evaluation score for the criteria variable *i* in the corridor being examined (from 3 to 0, explained in following sections), 50 = the sum of the weights

A TSP viability index below one would indicate that TSP is unlikely to be a good investment for the area under consideration. A value between one and two would indicate that additional improvements to the area may be needed to have a successful implementation of TSP. A value between two and three would indicate that TSP implementation may be viable in the area under consideration.

Calibrating and Validating the Criteria Table

The calibration and validation of the final weighted criteria table was accomplished by referencing literature review case studies and assigning values for each of the metrics. The research team identified aspects in the literature that were commonly regarded as positive to transit, network operations, and pedestrians when TSP was implemented. Such aspects were given a high weighting, and those that did not were given lower weights.

The overall goal of the calibration and validation process was to ensure that the characteristics considered in the criteria table corresponded to characteristics that influence TSP and pedestrian operations. Therefore, the calibration and validation of the constructed criteria table was completed by ensuring results were not differing substantially from reported results in the literature. Many of the criteria were obtained from trusted and published manuals and publications. However, the weight adjustment and model equations utilized to develop the criteria score were developed with the judgment of the research team to capture characteristics unique to TSP candidate corridors in Virginia.

The final criteria table was reviewed by the study's Technical Review Panel to ensure that the characteristics considered in the criteria table correspond to characteristics that influence TSP and pedestrian operations. The calibrated and validated criteria table was refined and developed into a usable tool in Microsoft Excel format.

Collecting Data

The research team looked to open-source data as the first option for data collection. This included information from transit agencies (routes, ridership, and operations data), the Virginia

Department of Transportation (VDOT) (roadway demand and configurations), and planning departments (planning studies and other data collected as part of the planning process). If data were not publicly available, the research team contacted transportation officials in the areas for which data were needed.

The following sources were used for data collection for each of the five main characteristics of the corridor that TSPRT analyzes. The details of the data collection are provided below:

1. Geometric Characteristics – Google Street View, Google Maps

2. Transit Characteristics – transit agency open-source information and reports

3. Pedestrian Characteristics – Walk Score website and Census data

4. Traffic Characteristics – VDOT traffic count data, Google Maps data, and city/county planning studies

5. Signal Characteristics – city/county planning agencies and observation of traffic operations

One data element involved identifying the percentage of an area's population that is transit-dependent. The method for determining the transit-dependent population and proportion of the population that bikes and walks focused on vehicle availability and the number of drivers, rather than individual characteristics such as age and income. The methodology was originally developed by the U.S. Department of Transportation, Federal Highway Administration, and Bureau of Transportation Statistics, in conjunction with the Transportation Research Board Census Subcommittee and published by the Federal Transit Administration in the *Census Transportation Planning Package 2000 Status Report* (United States Department of Transportation, 2006). The following equations were used to determine the transit-dependent population (Jiao and Dillivan, 2013; Steiss, 2006).

- Household drivers = (population age 16 and over) – (persons in group quarters)
- Transit-dependent household population (16+ within households) = (household drivers) - (vehicles available)
- Transit-dependent population = (Transit-dependent household population) + (Population 12-15 years of age) + (Non-institutionalized population in group quarters)

Note that the category of group quarters describes living arrangements other than the typical household, including "college residence halls, residential treatment centers, skilled nursing facilities, group homes, military barracks, correctional facilities, and workers' dormitories" (United States Census Bureau, 2010). Further, group quarters are owned or managed by an entity that provides services such as custodial or medical care to residents along with housing.

Applying the TSP Recommendation Tool on Virginia Corridors

The TSP Recommendation Tool (TSPRT) was applied to three Virginia corridors where TSP may be applicable. These corridors were selected based on differing geographic areas, transit agency sizes, and available data to test the tool. The localities, transit systems, and corridors where the method was tested were as follows:

- Charlottesville (Charlottesville Area Transit), East High Street
- Blacksburg (Blacksburg Transit), South Main Street
- Arlington (Arlington Transit and Washington Metropolitan Area Transit Authority), Columbia Pike

The technical approach and proof of concept consisted of implementing the finalized criteria table (TSPRT) for these three corridors. The results were evaluated and utilized to provide feedback and final verification of the tool. Engineering judgment and discussion with transit leaders about the effectiveness of the TSPRT were sought, and adjustment to the weights and models was implemented during this process. A summary of inputs into the criteria table is provided for each corridor, and the final recommendation score for TSP is shown. A report for each corridor considered explains the input criteria in detail, as well as how each criterion's weight and score affected the final TSPRT result.

Conducting Simulation and Analysis of Test Corridors

To provide final verification of the TSPRT, the corridor with the highest recommendation score and the one with the lowest recommendation score were analyzed in a VISSIM simulation to provide additional information on the effect of TSP implementation. The results for this procedure were used to verify that there would be greater benefits of TSP in a corridor with a higher TSP viability score than in a corridor with a lower TSP viability score.

VISSIM is a microscopic traffic flow simulation package developed by PTV Group. The latest version of VISSIM 11 was released in 2018 (PTV Group, 2018). Many TSP studies have utilized VISSIM for microsimulation (Abdy and Hellinga, 2010; He et al., 2011; Ma et al., 2013; Vlachou et al., 2010; Xu and Zheng, 2012). Other simulation tools including INTEGRATION (Dion et al., 2004; Rakha and Zhang, 2004; Van Aerde et al., 1996), PARAMICS (Lee et al., 2005; Satiennam et al., 2005), SYNCHRO (Ekeila et al., 2009 and Qing et al., 2014), SIMBOL, and NETSIM also have been used in previous TSP studies. The project team chose VISSIM because of its ability to accurately simulate the TSP scenarios and the team's familiarity with the software package. VISSIM was utilized to perform the planning-level analysis, TSP and signalization analysis, and pedestrian analysis. For the two considered corridors, two cases were evaluated: the base case without TSP (pre-TSP) and with TSP implementation (post-TSP).

The simulation used an evening peak hour of 4:30-5:30 p.m. A 15-minute warm-up period was used in order to allow a steady state of traffic to be on the network before analysis occurs. The simulation assumed that all signals operate on actuated signal control. The base scenario used the current day configuration of each corridor (i.e., the before-TSP implementation scenario), and the alternative scenario was after TSP implementation. Each scenario was run ten times with different random seeds (to account for natural traffic variation). The measures of effectiveness (MOEs) in the simulation include stop delay for all vehicles, overall stop delay for buses, and pedestrian delay (obtained by subtracting the theoretical travel time from the actual travel time) for each intersection along the simulated corridor.

RESULTS

Literature Review

TSP Manuals and Guidelines

The third edition of the Transit Capacity and Quality of Service Manual (TCQSM) describes transit performance measures and the calculation of the multimodal Level of Service (LOS) (Kittelson and Associates et al., 2013). Those measures were developed for transit performance, not specifically for evaluating TSP performance. However, the TCQSM provides useful tools to evaluate the quality of service in transit corridors before implementing TSP.

The TSP Handbook and the TSP Research Tools are two important resources for TSP implementation and evaluation (Li et al., 2008; Smith et al., 2005). The TSP Handbook provides case studies where operational improvements of transit vehicles were documented, using the reduction in delay and travel time after implementation as performance metrics. The TSP Research Tools document provides methodologies for the evaluation of TSP but does not include pedestrian metrics as a performance measure for TSP. The document provides a description of the technologies, implementations, and system evaluation for TSP technologies.

Transit Capacity and Quality of Service Manual (TCQSM), 3rd Edition

Chapter 1 of the TCQSM provides examples of transit performance measures in eight categories: travel time, availability, service delivery, safety and security, maintenance and construction, economic, transit impact, and capacity. Table 1 provides the transit performance measure categories and example performance measures for each category. The report showed that transit performance could be measured from a variety of viewpoints, such as passenger, agency, driver, and community. One area of transit performance measurement is the impact that transit has on the community it serves in terms of jobs created or supported, property value increases resulting from investments in transit service, and reductions in pollution and congestion. These transit performance measures can be utilized to measure and evaluate the current transit service before the TSP analysis (Kittelson and Associates et al., 2013).

The TCQSM also provided concepts and calculation examples for both technical and non-technical users. Exhibit 5-26 of the TCQSM (Kittelson and Associates et al., 2013) provides a list of the input data needed to calculate a transit LOS value. Input data come from three main categories: transit operations data, transit amenity data, and pedestrian environment data. Data for transit operations, transit amenities, and the pedestrian environment can be collected in the field if there is not a GIS system or other database with the data readily available.

Table 1. Transit Performance Measures

Category	Performance measure examples
Travel time	Transit-auto travel time, Transfer time
Availability	Service coverage, Service denials, Frequency, Hours of service
Service delivery	Reliability, Comfort, Passenger environment, Customer satisfaction
Safety & security	Vehicle accident rate, Passenger accident rate, Crime rate, Percent of vehicles with safety devices
Maintenance & construction	Road calls, Fleet cleaning, Spare ratio, Construction impact
Economic	Ridership, Fleet maintenance performance, Cost efficiency, Cost-effectiveness
Transit impact	Community economic impact, Employment impact, Environmental impact, Mobility
Capacity	Vehicle capacity, Volume-to-capacity ratio, Roadway capacity

Note: Adapted from Kittelson and Associates et al. (2003 and 2013)

There are four steps in the calculation of transit LOS. First, the transit wait-ride score is calculated using the headway factor ("the ratio of the estimated ridership at the transit headway being evaluated to the estimated ridership at a base headway of 60 minutes") and perceived travel time factor ("the ratio of the estimated ridership at the perceived transit speed being evaluated to the estimated ridership at a base speed") (Kittelson and Associates et al., 2013). Second, the pedestrian environment score is calculated using the length of the crosswalk, vehicle volume, and speed adjustment factors. Third, a numerical transit LOS score is determined using the transit wait-ride score and pedestrian environment score from the previous steps. Lastly, the transit LOS (letters A through F) is determined based on a criteria table. The detailed calculation of the factors can be found in Chapter 5 in the TCQSM (Kittelson and Associates et al., 2013).

Step 1: Determine the transit wait-ride score: The transit wait-ride score is a performance measure of a transit system that is compared to a low-level baseline transit service. The baseline transit service only operates once an hour, with a low average travel speed. If there is no service provided in the direction being analyzed, then the transit wait-ride score is 0.0. If there is service provided, Equation (2) is used to calculate the wait-ride score. A higher score corresponds to better performance.

$$s_{w-r} = f_h f_{tt} \tag{2}$$

Where $\mathrm{s}_{\mathrm{w-r}}$ is the transit wait-ride score, f_h is a headway factor, and $f_{tt}$is a perceived travel time factor. Equations to calculate these factors are provided in the TCQSM.

Step 2: Determine the pedestrian environment score: The pedestrian environment score is a measurement of the quality of the pedestrian environment near a transit stop and is calculated by Equation (3). A lower score corresponds to better performance.

$$\mathrm{I}_p = 6.0468 + f_w + f_v + f_s \tag{3}$$

Where I_p is a pedestrian environment score, f_w is a cross-section (crosswalk length in feet) adjustment factor, f_v is a motorized vehicle volume adjustment factor, and f_s is a motorized vehicle speed adjustment factor. Equations to calculate these factors are provided in the TCQSM.

Step 3: Determine the transit LOS score: The transit LOS score is calculated by the following equation:

$$\mathrm{I_t} = 6.0 - 1.50 s_{w-r} + 0.15 I_p \tag{4}$$

Where $\mathrm{I_t}$ is the transit LOS score, s_{w-r} is the transit wait-ride score, and I_p is the pedestrian environment score.

Step 4: Determine transit LOS: A LOS score above 5.00 equates to LOS F, a score above 4.25 but below 5.00 equates to LOS E, a score above 3.50 but below 4.25 equates to LOS D, a score above 2.75 but below 3.50 equates to LOS C, a score above 2.00 but below 2.75 equates to LOS B, and a score of less than or equal to 2.0 equates to LOS A. These levels of service provide a baseline for the transit service before the implementation of TSP.

Chapter 6 of the TCQSM explains TSP measures. However, neither data inputs nor MOEs are provided. The TCQSM defines TSP as "altering traffic signal timing at intersections to give priority to transit operating in a median busway, exclusive bus lanes, or mixed traffic. TSP modifies the regular signal operation to accommodate transit vehicles better while maintaining signal coordination along a route and overall signal cycle length at individual intersections" (Kittelson and Associates et al., 2013).

Table 2 shows the types of bus signal priority systems and descriptions described in the TCQSM. Passive strategies accommodate transit operations through the use of pre-timed modifications to the signal system that occur even when buses are not present. Active strategies adjust the signal timing after a bus is detected to be approaching an intersection. Real-time strategies consider both non-transit vehicles and bus arrivals at a single intersection or a network of intersections in terms of overall system performance. Preemption terminates the current signal and returns to the bus phase.

Table 3 shows the TCQSM breakdown of service volumes in a bus lane for a downtown street. When the service volume in the bus lane is 20 buses/lane/hour or less, it is free-flow. When it is over 60 buses/lane/hour, buses start forming platoons and queuing. In other words, at such high volumes, because a bus arrives at a bus stop on average every minute, buses may form queues.

The location of bus stops along a route can directly influence bus travel time and reliability (Kittelson and Associates et al., 2013). Figure 1 illustrates the near-side, mid-block, and far-side bus stop locations. Far-side stops are placed downstream of a signalized intersection, and near-side stops are placed upstream of a signalized intersection.

Far-side stops have the most benefits for bus speeds and capacity, followed by mid-block stops and near-side stops (Kittelson & Associates et al., 2013). However, in practice, transit agencies must also consider other factors when choosing stop locations, such as conflicts with other vehicles operating on the roadway, transfers, passenger walking distances, locations of passenger generators, signal timing, driveways, physical obstructions, and the implementation of preferential transit treatments.

Table 2. Types of Bus Signal Priority System

Treatment	Description
PASSIVE PRIORITY	
Adjust cycle length	Reduced cycle lengths at isolated intersections to benefit buses
Split phases	Introduce special phases at the intersection for the bus movement while maintaining the original cycle length
Areawide timing plans	Preferential progression for buses through signal offsets
Bypass metered signals	Buses use specially reserved lanes, special signal phases, or are rerouted to non-metered signals
Adjust phase length	Increased green time for approaches with buses
ACTIVE PRIORITY	
Green extension	Increase phase time for current bus phase
Early start (red truncation)	Reduce other phase times to return to green for buses earlier
Special phase	Addition of a bus phase
Phase suppression	Skipped non-priority phases
REAL-TIME PRIORITY	
Delay-optimizing control	Signal timing changes to reduce overall person-delay
Network control	Signal timing changes considering the overall system performance
PREEMPTION	
Preemption	Current phase terminated and signal returns to bus phase

Note: Source - (Kittelson and Associates et al., 2013). Reproduced with Permission from the Transportation Research Board

Table 3. Planning-Level Bus Lane Service Volumes, Downtown Streets

Description	Service Volume (buses/lane/hour)	Average (buses/lane/hour)
Free Flow	20 or less	15
Stable flow, unconstrained	21 to 40	30
Stable flow, interference	41 to 60	50
Stable flow, some platooning	61 to 80	70
Unstable flow, queuing	81 to 100	90
Forced flow, poor operation	Over 100	110

Note: Source - (Kittelson and Associates et al., 2013). Reproduced with Permission from the Transportation Research Board

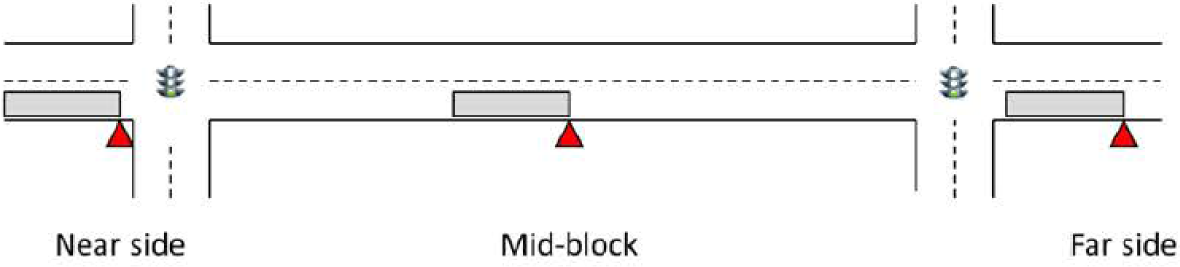

Figure 1. On-Street Bus Stop Locations (Kittelson & Associates et al., 2013)
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The placement of a bus stop on the far side of an intersection provides many advantages in the design of a TSP system. Near-side and mid-block stops, however, do not benefit as much from TSP (Smith et al., 2005). According to a case study in Vancouver, near-side bus stops cause a higher delay than far-side bus stops (Ekeila et al., 2009). Far-side stops help disentangle the bus from conflict with right-turning traffic. They also simplify the green extension calculation while preventing the bus from stopping twice, thereby ensuring that the green phase is only extended as much as is needed, rather than based on a prediction of stop dwell time.

Transit Signal Priority (TSP): A Planning and Implementation Handbook

The TSP Handbook (Smith et al., 2005) provides MOEs and a process for the simulation of TSP. The handbook also includes TSP case studies, MOEs, and benefits. The results from five different case studies provided in the handbook show that travel time and delays substantially decreased after TSP implementation. Table 4 summarizes the MOEs and benefits from the case studies in the document.

Table 4. TSP Case Studies: MOEs and Benefits

Agency	MOEs	Benefits
AC[a] Transit, Oakland, California	Bus travel time savings	Approximately 9% reduction in travel times
King County Metro, Seattle	Average intersection control delay, Average minor movement delay, Minor movement cycle failures, Bus corridor travel times, Bus schedule reliability, Average intersection bus delay, Average person delay, Vehicle emissions, and Accidents	25-34% reduction of average intersection delay 14-24% reduction of stops at intersections 35-40% reduction in trip travel time variability 5.5-8% reduction in travel time along the corridors during peak hour
MTA[b], Los Angeles	Reduced bus travel time Increased transit ridership Increased delay to motorists	19 to 25% reduction in travel times Ridership on Metro Rapid lines increased 4% - 40%
Pace, Chicago	Average vehicle delay, Average vehicle speed, Average bus delay, and Average bus speed	Average 15% reduction in bus running time
Pierce Transit, Tacoma, Washington	Bus travel time, Stop and signal delay, Fuel savings, and Air quality benefits	The combination of TSP[c] and signal optimization reduced transit signal delay about 40% Implementation of TSP provided substantial economic benefit to the public

[a] AC = Alameda-Contra Costa; [b] MTA = Metropolitan Transit Authority; [c] TSP = transit signal priority

To evaluate a potential TSP project, MOEs need to be selected that relate to the objectives of the project. Examples of MOEs are as follows: reduced travel time for buses, reduced stop and signal delay for buses, reduced variability in operations or schedule adherence for buses, reduced recovery time at the end of a run, fuel savings, air quality benefits, reduced operating resources required, reduced number of signal cycles to clear a queue before/after granting TSP, reduced queue on mainline, and minimal additional delay to other vehicles.

For TSP applications, a microscopic simulation is valuable due to its ability to simulate individual vehicles in the network and its analysis capabilities. This allows the user to test a new system or redesign an old system before deploying it in the field. It also allows the user to test different alternatives or “what if” scenarios that cannot be tested in real life (Li et al., 2008; Smith et al., 2005).

The development of a TSP simulation requires the collection of detailed data on field conditions along with calibration and validation of the model before testing scenarios. The process of TSP simulation is: selecting a model; collecting data (geometric, signal timing plans, speed of transit vehicles, and the number of transit vehicles); developing the network for simulation, calibration, and validation; conducting multiple simulations; and analyzing the output (Smith et al., 2005).

Transit Signal Priority Research Tools

The Transit Signal Priority Research Tools were developed by the California Department of Transportation (Caltrans) and the University of California Berkeley PATH Program. The research recommended a set of MOEs to evaluate TSP performance and proposed a database design (Li et al., 2008). The tools can assess the effects of TSP on non-priority street traffic and help determine the specific conditions under which TSP is most cost-effective. PATH also developed a set of detailed MOEs and a comprehensive evaluation method that support an objective evaluation of TSP system performance and its impact on traffic, and these evaluation methods are included in the methods for this project.

The document presents MOEs for different categories of evaluation for TSP than this research. These MOEs are as follows:

- Reliability - Percentage of on-time runs at timepoint, average arrival deviation at timepoint, the variance of arrival deviation at timepoint, most substantial arrival deviation at timepoint, variance of segment travel time, number of missed connections at the transfer point, and variance of total route travel time

- Travel Time/Speed - Average travel time on a segment, dwell time, intersection delay, running time, average travel speed on a segment, average delay at the prioritized intersection, and number of stops at red

- Operating Cost - Average fuel consumption, fleet size requirement, number of operators

- Pollutant Emission - Average vehicle emission (carbon monoxide and nitrogen oxide)

- Ridership - Average passenger occupancy per bus, Number of passengers per mile

- Safety - Number of crashes (involving buses and signal priority), number of pedestrian crashes, and average reduction of time dedicated to pedestrian walk phases

- TSP System Performance and Signal System - Frequency of TSP calls (cycle-based), frequency of TSP executions (cycle-based, early green, green extension, and other operations, respectively), TSP success rate (early green, green extension, and other operations, respectively), missed coordination steps, and effects on bandwidth

Detailed data collection is necessary to measure TSP performance. Devices commonly installed on buses that record data and that can be used to calculate performance measures include automatic vehicle location, automatic passenger counters, and TSP GPS. How often data points are recorded, what information is recorded, and how data are stored, accessed, and shared have a substantial impact on how well TSP performance can be measured.

TCRP Synthesis Report 149

TCRP Synthesis Report 149 (Anderson et al., 2020) examined the current state of the practice of TSP in North America. The authors surveyed 46 transit agencies and documented 5 case studies of TSP in San Diego; San Francisco; Toronto; Providence, RI; and Seattle. These case studies ranged from 50 to 450 intersections and 130 to 2,000 vehicles in corridors where TSP was implemented. According to the survey results, 77% of transit agencies had implemented decentralized systems. Also, 77% allowed buses to request priority at intersections with near-side bus stops. The survey revealed that 57% of agencies surveyed had integrated automatic vehicle location (AVL) into their TSP systems. The study also showed that the transit industry needed updated and more comprehensive guidance, toolkits, and training for successful TSP implementation.

Previous TSP Studies

A TSP study in Northern Virginia (Rakha and Ahn, 2006) used the following MOEs for evaluation: total delay (vehicle-hours), average delay (minutes/vehicle), average stop duration per vehicle, average bus delay (minutes/vehicle), average fuel consumption (1/vehicle), average hydrocarbon (grams/vehicle), average carbon monoxide (grams/vehicle), and average nitrogen oxide (grams/vehicle). In the Northern Virginia study, the intersection delay was computed as follows to obtain total delay.

$$\mathrm{d_k} = \int_{\alpha}^{\beta} \left[1 - \frac{\min(\nu_f, \nu_i)}{\nu_f}\right] \Delta t \tag{5}$$

Where: $\mathrm{d_k}$ = the delay incurred at intersection k (seconds), Δt = the duration of the time interval (seconds), α = the time interval when the transit vehicle is 100m upstream of the intersection, β = the time interval when the transit vehicle passes the approach stop bar, ν_f = the free-flow speed (meters/second), and ν_i = the vehicle speed at instant i

In a study of a bus rapid transit (BRT) system utilizing TSP in Orlando (Al-Deek et al., 2017), four MOEs were used for evaluation of effects for both all vehicles and buses: average travel times, average speed profiles, average delays, and the average number of stops. The results showed that BRT with conditional TSP (only activated when the transit vehicle is behind schedule) could substantially improve travel times, average speed, and average total delay per vehicle. Metrics for pedestrian traffic were not considered in the simulation process.

TSP with advanced detection was simulated in Boston. The MOEs for this study included transit and other traffic delays per vehicle per intersection, transit travel time, headway regularity, and crowding impact. TSP implementation contributed to a substantial improvement in transit delay, and its effects on pedestrians and other road users were minor (Wadjas and Furth, 2003). Another microsimulation study identified the impacts of implementing TSP strategies on an arterial corridor segment in East Lansing, Michigan, and showed that the reduction in delay for transit vehicles was confirmed from TSP implementation. However, the impact on non-transit vehicles was slightly negative as delay increased. All scenarios of TSP implementation in East Lansing showed no effect on pedestrian delay (Ghanim et al., 2013).

TSP with vehicle-to-infrastructure (V2I) communication was studied on two coordinated intersections in Tucson, Arizona. Bus delay, car delay, and pedestrian delay were used as MOEs. A request-based mixed-integer linear program was formulated that explicitly accommodated multiple priority requests from different modes of vehicles and pedestrians while simultaneously considering coordination and vehicle actuation. The simulation experiments found that the proposed control model was able to reduce average bus delay, average pedestrian delay, and average passenger car delay, especially for highly congested conditions with a high frequency of transit vehicle priority requests (Qing et al., 2014).

A simulation study evaluated a conventional TSP and compared it to a TSP system with connected vehicle communications (TSPCV) in Charlottesville, Virginia. Bus delay (seconds) and delay per person (seconds) were used as MOEs. The results showed that TSPCV would substantially reduce bus delay at signalized intersections without causing adverse effects on side streets (Hu et al., 2014).

A study in Newark, New Jersey evaluated TSP and optimal signal timing plans on an arterial with high bus frequency. Twelve scenarios were developed based on the traffic demand, signal control, and presence of TSP and were simulated using the VATSim simulation model. After the simulation model was executed, outputs such as bus dwell times, vehicle trips, and headway distributions were checked for consistency with the field data. The bus travel time and general traffic travel time were used as MOEs. The study found that combining signal optimization and TSP produced the best performance for both bus and car travel; TSP can reduce the number of buses needed to service a route, with substantial operating cost benefits; and TSP can provide economic benefits from the reduction in person-hours of travel and enhancement of the attractiveness of transit as a mode of travel (Muthuswamy et al., 2007).

A research study of TSP with a GPS/AVL system onboard the bus was conducted in Minneapolis. With the GPS/AVL, TSP can provide reliable and efficient service with minimal impact on traffic flow, because GPS offers better information than existing TSP detectors. This study used the AIMSUN microscopic traffic simulation package to simulate the adaptive bus signal priority strategy. The average bus travel time and average delay were used as MOEs. The results indicated that TSP could reduce bus travel time and average bus delay during AM and PM peak hours (Liao et al., 2007). GPS-based TSP studies with BRT were also conducted in Salt Lake City. The corridor studied was 2.3 miles, with 11 signalized intersections with high traffic volumes. The study simulated eight scenarios of TSP, GPS-based TSP, and BRT (with dedicated lanes) in VISSIM. The results indicated that both traditional TSP and GPS-based TSP had reduced delay compared to no TSP implementation. Also, the BRT upgrade had a substantial effect on reducing transit travel time and transit delays. In the simulation, conditional TSP strategies were not as effective as unconditional strategies in reducing transit delays. This is because conditional TSP grants priority only to transit vehicles that satisfy the given constraints, which included at least 20 passengers and running at least 60 seconds behind schedule (Song et al., 2016).

Table 5 shows a summary of the previous TSP studies. The majority of these studies used average travel time and average delay for transit and other vehicles as MOEs, because those measures are easy to obtain from the microsimulation results and easy to compare with the base condition. There were a few pedestrian-related MOEs from the previous TSP studies, and the results indicated two different impacts of TSP. Two studies showed that the TSP had no effect or a negligible impact on pedestrian delay (Wadjas and Furth, 2003 and Ghanim et al., 2013). A third study showed that TSP reduced the pedestrian delay by 14% (Qing, et al., 2014).

Table 5. Example of Transit Signal Priority Measures of Effectiveness from Previous Studies

Study	MOEs
TSP[a] in Northern Virginia (Rakha and Ahn, 2006)	Total delay, average delay, average stop/vehicle, average bus delay, average fuel consumption, average hydrocarbon, average carbon monoxide, average nitrogen oxide
Bus rapid transit with TSP in Orlando (Al-Deek et al., 2017)	Average travel time, average speed profile, average delay, the average number of stops for both all vehicles and bus
TSP with advanced detection in Boston (Wadjas and Furth, 2003)	Transit and other traffic delays per vehicle per intersection, transit travel time, headway regularity and crowding impact
TSP and optimal signal timing plans in Newark, New Jersey (Muthuswamy et al., 2007)	Bus travel time, general traffic travel time
TSP with GPS/AVL[b] system on the bus in Minneapolis (Liao et al., 2007)	Average bus travel time, average delay
Conventional TSP and TSP with connected vehicle communication in Charlottesville, Virginia (Hu et al., 2014)	Bus delay, delay per person
TSP strategies on an arterial corridor segment at East Lansing, Michigan (Ghanim et al., 2013)	The transit and non-transit delay, pedestrian delay
TSP with signal actuation and coordination in Tucson, Arizona (Qing et al., 2014)	Average bus delay, vehicle delay, pedestrian delay

[a] TSP = transit signal priority; [b] GPS/AVL = global positioning system with automatic vehicle location

Virginia Implementations of TSP

The Metropolitan Washington Council of Governments (MWCOG) conducted a Priority Bus Transit program that began in 2010 and was funded by $58.8 million from a Transportation Investment Generating Economic Recovery (TIGER) grant. The program consisted of 16 projects throughout the Washington, D.C. metropolitan area in the District of Columbia, Virginia, and Maryland (MWCOG, 2015). Stop improvement, queue jumps, TSP, and Transportation System Management (TSM) projects were implemented to improve transit service. TSM is defined as "the use of techniques for increasing the efficiency, safety, capacity, or level of service of a transportation facility without increasing its size" (City of Bend, Oregon, 2019). The following two TIGER-funded projects in Virginia implemented TSP:

- The Leesburg Pike project constructed stop improvements and implemented TSP between the King Street Metro station and the Tysons Corner Transit Center. TSP/TSM was implemented at 35 locations along the corridor.

- The Van Dorn - Pentagon Bus Priority Corridor Enhancement project implemented TSP at eight intersections.

Summary of Literature Review

The literature review conducted to support this research provides the necessary tools to address the research goals for this project. The literature referenced in this review provides the basis for the development of a tool to assist decisionmakers in the implementation of TSP in a corridor as detailed in the following sections. The literature review revealed that improved methods are needed to help decision-makers parse the limited and conflicting data that have been collected from previous implementations of TSP. The literature review also serves to identify the current gaps in knowledge for this research but provides guidance for future research as well, such as the need stated in TCRP Synthesis Report 149 that improved tools to help with the planning and implementation of TSP are needed.

Major conclusions that are drawn from the literature review are as follows:

- TSP effectiveness is based on a multitude of factors, including geometric, transit, pedestrian, traffic, and signal characteristics of a corridor.
- A successful TSP implementation will be influenced by the operating conditions of the corridor.
- Microsimulation is commonly used as a method of evaluating the impact of a proposed TSP project before implementation.
- The success of a TSP system is a function of its configuration, architecture, and the policy for operations. (The architecture and policy for operations were outside the scope of this study).

These conclusions led to the formulation of a criteria table used to evaluate the viability of TSP in a corridor. This criteria table is presented below and forms the basis of the TSPRT.

Criteria Table

This section outlines the characteristics of the five categories comprised within the criteria table that was used to evaluate the viability of TSP implementation. This information was collected in order to logically identify different roadway factors that likely impact TSP. Weight values and score increments were decided based upon engineering judgment that was derived from evaluating where TSP has been successful in the past and translating these judgments into the metrics. Because of some subjectivity seen in the literature review, the criteria table was built as a filtering mechanism for planners, engineers, and other stakeholders to make a first evaluation for the suitability of TSP in a selected corridor.

Geometric Characteristics

Three geometric characteristics with their corresponding weights are summarized in Table 6. The following subsections provide details on the scoring of each characteristic.

Table 6. Geometric Criteria with Weights

Geometric Criterion	Dedicated Right-of-Way	Number of Lanes per Direction	Vertical Alignment
Weight	5	3	2

Dedicated Right-of-Way

Dedicated right-of-way for buses offers advantages that can improve service quality. A weight of 5 was assigned to it, because bus travel times, schedule adherence, and transit vehicle productivity are improved when buses can use higher-speed and uncongested facilities (Kittelson and Associates et al., 2013). Transit in a dedicated lane is unaffected by traffic congestion compared to transit in mixed traffic (SF County Transportation Authority, 2007). Table 7 shows the scores of different scenarios of dedicated bus right-of-way. The following list provides additional detail on the definition of dedicated right-of-way.

- Physically Separated Dedicated Right-of-Way means there is a physical barrier, such as jersey barriers, separating bus and general traffic lanes.
- Partial Physically Separated Dedicated Right-of-Way means some sections of the bus lane will have physical separation, and some sections of the roadway will not have physical separation from general traffic.
- Dedicated Right-of-Way not Physically Separated means the lane(s) is bus-only, but there is no physical separation from general traffic.
- Shared Right-of-Way means buses operate in mixed traffic.

Table 7. Dedicated Right-of-Way Score (Weight = 5)

Score	Type of Right-of-Way
3	Physically Separated Dedicated Right-of-Way
2	Partial Physically Separated Dedicated Right-of-Way
1	Dedicated Right-of-Way not Physically Separated
0	Shared Right-of-Way

Additional scoring examples/interpretation:

- Median lanes that are physically separated would receive a score of three. If the median lane is not physically separated it would receive a one (such as the Pulse in Richmond)
- A red carpet bus lane (painted bus lanes without physical separation) would be considered not physically separated and receive a score of one

- Curbside bus lanes that also allow other vehicles making right turns would receive a score of one

Number of Lanes per Direction

The number of lanes per direction is a consideration when designing a TSP system. A weight of 3 was assigned, because the number of lanes affects the potential for creating restricted transit lanes that can be beneficial for TSP implementation (Fambro et al., 1991).

Table 8 shows the score for the number of lanes per direction. Three points are given to a road with two or more lanes per direction. This can provide room for installing a dedicated bus lane to increase the accuracy of transit vehicle detection for establishing successful TSP operation. This condition can also increase the feasibility of adding queue jumps (i.e., a bus lane approaching intersections, as shown in Figure 2). Two points are given to a corridor with one lane per direction with left-turn pockets or right-turn pockets at intersections or with a two-way left-turn lane. This could enable special bus-only signal phases, queue jumps, or prioritization of turn phases. Lastly, one point is assigned to a road that has one lane per direction with shoulders large enough for the bus to maneuver around traffic, and zero points are assigned to a road that only has one lane per direction without a full-lane shoulder. Figure 3 provides examples of cross-sections and their score levels.

Table 8. Number of Lanes per Direction Score (Weight = 3)

Score	Number of Lanes per Direction
3	Two and above
2	One plus left/right-turn pockets or two-way left-turn lane
1	One with shoulder
0	One

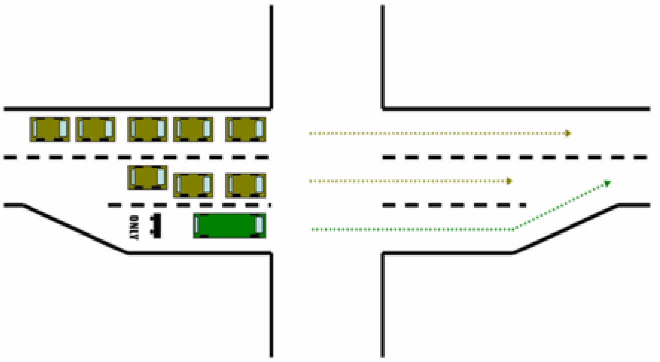

Figure 2. Queue Jumping (Bossi, 2007). *Reproduced under Creative Commons license: https://creativecommons.org/licenses/by-sa/3.0/deed.en.*

Additional scoring examples/interpretation:

- If there is one lane in one direction and two lanes in the other direction, choose the direction in which TSP is to be implemented. If TSP is to be implemented in both directions, choose the lower value.

- If a corridor has different numbers of lanes, choose the lower value.

Score = 3 Score = 2 Score = 0

Columbia Pike, Arlington, VA North Main St., Blacksburg, VA North Main St., Blacksburg, VA

Figure 3. Number of Lanes Examples

Vertical Alignment

The operational characteristics of transit vehicles suggest that vertical alignment has an impact on TSP implementation, so a weight of 2 was assigned. Heavy vehicles usually need more time to decelerate and accelerate on steep slopes than smaller passenger vehicles, leading to increased bus travel times and fuel consumption (Donnell et al., 2001). Therefore, it is more desirable to implement TSP on steeper terrain, assuming that TSP could reduce the need for transit vehicles to decelerate and accelerate at intersections.

Table 9 shows the vertical alignment score. Three points are assigned to uphill grades over five percent, two points for two to 4.9 percent grade, one point for under two percent but not level, as determined by the grade definitions for level and rolling terrain from the Highway Capacity Manual (Transportation Research Board, 2016), and zero points for level grade or downhill. This is calculated by the average uphill grade observed in the corridor. (It should be noted that the rating of 0 for this metric does not imply that a level grade is disadvantageous for TSP.)

Table 9. Vertical Alignment Score (Weight = 2)

Score	**Corridor Peak Grade in Transit Operating Direction**
3	Uphill, equal to or greater than 5%
2	Uphill, 2 to 4.9%
1	Uphill, under 2% but not level
0	Level Grade or Downhill

Transit Characteristics

Six transit characteristics and their corresponding weights are shown in Table 10. The following subsections provide details on the scoring of each characteristic.

Table 10. Transit Criteria with Weights

Transit Criterion	Bus Schedule Adherence	Transit Frequency	GPS/AVL[a]	Number of Passengers	Transit Level of Service	Bus Stop Placement
Weight	5	4	4	3	3	3

[a] *GPS/AVL = global positioning system with automatic vehicle location*

Bus Schedule Adherence (On-time Performance)

Bus schedule adherence, also called on-time performance, is the most widely used reliability measure in the North American transit industry (Kittelson and Associates et al., 2013). It can be calculated using the ratio of on-time service to complete service. The researchers suggest the use of the on-time performance definition from the TCQSM, which defines on-time service as a departure 1 minute early to 5 minutes late or arrival at the route terminus less than 5 minutes late (Kittelson and Associates et al., 2013).

Table 11 shows the breakdown of the score, based on the ranges in peak-period on-time performance identified in the TCQSM. The weight is set at 5, because on-time performance is an essential factor when travelers choose a mode of transportation (Kittelson and Associates et al., 2013). From the perspective of TSP implementation, higher pre-TSP bus schedule adherence will obtain fewer points, because bus service is already reliable.

Table 11. Bus Schedule Adherence Score (Weight = 5)

Score	Peak On-Time Performance
3	< 80%
2	80-89%
1	90-94%
0	95-100%

Transit Frequency

In their case studies of Tacoma, WA, and Portland, OR, one of the considerations Smith et al. (2005) used for choosing a corridor for TSP was transit service frequency. For the present study, the TSPRT transit frequency score is based on the planning-level bus lane service volume in the TCQSM (Kittelson and Associates et al., 2013). Transit frequency data can be collected from transit agencies in the General Transit Feed Specification format. The evaluation will be modified from the TCQSM bus lane service volumes (provided in Table 3) to reflect the realities of mixed-traffic bus service that is prevalent in Virginia and to recognize that corridors with lesser bus volumes could still benefit from TSP. To account for transit service in Virginia, the number of buses was reduced by a factor of 2 in the criteria table from the values for stable flow shown in Table 3.

The transit frequency score is based on peak hour service volume, and Table 12 shows the breakdown and description of the score. This characteristic was given a weight of 4, because TSP will have the greatest impact in areas of high transit frequency. However, few Virginia corridors have frequencies of buses as high as the levels shown in Table 12. With higher bus frequencies, interference in traffic flow and bus bunching may occur, and the need for TSP implementation is greatest. With lower bus frequencies, there is less of a need for TSP implementation to alleviate bus bunching.

Table 12. Transit Frequency Score (Weight = 4)

Score	Peak Hour Service Volume in Corridor
3	Over 30 buses/hour
2	21-30 buses/hour
1	11-20 buses/hour
0	10 buses/hour or fewer

GPS/AVL

An AVL system uses GPS to obtain bus locations 2-3 times per second. With GPS/AVL, a transit agency can monitor bus locations in relation to the schedule to improve reliability, operations, and management. Also, the information from the GPS/AVL system can be integrated for traffic operations and can be used as the basis of a TSP system (Liao et al., 2007).

If all buses operating in the target corridor are equipped with a GPS/AVL system, it is relatively easy to use operations data for implementing TSP, so a weight of 4 was assigned. Table 13 shows the scores and descriptions for this criterion.

Table 13. GPS/AVL Score (Weight = 4)

Score	GPS/AVL[a] Presence on Corridor Buses
3	81-100% installed[b]
2	51%-80% installed
1	Less than or equal to 50% installed
0	Not installed

[a] GPS/AVL = global positioning system with automatic vehicle location; [b] % installed = the percent of buses operating in the corridor that have GPS/AVL installed

Number of Passengers

TSP is valuable in corridors with high volumes of transit passengers. Scoring was developed based on Exhibit 6-17 in the TCQSM, which illustrates maximum standard one-way bus passenger service volumes for planning purposes. This provides the number of people per hour that can be served by standard buses at various bus flow rates and passenger load factors (Kittelson and Associates et al., 2013).

A weight of 3 was assigned, because although other characteristics may be more beneficial for TSP implementation, passenger volume remains a key reason for implementing TSP. Scoring was based on the peak-hour bus passenger service volume in arterial streets. The values shown in Table 14 have been modified to take into consideration Virginia transit characteristics: the values were reduced by one-half to account for typical transit service throughout the Commonwealth based on the judgment of the research team after study of frequency of service. A corridor with over 750 passengers per hour can be considered a high-demand bus corridor and is given the highest score.

Table 14. Number of Passengers Score (Weight = 3)

Score	Peak Hour Bus Passenger Service Volume
3	Over 750 passengers/hour
2	501-750 passengers/hour
1	251-500 passengers/hour
0	250 passengers/hour or fewer

Transit LOS

The method for calculating transit LOS was provided in Chapter 5 of the TCQSM (Kittelson and Associates et al., 2013). The input data and calculations were described in this report's literature review. The advantage of the transit LOS score is compatibility across modes of transportation. According to the TCQSM, the LOS letter can be directly compared to automobile, pedestrian, and bicycle LOS letter scores.

Table 15 shows the breakdown of the score and its description. If the transit LOS is A, TSP cannot substantially improve it, and the corridor will receive zero points. If the transit LOS is E or F, the corridor will receive three points. A weight of 3 was assigned, as the level of service is descriptive of the quality of transit service in the corridor, and a low level of service could indicate positive benefits from TSP implementation.

Table 15. Transit LOS Score (Weight = 3)

Score	Transit LOS[a] (LOS Score)
3	LOS E, F (>4.25)
2	LOS C, D (>2.75-4.25)
1	LOS B (> 2.00-2.75)
0	LOS A (≤ 2.00)

[a] *LOS = level of service*

Bus Stop Placement (Near-side/Far-side)

When the bus stops at a near-side bus stop, it has a high chance of wasting a green extension during passenger boarding and alighting. Therefore, bus waiting time at a signalized intersection is lengthened, and bus delay increases. Because bus stop placement can affect TSP implementation, this criterion was given a weight of 3. Scoring was developed using engineering judgment based on the percentages of far-side corridor bus stops, as shown in Table 16.

Table 16. Bus Stop Placement Score (Weight = 3)

Score	Corridor Bus Stop Placement
3	81-100% far side
2	51-80% far side
1	1-50% far side
0	0% far side

Pedestrian Characteristics

Two pedestrian-related corridor characteristics and their weights are shown in Table 17.

Table 17. Pedestrian Criteria with Weights

Pedestrian Criteria	Walk Score	Transit-Dependent Population
Weight	3	2

TSP provides benefits to transit vehicles by modifying the signal timing and attempts to minimize the impact on cross-traffic, pedestrians, and bicyclists (Tindale-Oliver & Associates, 2014). From this perspective, pedestrian characteristics must be considered to select target corridors for TSP implementation. The following subsections provide details on the scoring of each characteristic.

Walk Score

This research uses Walk Score, a metric devised to encourage walkable communities and to provide information to inform real estate professionals and buyers. The Walk Score advisory board has urban planning, environmental and technical experts from institutions such as The Sightline Institute and The Brookings Institution. Table 18 shows the breakdown of the Walk Score scoring and its description. A weight of 3 was assigned, because the Walk Score is an indicator of the ability for people to access transit, and with high transit demand, TSP can support a high-quality transit system. The Walk Score is based on the corridor of interest and can change throughout the corridor (Walk Score, 2020). For large corridors, Walk Scores should be obtained for areas of high passenger demand and averaged. If the Walk Score is 90 points or greater, a corridor will receive 3 points, because pedestrian-friendly areas tend to attract more transit users. If the Walk Score is 49 or less, a corridor will receive 0 points, because many people in the area are car-dependent with a high chance of having poor transit access.

Table 18. Walk Score Scoring (Weight = 3)

Score	Walk Score
3	90-100: "walker's paradise"
2	70-89: most errands can be accomplished on foot
1	50-69: some amenities within walking distance
0	0-49: car-dependent

Transit-Dependent Population

Identifying the transit-dependent population is an important tool for determining where new transit services should be provided or how existing systems can be modified to better serve the population in need. Table 19 shows the breakdown of the scoring for the transit-dependent population. A weight of 2 was assigned, because there may still be a high demand for transit even without a high percentage of the population being transit-dependent, so this criterion is relatively less important for TSP implementation. Scoring was based on percent transit-dependent population within ¼ mile of each bus stop, and percentage breakpoints were determined based on engineering judgment.

Table 19. Transit-Dependent Population Score (Weight = 2)

Score	Percent Transit-Dependent
3	26-100
2	11-25
1	1-10
0	0

Traffic Characteristics (Intersection Control Delay)

One traffic characteristic is used in the TSPRT: Intersection Control Delay, with a weight of 4. The intersection control delay per vehicle (delay caused by a traffic signal) is calculated to measure the "intersection LOS" for all vehicles utilizing a signalized intersection. Table 20 shows the breakdown of the control delay score and its description, based on the 75th percentile for corridors with more than 5 intersections or the worst intersection of a corridor with 5 or fewer intersections. A weight of 4 was assigned, because if there is no control delay, then there is little need for TSP. When the control delay per vehicle is greater than 55 seconds, the corridor obtains three points, because it needs TSP to reduce transit delay at the intersection.

Table 20. Intersection Control Delay Score (Weight = 4)

Score	Intersection Control Delay (all vehicles)
3	LOS[a] E, F (Control delay per vehicle > 55 sec)
2	LOS C, D (Control delay per vehicle of 20-55 sec)
1	LOS B (Control delay per vehicle of 10-20 sec)
0	LOS A (Control delay per vehicle ≤ 10 sec)

[a] *LOS = level of service*

Signal Characteristics

Two signal characteristics and their weights are included in Table 21. The following subsections provide details on the scoring of each characteristic.

Table 21. Signal Criteria with Weights

Signal Criteria	Signal Control System	Signal Coordination
Weight	5	4

Signal Control System

In general, fixed-time signals have lower initial and maintenance costs than actuated signals, which are signals where phases “are at least partially controlled by detector actuators” (Koonce et al., 2008). However, it is more cost-effective to implement adaptive TSP on actuated control systems than to replace the existing traffic control system (Li et al., 2011). Therefore, corridors with more than 80 percent actuated signals receive 3 points. Corridors with no actuated signals receive 0 points. Table 22 shows the breakdown of the scoring based on the signal control system, where the breakpoints were determined based on engineering judgment. A weight of 5 was assigned, because actuated signals are essential for implementing TSP.

Table 22. Signal Control System Score (Weight = 5)

Score	Percentage of Signalized Intersections in the Corridor that are Actuated
3	81-100
2	51-80
1	1-50
0	0

Signal Coordination

Signal coordination requires the implementation of technologies in the traffic signal controller that are compatible with TSP technology. Coordination of signals within the corridor allows for smooth traffic flow and the ability for reduced travel time for all vehicles, including transit vehicles. Signal coordination is an enabling technology for efficient TSP and was given a weight of 4. Table 23 provides detail of the scoring for this metric.

Table 23. Signal Coordination Score (Weight = 4)

Score	Corridor Signal Coordination
3	Corridor Completely Coordinated
2	75%-99% of Signals Coordinated
1	1%-74% of Signals Coordinated
0	No Signal Coordination

TSPRT Summary

Table 24 lists the TSPRT criteria with weights, scores, and descriptions. The weight and score levels were assigned based on the literature review results and the researchers' judgment, with adjustments specific to Virginia in some cases.

Table 24. Criteria with Weights, Scores, and Descriptions

Criterion	Weight	Score	Description
Geometric Characteristics			
Dedicated Right-of-Way	5	3	Physically Separated Dedicated Right-of-Way
		2	Partial Physically Separated Dedicated Right-of-Way
		1	Dedicated Right-of-Way not Physically Separated
		0	Shared Right-of-Way
Number of Lanes per Direction	3	3	Two and above
		2	One plus left/right-turn pockets or two-way left turn lane
		1	One with shoulder
		0	One
Vertical Alignment	2	3	Uphill, equal to or greater than 5%
		2	Uphill, 2 to 4.9%
		1	Uphill, under 2% but not level
		0	Level Grade or Downhill
Transit Characteristics			
Bus Schedule Adherence	5	3	< 80%
		2	80-89%
		1	90-94%
		0	95-100%
Transit Frequency	4	3	Over 30 buses/hour
		2	21-30 buses/hour
		1	11-20 buses/hour
		0	10 buses/hour or fewer
GPS/AVL[a]	4	3	81-100% installed[b]
		2	51%-80% installed
		1	Less than or equal to 50% installed
		0	Not installed
Number of Passengers	3	3	Over 750 passengers/hour
		2	501-750 passengers/hour
		1	251-500 passengers/hour
		0	250 passengers/hour or fewer
Transit Level of Service	3	3	Transit LOS[c] E, F
		2	Transit LOS C, D
		1	Transit LOS B
		0	Transit LOS A

Criterion	Weight	Score	Description
Bus Stop Placement	3	3	81-100% far side
		2	51-80% far side
		1	1-50% far side
		0	0% far side
Pedestrian Characteristics			
Walk Score	3	3	90-100: “walker’s paradise”
		2	70-89: most errands can be accomplished on foot
		1	50-69: some amenities within walking distance
		0	0-49: car-dependent
Transit-Dependent Population	2	3	26%-100% transit-dependent
		2	11%-25% transit-dependent
		1	1%-10% transit-dependent
		0	0% transit-dependent
Traffic Characteristics			
Intersection Control Delay	4	3	Intersection LOS E, F (Control delay per vehicle > 55 seconds)
		2	Intersection LOS C, D (Control delay per vehicle > 20-55 seconds)
		1	Intersection LOS B (Control delay per vehicle > 10-20 seconds)
		0	Intersection LOS A (Control delay per vehicle ≤ 10 seconds)
Signal Characteristics			
Signal Control System	5	3	81-100% of signals are actuated
		2	51%-80% of signals are actuated
		1	1%-50% of signals are actuated
		0	0% of signals are actuated
Signal Coordination	4	3	Corridor Completely Coordinated
		2	75%-99% of Signals Coordinated
		1	1%-74% of Signals Coordinated
		0	No Signal Coordination

[a] GPS/AVL = global positioning system with automatic vehicle location; [b] % installed = the percent of buses operating in the corridor that have GPS/AVL installed; [c] LOS = level of service

Application of TSP Recommendation Tool on Virginia Corridors

The TSPRT was tested in the following three transit-oriented networks in Virginia corridors where TSP may be applicable. The test corridors were selected based on data availability to score the TSPRT criteria and as examples of locations that did not currently have TSP but could be candidates for the implementation of the technology.

- E. Market Street, 9th Street NE, and E. High Street, Charlottesville
- Main Street, Blacksburg
- Columbia Pike, Arlington

E. Market Street, 9th Street NE, and East High Street, Charlottesville

Geometric Characteristics

This corridor was selected because a total of nine Charlottesville Area Transit routes travel this corridor, with three of the routes having at least two stops in the corridor. In addition, a large amount of data was available for the corridor. The total length of the corridor from the intersection of 7th St. and E. Market St. to the intersection of E. High St. and Locust Ave. is approximately 0.5 miles (Figure 4). The corridor contains four signalized intersections as described in Table 25. The average spacing between intersections is 0.07 miles.

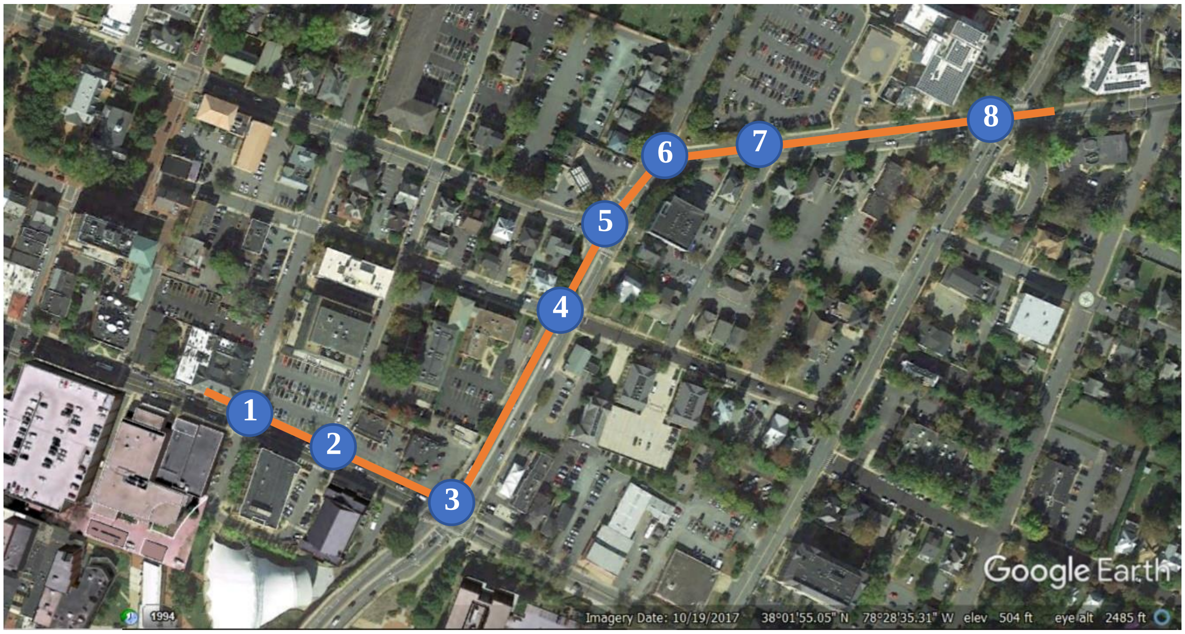

Figure 4. Overview of the East High Street Corridor in Charlottesville

Table 25. Geometric Characteristics of Charlottesville Corridor

No.	Intersection	Legs	Signalized	Distance to next signalized intersection (mi)
1	E. Market St. and 7th St.	4	Yes	0.08
2	E. Market St. and 8th St.	3	No	N/A
3	E. Market St. and 9th St.	4	Yes	0.11
4	9th St. and E. Jefferson St.	4	No	N/A
5	9th St. and E. High St.	3	Yes	0.16
6	E. High St. and Lexington Ave.	3	No	N/A
7	E. High St. and 9 ½ St.	3	No	N/A
8	E. High St. and Locust Ave./10th St.	4	Yes	N/A

There is no dedicated bus lane on this corridor, and most of the segments are a single lane per direction. The segment between intersections 3 and 5 is two lanes per direction. However, there is a funded project to alter this segment to one lane per direction, which is partly why this corridor was chosen as an example for TSPRT scoring (Kimley-Horn, 2019). According to the Google Earth elevation profile, the corridor's average uphill and downhill grades are 3.4% and 4.1%, respectively, whereas the maximum uphill and downhill grades are 18.7% and 14.2%, respectively. This study uses an average uphill (3.4%) and downhill (4.1%) grade for analysis.

Transit Characteristics

There are two transit stops located on E. High St. in the selected segment, which has three routes (1, 10, and 11) with stops on the corridor; 11 different routes utilize the Market St. portion of the corridor (1, 3, 4, 6, 7, 8, 9, 10, 11, and 12). Much of the bus service in Charlottesville is low frequency, with six of the 11 routes servicing the corridor having hourly service. The two bus stops in the corridor have three buses per hour in the peak hour. The closest stop on Market Street to the corridor (5th and Market Street) has 16 buses in the peak hour from the routes that service that stop. Conservative estimates for the ridership in this corridor show that the ridership is often below 535 passengers per hour. This resulted in a score of 0 for the number of passengers criterion; however, if there were a spike in ridership in the Downtown Mall area, the score would increase, making TSP a more attractive option for the corridor. Charlottesville Area Transit buses have installed GPS/AVL, and the agency supports a live online bus tracker, which shows that there is 100% AVL installation. The bus schedule adherence score is also assumed as 0, because although there is some congestion during peak periods, bus schedule adherence is not significantly impacted. The transit LOS was assumed to be LOS B for the purposes of applying the TSPRT.

Pedestrian Characteristics

The walking environment on the corridor includes marked crosswalks at each intersection, and sidewalks are well-maintained. According to the Walk Scores provided in Table 26, this area is very walkable. The transit-dependent population is calculated using the 2016 American Community Survey by block group. In the adjacent block groups, the transit-dependent population was 810 people, representing 17.2 percent of the total population in those block groups. The number of crossing pedestrians per hour was obtained from a traffic study prepared for the City of Charlottesville (Kimley-Horn, 2019).

Table 26. Pedestrian Walk Score of Charlottesville Corridor (From walkscore.com)

No.	Intersection	Walk Score
1	E. Market St. and 7th St.	99
2	E Market St. and 8th St.	99
3	E. Market St. and 9th St.	99
4	9th St. and E. Jefferson St.	94
5	9th St. and E. High St.	94
6	E. High St. and Lexington Ave.	94
7	E. High St. and 9 ½ St.	94
8	E. High St. and Locust Ave./10th St.	92

Traffic Characteristics

The intersection saturation rate and intersection control delay are used for determining traffic characteristics. The control delay and LOS were collected from the Kimley-Horn (2019) study and are provided in Table 27.

Table 27. Traffic Characteristics of Charlottesville Corridor

No.	Intersection	Control Delay (seconds)	Level of Service
1	E. Market St. and 7th St.	8.0	A
2	E Market St. and 8th St.	N/A	N/A
3	E. Market St. and 9th St.	35.4	D
4	9th St. and E. Jefferson St.	N/A	N/A
5	9th St. and E. High St.	19.8	B
6	E. High St. and Lexington Ave.	N/A	N/A
7	E. High St. and 9 ½ St.	N/A	N/A
8	E. High St. and Locust Ave./10th St.	32.0	C

Note: N/A = Not applicable

Signal Characteristics

The signals at the four signalized intersections on the Charlottesville corridor have signal coordination and are fully actuated, according to the City of Charlottesville.

Summary of the Corridor

Table 28 lists the scores and the weighted scores by criterion. The TSPRT score for the Charlottesville corridor is 83, a medium score. Negative factors included having no bus lane, low transit frequency, and a small number of passengers. Positive factors included an excellent walking environment that provides passengers the opportunity to access transit easily.

Table 28. Overall Result of TSPRT Application to Charlottesville Corridor

Criterion	Weight	Score	Weighted Score
Geometric Characteristics			
Dedicated Right-of-Way	5	0	0
Number of Lanes per Direction	3	2	6
Vertical Alignment	2	2	4
Transit Characteristics			
Bus Schedule Adherence	5	2	10
Transit Frequency	4	0	0
GPS/AVL	4	3	12
Number of Passengers	3	0	0
Transit LOS	3	1	3
Bus Stop Placement	3	0	0
Pedestrian Characteristics			
Walk Score	3	3	9
Transit Dependent Population	2	2	2
Traffic Characteristics			
Intersection Control Delay	4	2	8
Signal Characteristics			
Signal Control System	5	3	15
Signal Coordination	4	3	12
Total Score			**83**
TSP Viability Index			***1.66***

South Main Street, Blacksburg

Geometric Characteristics

Table 29 describes the intersections on the corridor on S. Main St. from Miller St. to Washington St., which is approximately 0.2 miles, as shown in Figure 5.

Table 29. Geometric Characteristics of Blacksburg Corridor

No.	Intersection	Legs	Signalized	Distance to next signalized intersection (mi)
1	S. Main St. and Miller St.	3	No	0.05
2	S. Main St. and Clay St.	4	Yes	0.06
3	S. Main St. and Washington St.	4	Yes	NA

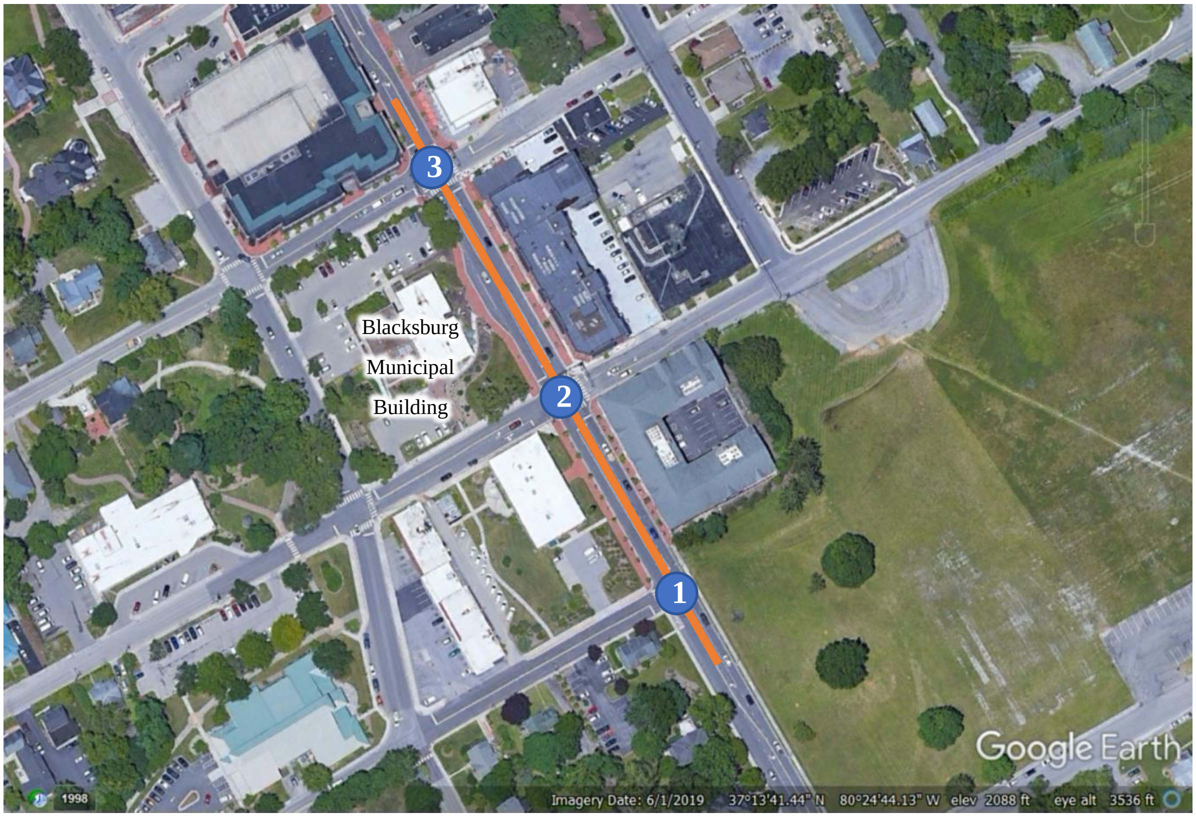

Figure 5. Overview of the South Main Street Corridor in Blacksburg

There is no dedicated transit lane on the target corridor, which is one lane per direction with left-turn pockets. According to the Google Earth elevation profile for the corridor, the grade is 2.5%.

Transit Characteristics

There are two bus stops on the corridor located mid-block. Two bus routes (Main Street South and Two Town Trolley) service those stops. The routes have four buses per hour based on the Blacksburg Transit (BT) schedule. The number of passengers per hour was assumed to be less than 535 based on the bus frequency, resulting in a score of zero for that criterion. BT has GPS/AVL on its buses and uses the data to provide live bus location information on the BT website and app. Bus schedule adherence data were not available, so this study assumed that buses adhered to the schedule in the 80-89 percent range.

Pedestrian Characteristics

The average Walk Score is 86, representing a very walkable environment. Most errands can be accomplished on foot in this area. The transit-dependent population was calculated using the 2016 American Community Survey by block group. In the adjacent block groups, the transit dependent population was 695 people, which represents 16.7 percent of the total population.

Traffic Characteristics

According to a Blacksburg Planning report, the corridor's overall delay is 11.5 seconds, and LOS is B, as shown in Table 30 (Whitman, Requardt and Associates, 2019).

Table 30. Traffic Characteristics of Blacksburg Corridor

No.	Intersection	Delay (sec)	Level of Service
1	S. Main St. and Miller St.	2.2	A
2	S. Main St. and Clay St.	16.8	B
3	S. Main St. and Washington St.	15.6	B

Signal Characteristics

The signal control system is fully actuated, and signal coordination is not installed for these traffic signals. There have been studies by Virginia Tech researchers on the coordination of these signals for future connected vehicle applications, which would allow for TSP applications with connected vehicle technologies.

Summary of the Corridor

Table 31 lists the scores and the weighted scores by criterion. The TSPRT score for the Blacksburg corridor is 64, 19 points lower than the Charlottesville score. Similar to Charlottesville, the target segment in Blacksburg has no bus lane, low transit frequency, and a small number of passengers, characteristics that lowered the overall score.

Table 31. Overall Result of TSPRT Application to Blacksburg Corridor

Criterion	Weight	Score	Weighted Score
Geometric Characteristics			
Dedicated Right-of-Way	5	0	0
Number of Lanes per Direction	3	2	6
Vertical Alignment	2	2	4
Transit Characteristics			
Bus Schedule Adherence	5	2	10
Transit Frequency	4	0	0
GPS/AVL	4	3	12
Number of Passengers	3	0	0
Transit LOS	3	1	3
Bus Stop Placement	3	0	0
Pedestrian Characteristics			
Walk Score	3	2	6
Transit Dependent Population	2	2	2
Traffic Characteristics			
Intersection Control Delay	4	1	4
Signal Characteristics			
Signal Control System	5	3	15
Signal Coordination	4	0	0
Total Score			**64**
TSP Viability Index			***1.28***

Columbia Pike, Arlington

Geometric Characteristics

Columbia Pike in Arlington was selected as the urban corridor for analysis in this project, and the geometric details of the intersections in the corridor are provided in Table 32. The corridor stretches 0.8 miles from S. Courthouse Rd. to S. Monroe St (Figure 6). The corridor is comprised of seven signalized intersections with an average intersection spacing of 0.13 miles. There is no dedicated bus lane and no current TSP implementation on this corridor. The number of lanes per direction varies, but most segments consist of two lanes per direction. The average grade is approximately 2.4%.

Table 32. Geometric Characteristics of Signalized Intersections in Arlington Corridor

No.	Intersection	Legs	Distance to next signalized intersection (mi)
1	Columbia Pike and S. Courthouse Rd.	4	0.11
2	Columbia Pike and S. Wayne St.	3	0.11
3	Columbia Pike and S. Barton St.	4	0.17
4	Columbia Pike and S. Walter Reed Dr.	4	0.11
5	Columbia Pike and S. Highland St.	3	0.17
6	Columbia Pike and S. Glebe Rd.	4	0.11
7	Columbia Pike and S. Monroe St.	4	N/A

Figure 6. Overview of the Columbia Pike Corridor in Arlington

Transit Characteristics

Arlington Transit (ART) and Washington Metropolitan Area Transit Authority (WMATA) both operate buses in this corridor. ART routes 41, 42, 45, 74, 77, and WMATA route 16 have stops on the corridor. The bus stop names, number of buses in the peak hour, and the placement of each stop are shown in Table 33. Since WMATA and ART buses provide real-time information using GPS technology, it was assumed that the buses on this segment are equipped with GPS/AVL. Researcher observation of the buses in the corridor concluded that many of the buses in the peak hour did not have ridership above 30 passengers (the level needed for the corridor to have over 1610 passengers per hour) but did have at least 20 passengers (the level needed for the corridor to have 965-1610 passengers per hour). The number of passengers criterion thus received a score of 2. ART published a report card from July 2018 stating that the average on-time performance for the corridor was 81.5% (Arlington Transit, 2018).

Table 33. Transit Stop Characteristics of Arlington Corridor

Bus Stop Name (EB = eastbound; WB = westbound)	Scheduled Buses in the Peak Hour	Bus Stop Placement
Columbia Pike/ S. Scott St EB	41	Near
Columbia Pike/ S. Veitch St EB	36	Near
Columbia Pike/ Barton St EB	36	Far
Columbia Pike/ S. Walter Reed Dr EB	43	Far
Columbia Pike/ S. Highland St EB	28	Near
Columbia Pike/ S. Glebe Rd EB	37	Far
Columbia Pike/ S. Monroe St EB	49	Far
Columbia Pike/ S. Oakland St EB	40	Near
Columbia Pike/ S. Scott St WB	41	Far
Columbia Pike/ S. Veitch St WB	36	Far
Columbia Pike/ Barton St WB	36	Far
Columbia Pike/ S. Walter Reed Dr WB	43	Near
Columbia Pike/ S. Highland St WB	28	Near
Columbia Pike/ S. Glebe Rd WB	37	Near
Columbia Pike/ S. Monroe St WB	49	Near
Columbia Pike/ S. Oakland St WB	40	Near

Pedestrian Characteristics

The average Walk Score in this area is 88, which means it is a very walkable area with the ability to accomplish most errands on foot. The transit-dependent population in this area is 3,909 persons (22.8% of the population).

Traffic Characteristics

According to a report by Kimley-Horn (2012), the intersection delay in this corridor varied, but the average intersection control delay was 16 seconds (Table 34). Overall, it was categorized as LOS B.

Table 34. Traffic Characteristics of Arlington Corridor

No.	Intersection	Control Delay (sec)	Level of Service
1	Columbia Pike and S. Courthouse Rd.	17.1	B
2	Columbia Pike and S. Wayne St.	5.0	A
3	Columbia Pike and S. Barton St.	4.9	A
4	Columbia Pike and S. Walter Reed Dr.	28.8	C
5	Columbia Pike and S. Highland St.	4.4	A
6	Columbia Pike and S. Glebe Rd.	43.5	D
7	Columbia Pike and S. Monroe St.	9.6	A

Signal Characteristics

The signals at the seven intersections on the Arlington corridor have signal coordination and are fully actuated.

Summary of the Corridor

Table 35 shows the scores for the Arlington corridor. Among the three corridors, Columbia Pike in Arlington has the highest weighted score of 102. It has higher transit frequency and passenger numbers than the Charlottesville and Blacksburg corridors, contributing to the higher score of the Arlington corridor.

Table 35. Overall Result of TSPRT Application to Arlington Corridor

Criteria	Weight	Score	Weighted Score
Geometric Characteristics			
Dedicated Right-of-Way	5	0	0
Number of Lane per Direction	3	3	9
Vertical Alignment	2	0	0
Transit Characteristics			
Bus Schedule Adherence	5	2	10
Transit Frequency	4	3	12
GPS/AVL	4	3	12
Number of Passengers	3	2	6
Transit LOS	3	3	9
Bus Stop Placement	3	1	3
Pedestrian Characteristics			
Walk Score	3	2	6
Transit Dependent Population	2	2	4
Traffic Characteristics			
Intersection Control Delay	4	1	4
Signal Characteristics			
Signal Control System	5	3	15
Signal Coordination	4	3	12
Total			**102**
TSP Viability Index			***2.04***

Simulation and Analysis of Test Corridors

Of the three above corridors (in Charlottesville, Blacksburg, and Arlington), the effects of TSP implementation on the highest (Arlington) and lowest (Blacksburg) scoring corridors were tested using microsimulation in VISSIM. Traffic and pedestrian data were obtained from prior local planning studies, and the model was developed to reflect reality as much as possible (Kimley-Horn, 2012; Whitman, Requardt and Associates, 2019; and Stevanovic et al., 2008). Additionally, the research team conducted data collection for items not found in the local planning studies. The values reported below are the average of the ten runs of the simulation.

Blacksburg

The two signalized intersections and one two-way stop-controlled intersection on Main Street were simulated. The direction of TSP implementation at each intersection is listed in Table 36.

Table 36. TSP Directions by Intersections, Blacksburg

No	Intersection	Signal Control	TSP Implementation
1	Main St/Miller St	Stop Controlled (Minor Street)	None
2	Main St/Clay St	Signalized	Southbound through, northbound through
3	Main St/Washington St	Signalized	Southbound through, northbound through

The overall stop delay decreased very slightly with TSP implementation at both signalized intersections in the simulation (Figure 7). The stop delay at Clay St. decreased by 0.1 seconds, and the stop delay at Washington St. decreased by 0.2 seconds. The small magnitude of the changes (which are not practically significant) can be attributed to infrequent actuation of the TSP system because of there being only four buses per hour. The direction of the change (a decrease in stop delay) is because actuation of the TSP occurs in the direction of the majority of traffic at each of the intersections.

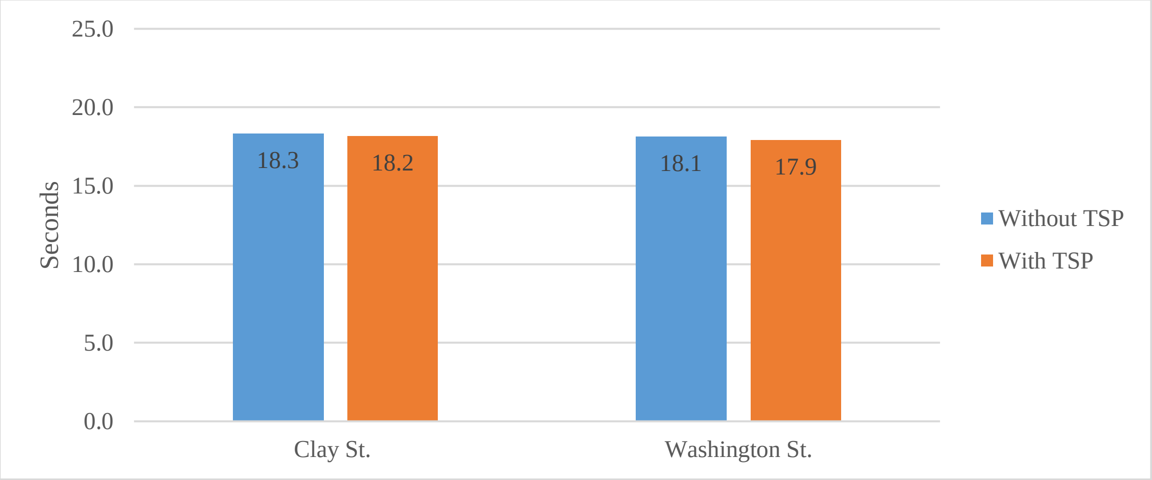

Figure 7. All-Vehicle Stop Delay, Blacksburg Simulation Results

For buses, the simulated stop delay decrease was more substantial (Figure 8). Before TSP implementation, the buses’ stop delays were 23.6 seconds and 14.6 seconds on Clay St. and Washington St., respectively. After TSP implementation, the stop delays for buses decreased 66% and 45%, respectively, to 8.0 and 8.1 seconds. The magnitude of this drop was caused by the TSP being activated whenever the buses use the intersection. TSP activation allows for any queuing to clear to facilitate the movement of the buses.

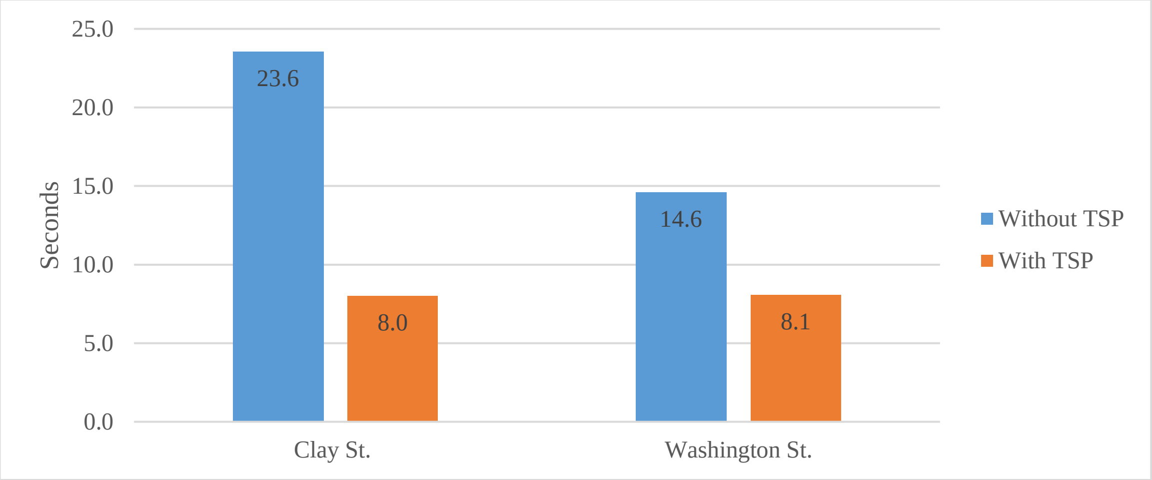

Figure 8. Overall Stop Delay for Buses, Blacksburg Simulation Results

TSP was only simulated on major movements, but it affected both the major and minor movements. The results in Table 37 show a slight increase in delay on minor roads. However, on the major road, buses received substantial delay reduction, and all vehicles also saw some delay reduction. For the traffic mix in Blacksburg, TSP implementation on the simulated corridor would have benefits for the majority of vehicles on the roadway. Since the vast majority of traffic travels on the major street, the effect of increased delay on the minor streets is negligible. In addition, the small number of actuations in an hour reduces the negative impact to the minor movements.

Table 37. Stop Delay Change After TSP Implementation by TSP Direction, Blacksburg Simulation Results

Name	All Vehicles	Bus only
No TSP Direction (minor roads)	0.2%	N/A
TSP Direction (major road)	-6.3%	-49.0%

Pedestrian counts were observed in the corridor by the research team. The simulation results suggest that the impact of TSP on the pedestrian would be negligible for the Blacksburg corridor. The number of cycles in one hour where TSP would be activated would be very low, thereby reducing any negative impact of the TSP on pedestrians. The simulated pedestrian delay slightly decreased at Clay St. but slightly increased at Washington St., as shown in Figure 9.

The simulation for the Blacksburg corridor showed that TSP can be effective in a small town in reducing the delay to transit vehicles with very limited impacts on traffic from minor streets and pedestrians. The simulated reduction in delay was substantial for the transit vehicles; in reality, however, the limited use and cost of TSP implementation may not warrant installation because of the infrequent transit service. The TSPRT tool takes factors into consideration that a simulation cannot incorporate, giving an agency a better picture of whether TSP is necessary and if TSP would truly be effective. If a TSP system could be installed with other signal updates or in conjunction with other development in the area, it could provide benefits to some BT routes with minimal costs to other road users.

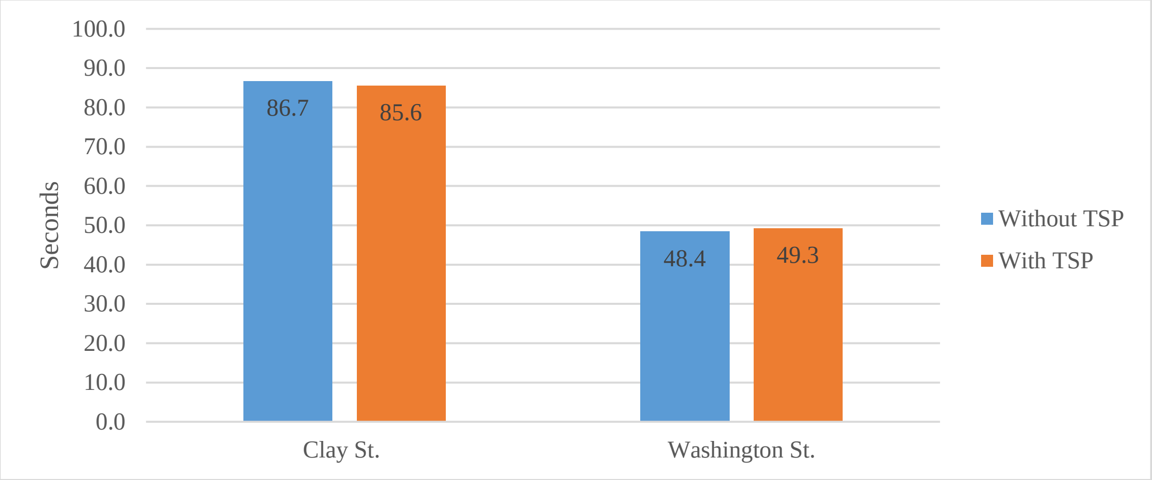

Figure 9. Pedestrian Delay, Blacksburg Simulation Results

Arlington

TSP was simulated for eastbound and westbound through traffic on Columbia Pike. Figures 10 and 11 illustrate the stop delay for all vehicles and buses, respectively. According to the simulation, the overall stop delay increased at six out of seven signalized intersections. Since TSP was simulated for the major approach (eastbound and westbound Columbia Pike), the minor approach experienced more stop delays and stops. The stop delays for all vehicles increased slightly at most intersections, but at the intersection of Columbia Pike and S. Courthouse Rd., it increased by 6 seconds. Two major roads come together at this intersection, with relatively high traffic volumes on both Columbia Pike and S. Courthouse Rd., which created a more noticeable increase in stop delay.

Figure 10. All-Vehicle Stop Delay, Arlington Simulation Results

After TSP implementation, the simulated stop delays for buses decreased at six out of the seven signalized intersections. The overall stop delay for buses at S. Courthouse Rd. substantially increased for the same reason mentioned previously. When TSP is implemented on Columbia Pike, the red time is increased for S. Courthouse Rd., thereby increasing the stop delay.

Figure 11. Overall Stop Delay for Buses, Arlington Simulation Results

Table 38 shows the simulated reduction of stop delay with TSP implementation by the direction of traffic. The "TSP direction" is the direction of traffic that is optimized for TSP operations. For Columbia Pike, this is inbound towards Washington in the morning and outbound from Washington in the evening peak. The reverse commute from these peak directions is referred to as the "No TSP direction" for this simulation.

Table 38. Stop Delay Change After TSP Implementation by TSP Direction, Arlington Simulation Results

Name	All Vehicles	Bus only
No TSP Direction	17.5%	N/A
TSP Direction	-8.1%	-26.3%

Figure 12 shows the pedestrian delay simulation results at the seven intersections. The pedestrian delay at S. Courthouse Road substantially increased after TSP implementation, because this intersection consists of two major roads. Both roads have substantial pedestrian volumes (Kimley-Horn, 2012), and TSP implementation increased red time on S. Courthouse Rd., causing increased delay to pedestrians. For the other six intersections, there were negligible effects on pedestrian delay, so it can be assumed that pedestrian delay is most affected when there are high volumes of pedestrians crossing the major road.

The simulated implementation of TSP on Columbia Pike was positive overall except at the intersection of S. Courthouse Rd. Based on these results, TSP implementation at the six intersections, excluding S. Courthouse Rd., would provide measurable positive benefits without substantial impacts to other road users on the corridor. Implementation of TSP in this corridor would also provide major benefits to bus services.

Figure 12. Pedestrian Delay, Arlington Simulation Results

DISCUSSION

The result of this research is the development of a tool to help decisionmakers determine if TSP could be successful on a corridor of interest. The work on this project was limited by the amount of data available to inform the research. This study may be limited by the lack of a baseline from the literature for comparing results, because previous studies have not attempted to create a tool to quantify the viability of TSP in a certain corridor. Many of the case studies and tools referenced were more concerned with the operational characteristics of TSP than in documenting the planning decisions that led to the implementation of TSP in a community. This research seeks to help fill that major gap in the literature.

The TSPRT provides a quantitative measurement that incorporates factors that led to the success of TSP in previous implementations. One way this tool can be used by planners is to understand what parts of the corridor have characteristics not typically associated with successful implementations of TSP and to upgrade those characteristics (if possible).

The TSPRT is quantitative to provide a comparison between the results of different corridors, but users should not interpret the quantitative score as an absolute difference between corridors (i.e., a corridor with a 5% higher score than another corridor is not necessarily going to be 5% better for TSP implementation). There are many intangibles beyond the ones presented in the tool that will help to determine if TSP will be successful. Examples of these intangible items include political and stakeholder buy-in, transit agency operations, community and rider buy-in, and technology implementation.

If the TSPRT identifies a corridor as viable for TSP, then conducting microsimulation is important for designing TSP that will be successful. The microsimulation of the Arlington corridor showed that there would be mostly positive impacts from the implementation of TSP. However, at an intersection with a high amount of cross-traffic, implementation of TSP would worsen conditions because of the impact on cross-street traffic, including pedestrians. Microsimulation helps designers of TSP systems understand the impact of the implementation and can aid in development of operational rules that will minimize the impacts at such intersections. One such rule would be to ensure that at high-volume cross-street intersections, the TSP system would only be activated if a bus was very behind schedule and/or had a large number of passengers onboard.

CONCLUSIONS

This study established the state of the practice in TSP implementation based on previous research, and developed a TSP implementation tool called TSPRT that considers geometric, transit, pedestrian, traffic, and signal characteristics. The TSPRT provides guidance on TSP viability on any corridor and could help agencies allocate budgets efficiently. The following conclusions can be made:

- *The TSPRT can help evaluate a corridor for conditions necessary for successful implementation of TSP.*
- *The TSPRT helps differentiate corridors by their likely transit operational improvement from TSP implementation, and benefits can be estimated via simulations.* Even corridors with relatively low TSPRT scores may exhibit benefits from TSP.
- *A higher TSPRT score will not necessarily yield better delay reduction.* The impact of TSP depends on the target area's characteristics. This can be measured through the use of microsimulation.
- *The effect TSP has on pedestrians is negligible, unless large volumes of pedestrians cross the street that has TSP, based upon the literature review and confirmed by the simulations.*
- *TSP may result in increased vehicle delay for approaches on minor roads of an intersection, based on the simulations.*
- *Microsimulation provides valuable insights—in addition to the results from the TSPRT—into the effects of TSP on different corridors.*

RECOMMENDATIONS

This study recommends the following:

1. *DRPT's Public Transportation Division should consider which of its business processes could benefit from incorporation of the TSPRT.* Business processes at DRPT that could benefit might include evaluating potential TSP projects as part of the statewide transit grants program, such as Technical Assistance or Demonstration, and comparing candidate TSP corridors as part of developing transit development plans or transit strategic plans for individual transit agencies.

2. *VDOT's Transportation and Mobility Planning Division should disseminate information regarding the use of the TSPRT tool to regional and local planning partners such as Virginia metropolitan planning organizations (MPOs) and localities.* The information will allow MPOs and localities to conduct evaluations on corridors in their jurisdictions to assess the feasibility of TSP implementation.

IMPLEMENTATION AND BENEFITS

Implementation

With regard to Recommendation 1, by Fall 2020, DRPT's Manager of Transit Planning and Corridor Development will review business processes and identify those that could benefit from incorporation of the TSPRT. A possible related implementation action could be for DRPT to apply the TSPRT as a resource for the development or evaluation of grant applications in its fiscal year 2022 grant cycle, starting in Fall 2020.

With regard to Recommendation 2, by winter 2020-2021, the Virginia Transportation Research Council (VTRC) will work with the researchers to produce and distribute a briefing on the TSPRT to VDOT's Transportation and Mobility Planning Director, who will identify opportunities to disseminate TSPRT information to local and regional planning partners. This could include outreach to localities via VDOT's Local Assistance Division.

Benefits

The primary benefit of implementing Recommendation 1 could be improved decision-making regarding TSP in processes of planning and project prioritization. Use of the TSPRT could help ensure that TSP implementation is targeted to the appropriate corridors and that limited funds are allocated efficiently.

The primary benefit of implementing Recommendation 2 may be increased evaluation of corridors via the TSPRT tool, which can enable decision-makers to assess the suitability of a corridor for TSP based on a number of criteria and location attributes. By disseminating information to localities, a standard procedure for using the TSPRT could be established, guiding decisionmakers to be able to easily compare potential projects.

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