



Final Report - Part 1

DEVELOPING A CONNECTED VEHICLE TRANSIT SIGNAL PRIORITY SYSTEM

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16. Abstract This study developed an advanced decentralized transit signal priority (TSP) system using a cycle-free Nash bargaining (NB) signal control system. TSP is recognized as an innovative technology solution capable of enhancing traditional transit services. TPS allows transit vehicles to utilize additional or alternative green time to clear the intersection by adjusting signal timing. TSP operations allow a transit vehicle to be promptly served and significantly reduce delay to prevent long waits at signalized intersections. The developed DNB-TSP system was applied to obtain an optimal control strategy on an isolated intersection and on an arterial corridor, considering a variable phasing sequence and free cycle length. The developed system was implemented and evaluated in INTEGRATION microscopic traffic assignment and simulation software. The new DNB-TSP system was compared to the operation of an optimum fixed time plan (FP) controller, a centralized adaptive phase split (PS) controller, a decentralized phase split and cycle length (PSC) controller, and a DNB controller without TSP to evaluate the developed controller's performance in different scenarios. The study found that the new DNB-TSP system significantly improved various margins of error at a four-legged isolated signalized intersection. In particular, the new system reduced average vehicle delay up 67.5%, 73.2%, 71.1%, and 3.4% compared to FP, PS, PSC, and DNB controllers, respectively. Further, the study found that transit vehicles reduced their average travel time up to 15.6%, average passenger travel time up to 15.2%, average total delay up to 23.3%, average stopped delay up to 68.3%, and fuel consumption up to 6.17% with the DNB-TSP system relative to the DNB controller. The study also investigated the performance of the new system at an arterial corridor. Findings revealed that the new system reduced vehicle stops, vehicle travel time, passenger travel time, vehicle total delay, vehicle stopped delay, fuel, and CO2 emissions up to 14.2%, 21.3%, 18.7%, 66.5%, 82.9%, 13.1%, and 13.1%, respectively, at a test arterial corridor compared to the other traffic signal controllers.			
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Abstract

This study developed an advanced decentralized transit signal priority (TSP) system using a cycle-free Nash bargaining (NB) signal control system. TSP is recognized as an innovative technology solution capable of enhancing traditional transit services. TSP allows transit vehicles to utilize additional or alternative green time to clear the intersection by adjusting signal timing. TSP operations allow a transit vehicle to be promptly served and significantly reduce delay to prevent long waits at signalized intersections. The developed DNB-TSP system was applied to obtain an optimal control strategy on an isolated intersection and on an arterial corridor, considering a variable phasing sequence and free cycle length. The developed system was implemented and evaluated in INTEGRATION microscopic traffic assignment and simulation software. The new DNB-TSP system was compared to the operation of an optimum fixed time plan (FP) controller, a centralized adaptive phase split (PS) controller, a decentralized phase split and cycle length (PSC) controller, and a DNB controller without TSP to evaluate the developed controller's performance in different scenarios. The study found that the new DNB-TSP system significantly improved various margins of error at a four-legged isolated signalized intersection. In particular, the new system reduced average vehicle delay up to 67.5%, 73.2%, 71.1%, and 3.4% compared to FP, PS, PSC, and DNB controllers, respectively. Further, the study found that transit vehicles reduced their average travel time up to 15.6%, average passenger travel time up to 15.2%, average total delay up to 23.3%, average stopped delay up to 68.3%, and fuel consumption up to 6.17% with the DNB-TSP system relative to the DNB controller. The study also investigated the performance of the new system at an arterial corridor. Findings revealed that the new system reduced vehicle stops, vehicle travel time, passenger travel time, vehicle total delay, vehicle stopped delay, fuel, and CO₂ emissions up to 14.2%, 21.3%, 18.7%, 66.5%, 82.9%, 13.1%, and 13.1%, respectively, at a test arterial corridor compared to the other traffic signal controllers.

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Introduction

This study developed an advanced transit signal priority (TSP) system using a cycle-free decentralized Nash bargaining (NB) signal control system—the novel DNB-TSP system. Traffic signals and traffic congestion are two major sources of delay for traditional bus services. TSP is recognized as an innovative technology capable of enhancing traditional transit services. According to a previous study, TSP is defined as “an operational strategy that facilitates the movement of in-service transit vehicles, either buses or streetcars, through traffic-signal controlled intersections [1].” In recent years, TSP has been broadly implemented by transportation agencies in North America and worldwide.

Traditional TSP operations have utilized various TSP treatments, including green extension, green reallocation, red truncation, upstream green truncation, phase insertions, and phase reserビング. These TSP operations alter green or red timing or change phase sequence when a transit vehicle is expected to arrive at a traffic signal a few seconds after the end of the green indication. Consequently, the transit vehicle utilizes additional green time to allow it to clear the intersection before the traffic signal indication changes. These methods allow a transit vehicle to be served with priority and significantly reduce the delay to that vehicle relative to waiting for an early green or special transit phase. These systems generally consist of emitters installed on transit vehicles and optical detectors located at traffic signals. The emitters are typically installed on the roof of transit vehicles, while an optical detector and a confirmation light are set up on the traffic signal head. The TSP system is triggered when the optical detector receives a request from a transit vehicle during a green indication so long as there is no ongoing pedestrian phase at the time and no emergency vehicle preemption call is being made simultaneously.

Connected Vehicles (CVs) are an emerging technology that can generate transformative improvements in the roadway transportation system. CVs extend the benefits of Intelligent Transportation Systems to entire networks by improving the efficiency, safety, and energy consumption of the transportation system through the real-time exchange of information among vehicles and infrastructure. The real-time data exchange provided by CV applications offers many opportunities for proactive transit vehicle management and thus has the potential to overcome the limitations of traditional TSP. The exchanged CV trajectory and signal state data can provide real-time transit vehicle operational information throughout a network's links. In this study, we assumed that TSP utilized real-time high-fidelity data collected from vehicles through vehicle-to-infrastructure (V2I) wireless communications under a traffic simulation environment. The study developed a TSP algorithm that utilizes a de-centralized adaptive traffic signal controller using CV data.

A signalized intersection controls traffic flow so that it proceeds efficiently and safely by separating conflicting movements in time. Traffic signal controllers attempt to minimize vehicular delay by optimizing various traffic signal control variables, including cycle length, phase scheme and sequence, phase split, and offset. Traffic signal controllers can be categorized broadly as centralized or decentralized, where decentralized systems are computationally less demanding, as they only require and maintain the relevant information from the surrounding intersections. Decentralized controllers also guarantee robustness and scalability. However, centralized systems offer the ability to control traffic signals to optimize the entire system. Most currently implemented traffic signal systems can be categorized into one of the following categories: fixed-time control (FP), actuated control (ACT), traffic responsive control, or adaptive traffic signal control [2]. FP control systems are developed off-line using historical traffic data to compute traffic signal timings. In comparison, ACT systems respond to changes in traffic demand patterns by communicating with the controller based on the presence or absence of vehicles as identified by local detectors installed at intersection approach stop lines. While ACT systems have been proven to generally perform better than FP systems for very low demand levels, they cannot provide real-time optimization

to adapt to traffic fluctuations. Adaptive systems, however, have the potential to alleviate traffic congestion by adjusting traffic signal timing parameters in response to real-time traffic fluctuations. As such, these adaptive traffic signal controllers will be part of the proposed effort.

Adaptive traffic signal systems use detector inputs, historical trends, and predictive models to predict traffic arrivals at intersections. These systems have the potential to efficiently alleviate traffic congestion by adjusting the signal timing parameters in response to traffic fluctuations. Using these predictions, adaptive systems determine the best gradual changes in cycle length, splits, and offsets to optimize an objective function, such as minimizing the delay or the queue length, for intersections within a predetermined sub-area of a network. As noted above, state-of-the-practice adaptive traffic signal control can be categorized as either centralized or decentralized. Centralized controllers use on-line optimization methods to dynamically adjust signal timings while maintaining an offset between adjacent traffic signals (e.g., SCOOT and SCATS systems¹). SCOOT performs effectively in under-saturated traffic conditions. Optimization in SCATS is achieved in a centralized fashion that relies on communication, making it difficult to scale and complex to operate, with many parameters to be adjusted by a human operator. Compared to centralized systems, decentralized controllers, which use dynamic programming that captures the stochastic nature and dynamics of the traffic system, are computationally less demanding, and are more robust, scalable, and inexpensive.

The research team developed the novel DNB controller to improve transit flow. The DNB controller is a de-centralized adaptive traffic signal controller with a flexible phasing sequence and cycle-free operation that uses an NB game-theoretic framework to optimize the total queue length based on CV data. The DNB controller optimizes the traffic signal timings at each signalized intersection by modeling each phase as a player in a game, where players cooperate to reach a mutually agreeable outcome. The controller was implemented and tested in INTEGRATION microscopic traffic assignment and simulation software, and then its performance was compared to a decentralized phase split and cycle length optimization controller based on Highway Capacity Manual procedures and a SCOOT-like controller. The controller was tested on an isolated intersection [3] of an arterial network [4] in the town of Blacksburg, VA (38 traffic signalized intersections), and in downtown Los Angeles, CA (457 signalized intersections) [5]. The results demonstrate significant potential benefits of using the DNB controller over other state-of-the-art centralized and decentralized adaptive traffic signal controllers on small and large-scale networks and under both uncongested and congested conditions. Using the DNB controller, the queue length along signalized approaches was estimated considering a 100% CV market penetration and perfect communication. The real-time estimation of traffic density at different levels of market penetration is important for achieving better traffic signal operation in urban areas. Estimating queue length with limited probe vehicle data (CVs) is a challenge, especially when no additional data sources are available. Therefore, the team developed a novel approach based on the Kalman filter technique to estimate the total number of vehicles on multilane roads at signalized approaches using probe vehicle data only [6]. The DNB controller was extended to develop a new TSP system in this study—the DNB-TSP.

The objective of this study was to develop a TSP algorithm that utilizes a de-centralized adaptive traffic signal controller. While TSP operations can generally improve schedule adherence and reliability and reduce bus travel times, the system-wide impacts of TSP depend largely on the physical configuration of the network, including transit stop locations, major- and side-street traffic volumes, traffic signal timing parameters, and pedestrian volumes. This study evaluated the system-wide benefits of the developed TSP algorithm using a microscopic traffic simulation model. The remainder of this report is organized as

¹ SCAT: Sydney Coordinated Adaptive Traffic System; SCOOT: Split Cycle and Offset Optimization Technique

follows. The next sections present previous TSP studies; an overview of the DNB traffic signal controller; and the DNB-TSP simulation results. Conclusions are summarized in the final section.

Literature Review

TSP is a general term that refers to techniques and strategies that improve operation of a public transportation service (most commonly buses) at signalized intersections by extending green time or reducing red time or other types of signal phasing modifications at individual intersections, a corridor, or an entire network. Technological innovations have affected TSP approaches; most traditional TSP systems have been sensor-based designs intended to detect buses at a fixed or preset distance away from intersections. However, improved communication technology has led to its inclusion in various TSP systems, such as the wireless-based TSP strategy developed and tested in the City of Minneapolis, MN. This traditional system retrofit and upgrade to a wireless system led to an additional 3–6% travel time reduction for buses [7]. Similar wireless systems that could enhance bus detection reliability have been used by the Los Angeles Metro Transportation Authority (2.4 GHz) and in the King County, Seattle area of WA (4.9 GHz). These examples present a basis for applications of emerging CV technology [8]. There have been many studies of TSP systems in a CV environment—TSPCV is an umbrella term that refers to various TSP strategies applied in a CV environment that utilize some sort of CV technology and data in operations.

Hu et al. [9, 10] proposed an algorithm based on a mixed-integer linear program (MILP) that minimizes total passenger delay for all traffic users at signalized intersections or along a corridor. The algorithm is only activated when the bus is behind schedule and no additional delay per passenger is triggered by its use. The algorithm was extended to accommodating conflict request [11], and tested on the Virginia Smart Road in Blacksburg, VA [12, 13].

Yang et al. [14] developed a TSPCV vehicle-based control algorithm to minimize total delay of all passengers by optimizing departure sequence. The results of this study showed that when there is high bus flow entering the intersection, more reductions in delay can be expected when there are increments in CV penetration rate. The authors also claimed that, like previously developed algorithms, while implementing this algorithm may increase passenger vehicle (PV) delay, there would be a decrease in total delay and especially bus delay. They recommended that future studies consider more sophisticated intersections and bus speed guide strategies.

The United States Department of Transportation initiated Dynamic Mobility Applications to create CV applications that leverage the multi-source data collected from CVs, travelers, and roadway infrastructure. The Multi-Modal Intelligent Traffic Signal System (MMITSS), one of these application bundles, is a next generation of traffic signal systems that seeks to improve mobility through signalized intersections and corridors using advanced communications and data to facilitate the efficient travel of all modes. The research team previously evaluated the potential impacts and benefits of MMITSS and investigated the feasibility and applicability of MMITSS applications [15]. A MMITSS simulation model was also developed to assess the site-independent analysis of MMITSS applications [16]. MMITSS bundles include TSP, which utilizes real-time high-fidelity data collected from vehicles through V2I wireless communications. In the MMITSS TSP study, when an equipped bus reached the communications range, the roadside equipment received a service request message from the bus. The TSP system continuously tracked the movement of the bus, estimated its arrival time at the stop bar, and matched the estimated arrival time with Signal Phasing and Timing (SPaT) data to determine the signal phase when the bus was predicted to arrive at the intersection. The field study found that TSP operations improved connected transit travel times by 8.2% and the simulation study found that TSP effectively saved travel time for both transit and PVs on the corridor where TSP was operated, though it occasionally increased the system-wide delay due to reduced

green times on the side streets. In particular, TSP reduced travel time for both transit vehicles and PVs on the corridor by up to 29% and 28%, respectively, at a VA study site.

In TSP operations, the number and location of bus stops affect buses' performance (e.g., dwell times, delays, bus stop time, and stop time variation) and these are important keys in transit planning, as buses tend to spend more stop time at nearside stops [17, 18]. The possible bus stop locations are farside (downstream of the intersection), mid-block (between two intersections) or nearside (upstream of the intersection, right at the stop bar), each of which influences TSP performance. Relocating a nearside stop to a farside stop can reduce delays by up to 30 s per intersection [19]. A farside bus stop is the ideal situation for TSP because the level of certainty in estimations is high. A mid-block location has little impact on TSP depending on the distance between intersections. A nearside bus stop has a high uncertainty, however, and further, this configuration is the most common type of stop in urban areas [20]. Farside stops benefit more from TSP treatment than nearside stops [7]. Bus stop locations have been studied in a number of past TSP studies. For instance, Kim and Rilett [21] pointed to the issue of nearside bus stops for TSP systems that result in uncertainty in bus dwell time; accordingly, they developed a weighted-least-squares regression mode to improve the estimation of bus stop dwell time and the associated prediction interval. The authors' developed TSP system was traditional and was tested in VISSIM on an urban arterial section of Bellaire Boulevard in Houston, TX. In general, it was found that the proposed TSP algorithm was more effective than other algorithms, as it improved bus operations without statistically significant impacts on signal operations.

Wu et al. [22] proposed an integrated TSPCV control strategy considering bus schedule adherence. The provided model considered both farside and nearside stops at an isolated intersection where there was an exclusive bus lane to separate bus traffic flow from other vehicles. The results of this study showed that the proposed model was able to simultaneously reduce overall bus delay and whole traffic flow at the intersection. However, the proposed model considered only a one-lane bus route and a certain value was also considered for guidance of the transit vehicle approaching the intersection, while in reality an interval of time should be considered. Ignoring the driver's compliance rate was another of this study's shortcomings.

Luo et al. [23] proposed a dynamic control optimization model for bus transit priority systems to minimize the average travel time and in-vehicle travel time by focusing on heterogeneous conditions at bus stations, and using bus capacity as a constraint to minimize the cost of objective function. The authors tested the developed model in realistic traffic scenarios using archived AV location and integrated circuit smart data. Study results showed two main findings of interest: (1) bus compliance rates were more sensitive to passenger demand, and therefore the role of bus capacity is very important to finding the optimal solution; (2) the developed model could successfully minimize the total passenger cost by simultaneously considering bus capacity constraints. However, there are some faults in this model, the first of which is that the proposed model covered only one route; to be more realistic, the model should serve a multi-route network. This model's control strategies to avoid increasing passenger time costs could also use more efficient speed guidance strategies. One of the ideas that can be taken from this study is considering a sensitivity analysis of different passenger demand combinations in farside, nearside, and mid-block locations to examine the TSPCV system's performance under these conditions.

Truong et al. [24] explored the combined effects of TSP and road-space priority measures, including TSP with dedicated bus lanes and TSP with queue jump lanes. The TSP system in this study was traditional (i.e., sensor-based activation). Time-space diagrams were used to analyze the combined effect on bus delay at an intersection level and to discuss the combined effect on bus delay at an arterial level. In addition, an analytical delay model was proposed to further examine the effects of TSP and road-space priority

measures at an intersection level (accounting for nearside stops). Results indicated that, at an intersection level, the combined effect on bus delay savings was smaller than the additive effect if there was no nearside bus stop, and the traffic condition in the base case was undersaturated or near-saturated. With a near-side bus stop, the combined effect on bus delay savings at an intersection level was better than the additive effect (or over-additive effect), depending on dwell time, distance from the bus stop to the stop line, traffic demand, and cycle length. In addition, analytical results suggested that, at an arterial level, the combined effect on bus delay savings can be over-additive with suitable signal offsets. These results were confirmed by a micro-simulation case study.

Wu et al. [25] quantified the changes in intersection capacity, PV delay, and bus delay in a TSP system with nearside or farside bus stops. The analysis was on an isolated intersection with fixed cycle length. The TSP system was traditional and limited to either green extension or red truncation scenarios. A separate set of models were developed for nearside and farside bus stops. Variational and kinematic wave theories were used to estimate PV capacity and bus delay for oversaturated traffic conditions and queuing theory was used to estimate PV and bus delays for undersaturated conditions. The results showed interactions between bus and PV delays and intersection capacity. The results also revealed that bus stop locations significantly affect TSP measures. The bus delay decrease and PV delay increase were very sensitive to the bus stop location and the average dwell time. Some assumptions in this study call for further research, such as the assumption that buses and PVs have same kinematic characteristics, a static demand in undersaturated conditions, and the maximum of one bus arrival per cycle at the intersection.

Yang et al.[26] proposed a TSPCV algorithm for multimodal traffic control that covers scenarios with nearside or farside bus stops. The algorithm optimizes signal delay or schedule delay for buses and also additional delays for PVs. The authors' simulations included different volume to capacity ratios, bus arrivals, bus occupancies, and penetration rates. The authors stated that only a few works on signal control algorithms in CV environment have considered cooperation with bus stops. They therefore extended their previous research on using CV technology to improve the efficiency of intersections [27], to also cover public transit. The methodology features were as follows: a vehicle-based TSP control algorithm in a CV or semi-CV environment does not need platooning information, and total delay of all passengers is minimized online; the algorithm coordinates traffic signal operation with both the bus stops and the bus schedule; the algorithm only provides priority when it is optimal from a system-wide perspective. The study assumed the following: an isolated intersection with two single-lane, one-way roads; the intersection can have either no bus stop, a farside bus stop, or a nearside (+ dwell time) bus stop; all buses and a certain percentage of PVs can be assumed to be equipped with V2I technology (i.e., dedicated short range communication [DSRC]). Different sets of models were developed to cover different conditions, with or without a bus stop, with or without a bus schedule, with or without bus delay, and combinations of these. The SUMO microscopic simulation package was used to evaluate the proposed algorithms, as shown in Figure 1.

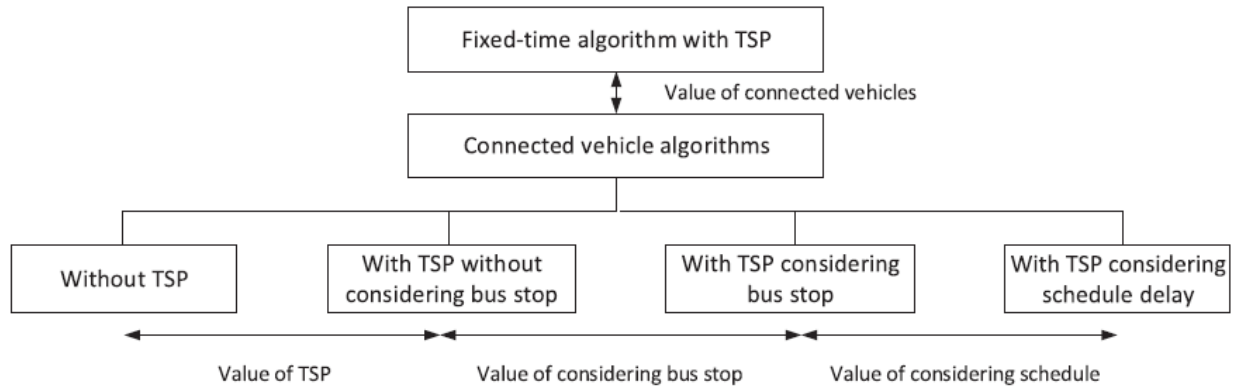


Figure 1. Evaluation Framework in a TSPCV with Bus Stop and/or Bus Schedule Delays ([26])

Bus stop location can influence transit in different ways; farside stops may cause a spillback effect and nearside stops may cause the bus to be blocked by traffic. The findings of this study shed light on the methods and significance of coordinating TSP algorithms with bus stop locations. The authors claimed that the algorithm was not sensitive to the assumed bus passenger occupancy, nor the estimation of bus dwell time, and hence did not require accurate information on these parameters, a finding which was confirmed by sensitivity analyses. Future work should consider more complex intersections and arterials with multiple lanes, bus speed profiles, multiple modes, and a central controller application.

TSP systems tend to improve transit performance and, in recent years, have minimized the impacts on side roads and non-priority PVs. Different evaluation studies have been undertaken to investigate and examine the realization of the former and latter promises. Moreover, in recent years, evaluations have been extended to include corridors or networks rather than traditionally isolated intersection evaluations. Ahn and Rakha [28] investigated the TSP implemented on US Route 1 in the Northern VA Area, and the simulation results indicated that TSP did not result in statistically significant changes in transit vehicle, PV, or system-wide travel times. Further, they found that TSP generally benefited transit vehicles but did not guarantee system-wide benefits. So far, the majority of past studies have focused on developing better TSP logic—including improved bus arrival-time prediction, new TSP strategies, and enhancing selective priority—to maximize the benefits of TSP and to reduce the negative impacts on non-transit users. However, the practice of TSP is often limited due to the high cost of the technology required for the system to work cooperatively between transit and traffic systems. A challenge faced by some agencies is the contradiction between engineering needs and practical management. For instance, very frequent TSP priority requests, especially in a bus rapid transit system, degrade a well-designed signal scheme [29]. The TSP system's effectiveness is uncertain for arterials serving heavy bus flows because frequent signal priority calls will inevitably disrupt the arterial signal plan and cause excessive delays for general traffic [30].

There are also some discussions about the scalability of TSP systems that just successfully only at an isolated intersection or in a limited network. Tärneberg et al. [31] investigated a cloud-based platform for the IoT (Internet of Things), such as Amazon Web Services (AWS), to design and implement a TSPCV system as an IoT use-case based on a concept that was examined in a past study by Hu et al. [9]. The main purpose of the study was to evaluate the feasibility of deploying a large testbed in the cloud, as opposed to current simulations and small real-world evaluations. The results indicated that existing IoT platforms, such as AWS, do not meet the required performance and scalability of many next-generation scientific IoT use-cases (such as TSPCV), and that manageability/modifications of a scientific IoT scenario can be challenging for moderate- to large-scale deployments.

To overcome the aforementioned challenges, TSP research has been extended to designs that are more comprehensive and are aimed at achieving multiple objectives through innovative analysis methods and more realistic evaluations; these include studies that have coupled TSP research with technological progress. Xinag and Chen [32] proposed a multi-agent-based traffic control optimization method for an integrated adaptive signal controller under a CV environment. The result of this study showed that the optimization algorithm could decrease the queue length of CVs at intersection as well as coordinate travel and delay time. They recommended that future studies take into account optimization of the offset at the vehicle ad hoc network environment.

Liu and Qiu [33] proposed a multi-objective optimization model to weigh in the integrated delay-based evaluation of buses and private vehicles. The problem with two objectives of minimization of private vehicle delay and bus delay was solved with a nondominated sorting genetic algorithm. A simulation study was also conducted on a bus corridor using the ASC/3 simulator in VISSIM. The results showed that the proposed method could reduce average personal delay more effectively than the weighted method, which is commonly used in TSP algorithms.

Zamanipour [34], in his PhD dissertation, addressed a real-time decision making framework for multi modal traffic signal control by focusing on multi transportation modes under a CV environment. The methodology of this study was based on developing an algorithm consisting of a MILP model to optimize signal scheduling by considering the value of the total weighted sum of coordination delay and the weighted sum of priority eligible vehicles' delay. They conducted two field tests in CA and AZ, the results of which show that the model could decrease overall bus delay at two closely spaced coordinated signals without significant imposed delay on PVs. Furthermore, the authors concluded that queue prediction at an interstation in a multi-mode case is highly sensitive to the CV penetration rate, which means that when there are more CVs, delay prediction would be more accurate not only for buses but also for PVs. The author also stated that considering queuing shockwaves at the intersection might help improve estimation of delay due to the prevention of queue spills back on non-priority phases. This study provided some key points for future studies. First, since each mode behaves differently under a CV environment, it is necessary to consider speed profiling characteristics for each mode. Second, considering sending route and bus feature information to a priority signal generator is important, especially when a bus wants to turn left at an intersection. Third, the signal control logic at a nearside stop at an intersection should be evaluated accurately and efficiency so that the bus stop's logic can be compared with other locations. Fourth, the analysis results of the field data tests are effective for understanding the efficiency of an algorithm, especially in measuring the effectiveness of mode weight in real-world situations. Fifth, integrating pedestrian priority requests in the algorithm can make the algorithm more realistic.

Wu et al. [35] provided a modeling framework and lane chaining rule for bus lane with intermittent priority under a vehicle-to-vehicle communication environment. The results of their study revealed that larger clear distances and higher bus departure frequencies could play a privilege role in mitigating the traffic impacts on strategies for this framework. Although proposed strategies in this study decrease bus delay and travel time, reducing road capacity is an unavoidable outcome of using these strategies. The authors recommended that the probability of PVs who follow a mandatory lane changing pattern at the intersection should be taken into account in future simulation modeling

Chang et al. [36] presented a base signal progression model to optimize the offsets for an urban arterial street. They concluded that for avoiding interruption between traffic queues and bus progression at an intersection, the queue clearance time might be integrated with coordinated offsets in a framework.

Wang et al. [37] proposed a bi-level (traditional) TSP to improve the status of non-priority road delays considering the typical mixed-traffic flow pattern and heavy transit volume in China. The upper-level

model aimed at minimizing side roadway delays and keeping the delay variation in priority direction at an acceptable range. The lower-level model was targeted at minimizing the average passenger delay in the entire intersection. A hypothetical and real-world intersection were studied, and the average vehicle delay of the side roadway was found to decrease significantly, while the increase on the transit priority side was negligible. The authors recommended multiple intersections with the coordinated timing plans to be considered for future works, as well as considering other variables in addition to average passenger delay and vehicle delay.

Zhou et al. [38] proposed a developed and active TSP method for a bus rapid transit in a dedicated lane at a single intersection based on a vehicle infrastructure system. The results showed that the model could decrease average passenger delays up to 25% and improve the bus rapid transit up to 7.5% at a single intersection. However, this study did not consider bus stop location in the algorithm, and considering only one intersection reduces the algorithm's efficiency.

Bagherian [39] developed and validated a planning tool to evaluate and design priority strategies at the network level, including TSP at intersections and transit priority lanes on roadway segments. The author discussed the potential negative impacts of these systems on competent modes, which has raised concerns about their deployment, and urged thorough validation before implementation. The study also proposed the implementation of V2I communication to reduce bus fuel consumption at intersections and suggested V2I integration with TSP strategies.

Liu et al. [40] provided a dynamic clustering algorithm by integrating a cooperative reinforcement learning control method under a CV environment. The objective of the proposed algorithm was optimizing the signal control for vehicle-to-everything CVs. The results of this study showed that this algorithm could decrease the average waiting time of these types of vehicles up to 60% and improve traffic flow at the intersection. The authors noted that one important point that should be considered in future works is developing a structure in the algorithm to choose and combine the characteristics of the intersection controllers in order to better understand the trade-off between the algorithm's efficiency and communication costs.

Islam and Hajbabaie [41] proposed a distributed-coordinated methodology for a signal timing optimization model to maximize throughput of vehicles on different approaches under a CV environment, taking into consideration a long queue length. They showed that their proposed model could reduce the complexity of the signal timing optimization problem and was efficient in improving traffic performance measurements at intersections. The authors considered fully connected CVs in their algorithm; however, considering CVs with different levels of connectivity could be an extension of this study. They also recommended, in future studies, considering delay and disruption in communications not only between the bus and intersection but also between all modes of transit.

Han [42], in his MSc thesis, developed a game theoretic approach using an epsilon-equilibrium algorithm on online adaptive traffic signal control coordination using real-time data from connected autonomous vehicles (CAVs). The algorithm aimed to optimize the network at the network level by means of a real-time data-driven signal coordination. In this algorithm, intersections of the network act like individual and independent players in a game, and seek their own beneficial maximization. The network delay performances between CAVs and PVs were also compared. A simulation platform was built using MATLAB to code and evaluate the proposed algorithms and models. The game theoretical approach was proven to outperform systematical optimization on vehicle delay at the intersection level in terms of delay equity. The results also showed that the CAVs could achieve better delay performances compared to PVs. The author suggests that future works might consider flexible cycle length, green splits, and bigger networks.

Aakre and Aakre [43] studied a special case of TPS at roundabouts, which they named Continuous Median Lane Roundabout. The authors proposed replacing traffic signals at roundabout circulating lanes with yield signs. Microsimulations using AIMSUN 8.1 were used to validate the proposed design, and results indicated that (close to) zero delay for buses could be maintained, while delays for general traffic could be significantly reduced compared to existing solutions (i.e., traffic signals). There also were some potential CO2 reductions due to smoother traffic flows.

Aziz et al. [44] synthesized the current state of signal control algorithms and infrastructure as an initial step toward developing future control infrastructure with a transitional period of a heterogeneous mix of CVs, CAVs, and PVs while leveraging benefits to safety, congestion, and energy. The authors differentiated between CVs and CAVs and reviewed a variety of potential schemes on each side, including a safety pilot model deployment in Ann Arbor, MI, a Wyoming Department of Transportation plan, a New York City Pilot Study Plan, a Tampa Pilot Deployment Plan, and Smart City finalists.

Beak [45], in his PhD Dissertation, examined an integrated optimization of traffic signal control systems in a CV environment. He stated that selection of a proper traffic signal system is very important because there is no perfect strategy that fits every traffic network. Most previous research has focused on major movement along the coordinated routes without considering system-wide impacts on other traffic. Thus there are a lack of optimization models that account for the impacts on side street movements or other system-wide impacts. In Beak's research, an adaptive optimization algorithm was developed to integrate coordination with adaptive signal control using data from CVs. Via the algorithm, the coordination plan can be updated to accommodate traffic demand variation and remain optimal over the coordination period. The optimization framework consists of two levels: intersection (handles phase allocation) and corridor (deals with offsets optimization). Optimization at the intersection level is to create the optimal signal plan by considering all movements—the objective function is to minimize individual vehicle delay for both coordinated and non-coordinated phases using dynamic programming. The optimization target at the corridor level is the performance of the vehicle movement along the coordinated phase—the objective function is to minimize platoon delay for the coordinated phase using MILP. The dissertation and a subsequent journal paper [46] included a peer priority control strategy, a methodology that enhances the MMITSS priority control model. The strategy is based on a combination of peer-to-peer backhaul network between two adjacent intersections and DSRC in a CV environment. This strategy contributes to the possibility of a flexible long-term plan for prioritized vehicles, which can benefit from the long-term plan within a secured flexible region and can prevent the near-term priority actions from having a negative impact on other traffic by providing more flexibility for phase actuation. The strategy was designed and tested for farside bus stops. The formulation was in an MILP and simulations were done in VISSIM on AZ and UT networks. This strategy was effective in reducing the number of stops and delay for priority eligible vehicles, while minimizing the negative impact on PVs. There were several future work recommendations, such as lower CVs market penetration rates (in the analysis the assumption was 100%), online optimization in the adaptive coordination algorithm (in the analysis, it was offline), and integration of coordination and peer priority signal control. Other recommendations were estimation of accurate arrival time for peer requests and consideration of nearside bus stops in peer-to-peer priority signal control model.

Islam et al. [47] proposed a new mathematical model to simplify traffic timing optimization in a CV environment by combining exclusive bus lanes, bus routes, and TSP strategies. The results of this study revealed that the developed algorithm could increase PV travel time up to 5%, but could reduce intersection bus delay up to 23% and significantly improve network throughput flow. The authors recommended in their work that future studies consider multiple origins-destinations in a network to examine the reliability and validity of the TSP models.

Xianmin et al. [48] investigated an optimization method for TSPCV considering multi-request by reducing per person delay. CV features enhance the bus arrival time prediction accuracy and VISSIM and MATLAB were used to validate the proposed method in different conditions. Control types included No-TSP (NTSP in the paper), TSPCV (CVTSP in the paper), TSPCV with green time reallocation (CVTSP-GD in the paper), and TSPCV with the optimal signal timing plan for the next cycle considering arrival information about transit in the competition direction (CVTSP-CC in the paper). The bus stop locations were not part of the algorithm. In this algorithm, priority is not always guaranteed for all buses and priority is given to buses with least total intersection delay. VISSIM simulations confirmed that CVTSP-CC could reduce per person delay of buses significantly while taking into account the per person delay of PVs.

An et al. [49] developed an innovative TSPCV model using hierarchical colored petri nets. The intersection that was considered in the algorithm had four phases. Two types of transit priority were formulated: green extension and red truncation. The benefits of using hierarchical colored petri nets-based TSP were clear presentation of traffic light behaviors in terms of conditions and events that caused the detection of a priority request by a transit vehicle and convenient and easy analysis of the correctness and reliability of the proposed strategies. Experimental results showed that the proposed control model provided transit vehicles with better effectiveness at intersections. Future work should consider complex traffic control designs, including pedestrians, multiple overlapping transit lines, and non-deterministic phase transitions.

Jing et al. [50] reviewed past studies on adaptive traffic signal control under CV environments. The authors provided analytical analysis of 26 studies regarding advantages and disadvantages of current algorithms and models, and included some suggestions for future works on TSP using CV technologies. First, although CVs will decrease traffic congestion in urban traffic networks, traffic congestion, even at lower levels, will still be expected in future. Therefore, it is crucial to consider saturated and over-saturated traffic conditions at intersections. Second, optimization methods that have been used to control signal timing still need to improve intelligent control systems in a CV environment. Third, multi-modal traffic conditions have not been considered in most past studies, while TSPCV can serve tram, bus and other public transit modes simultaneously. Fourth, any future TSPCV algorithm should be flexible and more adaptive to different control system structures. In this regard, all benefits of distributed, centralized, and multilayer distributed traffic control systems should be attended. Finally, the role of emerging transit modes like AVs and CAVs with different penetration rates with PVs in a heterogeneous traffic condition should be considered in future studies.

Most previous studies focused on developing and evaluating TPS algorithms using traditional traffic signal systems. This research effort developed a CV-enabled TSP system using a novel cycle-free NB optimization approach to improve the overall efficiency of traditional TSP systems. The study implemented the CV-enabled cycle-free TSP traffic control system—DNB-TSP— to improve the travel time of equipped transit vehicles, while at the same time causing minimum dis-benefits to other vehicles.

Decentralized Nash Bargaining Transit Signal Priority System (DNB-TSP)

This section presents the developed decentralized TSP optimization approach, using an NB game-theoretic framework—the DNB-TSP. The NB solution is applied to obtain the optimal control strategy considering a variable phasing sequence and free cycle length.

A bargaining situation is defined as a situation in which multiple players with specific objectives cooperate and benefit by reaching a mutually agreeable outcome (i.e., agreement). In bargaining theory, there are two concepts: the bargaining process and the bargaining outcome. The bargaining process is the

procedure that bargainers follow to reach an agreement (i.e., outcome) [51]. Nash adopted an axiomatic approach that abstracts the bargaining process and considers only the bargaining outcome. The bargaining problem consists of three basic elements: players, strategies, and utilities (rewards). Bargaining between two players is illustrated in the bi-matrix shown in Table 1. Each player, $P1$ and $P2$, has a set of possible actions $A1$ and $A2$, whose outcome preferences are given by the utility functions u and v , respectively, as they take relevant actions.

Table 1. Two Player Matrix Game

Player	P2		
	Action	A1	A2
P1	A1	u_1, v_1	u_2, v_2
	A2	u_3, v_3	u_4, v_4

The space S , as shown in Figure 2, is the set of all possible utilities that the two players can achieve; the vertices of the area are the utilities where each player chooses their pure strategy. The disagreement or the threat point (d_1, d_2) corresponds to the minimum utilities that the players want to achieve. The disagreement point is a benchmark, and its selection affects the bargaining solution [52]. Each player attempts to choose their disagreement point in order to maximize their bargaining position. Subsequently, a bargaining problem is defined as the pair (S, d) where $S \in \mathbb{R}^2$ and $d \in S$ such that S is a convex and compact set, and there exists some $s \in S$ such that $s \geq d$.

Nash stated the following four axioms that identify properties that the bargaining solution must satisfy:

1. **Pareto efficiency:** at the bargaining outcome, no player can improve without decreasing the other player's utility.
2. **Symmetry:** the bargaining solution would not discriminate among the players if these players were indistinguishable.
3. **Invariance to equivalent utility representation:** the bargaining outcome varies linearly if the utilities are scaled using an affine transformation.
4. **Independence of irrelevant alternatives:** if the solution to the bargaining problem lies in a subset S' of S , then the outcome does not change if bargaining is performed on S' instead of S .

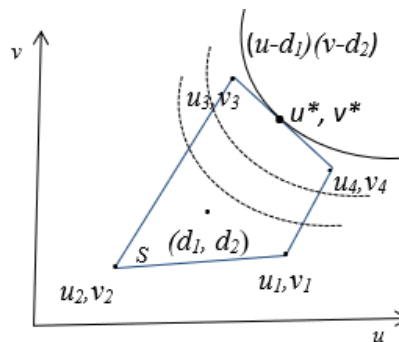


Figure 2. Utility Region

The NB solution (u^*, v^*) of this optimization problem can be calculated as the point in the bargaining set that maximizes the product of the players' utility gains relative to a fixed disagreement point.

$$\max_{u,v} (u - d_1)(v - d_2) \quad s.t. (u,v) \in S, (u,v) \geq (d_1, d_2) \quad (1)$$

The game model and the NB solution can be adapted for multiplayer (N) and applied to control a multi-phase signalized intersection, where each player represents an intersection phase [5]. In the game model, the intersection phases represent the players ($P1$ to PN) of an N players cooperation game. For each player (phase), there are two possible actions: maintain $A1$ or change $A2$. These actions represent the state of the traffic signal [4]. Specifically, maintain indicates that the state of the signal will not change (i.e., if it is green, it will remain green; if it is red, it will remain red.). Change means the state of the signal will change (i.e., if it is green, it will switch to yellow and then red; if it is red, it will become green) in the simulated time interval. The combinations of phases offer N possibilities, where only one player holds the green indication and all others hold red indications [53].

The previously developed DNB controller [3], is adapted and integrated with TSP to maximize transit vehicles' flow in real-time using high-fidelity data collected from vehicles through V2I wireless communication. V2I communication allows traffic signal controllers to dynamically respond to real-time traffic conditions to reduce the network delay and maximize traffic throughput. TSP facilitates the movement of in-service transit vehicles through traffic-signal controlled intersections, and the TSP decisions are granted locally by the intersection controller. TSP was integrated in the developed DNB controller (DNB-TSP), using vehicles' occupancy in terms of number of passengers in the vehicle (Occ), and was formulated as described below.

INTEGRATION traffic simulation software monitors vehicles occupancy, vehicle speeds, and the vehicle flow approaching the intersection, continuously updating each for every lane connected to the signalized intersection, assuming that vehicles have some form of communication to the traffic signal controller (i.e., V2I communication).

In simulations, If the vehicle (v) speed (s_v) is less than a certain threshold speed (s^{Th}) at time (t), the vehicle is assigned to the queue, and the current queue length associated with the corresponding lane (l) is updated. Once the vehicle's speed exceeds ($s^{Th} = 4.5(\text{km/h})$), the queue length is updated (i.e., shortened by the number of passengers in the vehicle leaving the queue) and formulated mathematically as

$$q_l^t = \sum_{v \in v_l^t} q_v^t \quad (2)$$

$$q_v^t = \begin{cases} Occ & \text{if } s_v^{t-1} > s^{Th} \text{ and } s_v^t \leq s^{Th} \\ -Occ & \text{if } s_v^{t-1} \leq s^{Th} \text{ and } s_v^t > s^{Th} \\ 0 & \text{if } s_v^{t-1} \leq s^{Th} \text{ and } s_v^t \leq s^{Th} \end{cases} \quad (3)$$

where q_l^t is the number of queued vehicles in lane l at time t , and Occ is the number of passengers in the vehicles.

The utilities (rewards) for each player (phase) in the game can be defined as the estimated sum of the queue lengths in each phase after applying a specific action. The estimated queue length after applying a specific action is calculated according to the following equation:

$$Q_P(t + \Delta t) = \sum_{l \in P} q_l^t + Q_{inl} \Delta t - Q_{outl} \Delta t \quad (4)$$

Where Δt is the updating time interval; q_i^t is the current queue length at time t ; $Q_p(t + \Delta t)$ is the estimated queue length after Δt for phase p ; Q_{inl} is the arrival flow rate (veh/h/lane); and Q_{outl} is the departure flow rate (veh/h/lane). The flow ratios Q_{inl} and Q_{outl} could be measured by traffic loop detectors. Q_{outl} detectors are generally located at the downstream end of the link, whereas Q_{inl} detectors are located from the downstream end of the link by distances equal to threat points over jam density. In the simulation, the INTEGRATION software monitors vehicles, assuming that they have some form of communication to the traffic signal controller (i.e., V2I communication), that includes detection of queue, vehicle direction, vehicle speeds, vehicle occupancy, and also calculates the vehicle flow approaching the intersection. These parameters are continuously updated for all approaching lanes. The threat point (d) represents the number of vehicles that could be accommodated in specific lanes.

The objective is to minimize the queue lengths (prioritizing transit vehicles through vehicle occupancy) across the different phases. We use minus queue length as the utility of each strategy. The DNB solution is extended to N players with N dimensional utility space and disagreement points. The solution for the DNB over the N phase combinations has the following formula:

$$\max_{(u_1, \dots, u_N)} \prod_{i=1}^N (u_i - d_i) \quad s. t. (u_1, \dots, u_N) \in S, (u_1, \dots, u_N) \geq (d_1, \dots, d_N) \quad (5)$$

The NB solution can be calculated as the vector that maximizes the product of the player's utility gains relative to a fixed disagreement point. The proposed DNB-TSP controller does not guarantee convergence to the optimal solution for over-saturated conditions, when queues spillback beyond the disagreement points. Consequently, for over-saturated conditions, the maximum measurable queue length was scaled not to exceed the disagreement point.

The network-wide Nash optimum solution is obtained by maintaining the Nash optimum solution at each signalized intersection [5]. As such, while the proposed NB controller is decentralized (i.e., DNB), it still produces the network-wide Nash-optimum control strategy relying solely on edge computing. The DNB-TSP controller thus provides a scalable and resilient controller that circumvents the problems inherent in complex centralized systems, while requiring minimum sacrifices in network-wide performance.

Simulation Results

In this section, the DNB-TSP solution is applied to obtain the optimal control strategy on an isolated intersection and on an arterial network, considering a variable phasing sequence and free cycle length. The system was implemented and evaluated in INTEGRATION microscopic traffic assignment and simulation software. The proposed controller was compared to the operation of an optimum fixed time plan (FP) controller, a centralized adaptive phase split (PS) controller, a decentralized phase split and cycle length (PSC) controller, and a DNB controller without TSP to evaluate the performance of the proposed DNB-TSP controller at different scenarios. To evaluate the performance of the DNB-TSP controller, each of the following was calculated: average travel time, average stopped delay, average total delay, average fuel consumption, and average CO2 emission levels.

Isolated Intersection Results

The simulations were conducted on an intersection with four approaches, comprised of three lanes each [3] as shown in Figure 3. The traffic demand origin-destination (O-D) matrix is provided in Table 2.

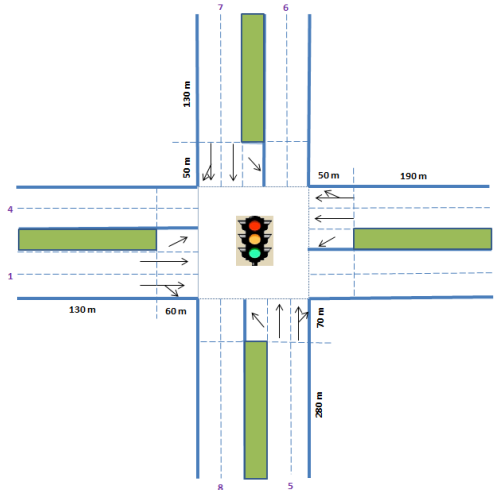


Figure 3. Testbed Intersection

Table 2. Origin Destination Demand Matrix

Zone	2	4	6	8
1	1223	-	134	121
3	-	844	86	278
5	88	71	721	-
7	188	100	-	806

The phasing scheme shown in Figure 4 represents the intersection phases, with protected, leading main street left-turn phases, where the four phases represent the four players (N = 4) in the game.

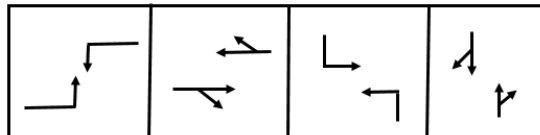


Figure 4. Phasing Scheme

The FP controller was optimized using the Webster method. The optimized effective green times for the four phases shown in Figure 4 were, 19 s, 45 s, 13 s, and 31 s, respectively. The simulations were conducted using the following parameter values: speed at capacity = 60 (km/h); free flow speed = 80 (km/h); jam density = 160 (veh/km/lane); and saturation flow rate = 1,900 (veh/h/lane). The PS and PSC controllers were optimized every 240 s. For the DNB controller, the threat points were chosen based on the number of PVs that left-turn pocket lanes could accommodate to prevent spillback into the through lane, where this number was duplicated for the right and through movements, with an update interval of 10 s. Three scenarios were conducted in order to study their effect on the performance of the DNB-TSP controller.

Scenario 1

This simulation was conducted using the following parameter values: 4,525 PVs with 1 passenger, 24 buses, bus length equivalency of 3 PVs, and mean bus occupancy of 20 passengers. In the simulation. the DNB

controller doesn't take in consideration the number of passengers ($OCC = 1$). In the 1-hour simulation, buses were scheduled for through movements every 15 minutes, and every 1 hour for the right and left turn movements for all approaches.

Table 3 shows the percent improvement in margins of error (MOEs) for different vehicle classes using the proposed DNB-TSP controller relative to the FP, PS, PSC and DNB controllers. Simulation results indicated significant improvements in various MOEs using the DNB-TSP controller. Specifically, average vehicle travel time decreased by 64.62%, average passenger travel time decreased by 65.09%, average total delay decreased by 67.48%, average stopped delay decreased by 80%, and fuel consumption decreased by 15.68% relative to the FP controller. Moreover, the results demonstrated that the DNB-TSP controller produced improvements in system performance relative to the DNB controller. Specifically, for transit vehicles, the DNB-TSP controller produced reductions in average vehicle travel time of 15.6%, average passenger travel time of 15.23%, average total delay of 23.32%, average stopped delay of 68.27%, and fuel consumption of 6.17%. The results showed that the DNB-TSP controller yielded significant improvements in the MOE values for different vehicle classes, with more improvements for transit vehicles over PVs, indicating improved system efficiency.

Table 3. DNB-TSP Improvement (%) Over FP, PS, PSC and DNB Controllers

MOEs	DNB-TSP over FP			DNB-TSP over PS			DNB-TSP over PSC			DNB-TSP over DNB		
	PV	Bus	Avg	PV	Bus	Avg	PV	Bus	Avg	PV	Bus	Avg
Vehicle stops	7.23	20.93	7.31	11.44	16.35	11.47	10.35	16.39	10.38	0.00	7.92	0.85
Vehicle Travel Time	64.60	68.73	64.62	74.02	69.03	74.00	74.06	70.60	74.05	1.76	15.60	1.85
Passenger Travel Time	64.60	68.83	65.09	74.02	68.89	73.57	74.06	70.49	73.73	1.76	15.23	3.37
Vehicle Total Delay	67.43	74.28	67.48	73.17	73.01	73.17	71.11	69.63	71.11	3.24	25.32	3.40
Vehicle Stopped Delay	80.00	93.93	80.10	83.15	92.89	83.20	82.12	92.16	82.17	6.60	68.27	6.99
Fuel	15.50	27.30	15.68	20.53	25.52	20.63	18.62	25.09	18.72	1.07	6.17	1.07
CO2	18.79	27.00	18.87	24.06	25.19	24.07	22.09	24.85	22.12	0.93	6.09	0.98

Scenario 2

This scenario examined the effect of increasing the number of passengers in transit vehicles on the performance of the proposed controller. This simulation was conducted using the following parameter values: 4,525 PVs with 1 passenger, 24 buses, bus length equivalency of 3 PVs, and mean bus occupancy of 30 passengers. In the 1-hour simulation buses were scheduled for through movements every 15 minutes, and every 1 hour for the right and left turn movements for all approaches.

Table 4 shows the percent improvement in MOEs for different vehicle classes using the proposed DNB-TSP controller relative to the FP, PS, PSC and DNB controllers. Simulation results indicated significant improvements in various MOEs using the DNB-TSP controller. Specifically, average vehicle travel time decreased by 64.7%, average passenger travel time decreased by 65.55%, average total delay decreased by 67.61%, average stopped delay decreased by 80.35%, and fuel consumption decreased by 15.68%

relative to the FP controller. Moreover, the results demonstrated that the DNB-TSP controller produced improvements in system performance relative to the DNB controller. Specifically, for transit vehicles, the DNB-TSP controller produced reductions in average vehicle travel time of 16.74%, average passenger travel time of 17.02%, average total delay of 27.16%, average stopped delay of 73.31%, and fuel consumption of 5.77%. The results showed that increasing the number of passengers in transit vehicles leads to increased MOE improvement.

Table 4. DNB-TSP Improvement (%) Over FP, PS, PSC and DNB Controllers

MOEs	DNB-TSP Over FP			DNB-TSP Over PS			DNB-TSP Over PSC			DNB-TSP Over DNB		
	PV	Bus	Avg	PV	Bus	Avg	PV	Bus	Avg	PV	Bus	Avg
Vehicle Stops	7.42	19.63	7.49	11.62	14.98	11.64	10.53	15.01	10.55	0.00	6.41	1.04
Vehicle Travel Time	64.68	69.15	64.70	74.08	69.45	74.06	74.12	71.00	74.10	1.97	16.74	2.07
Passenger Travel Time	64.68	70.12	65.55	74.08	70.30	73.61	74.12	71.82	73.82	1.97	17.02	4.38
Vehicle Total Delay	67.56	74.92	67.61	73.28	73.67	73.28	71.23	70.38	71.22	3.63	27.16	3.80
Vehicle Stopped Delay	80.25	94.89	80.35	83.36	94.02	83.41	82.34	93.40	82.40	7.76	73.31	8.18
Fuel	15.50	27.00	15.68	20.53	25.21	20.63	18.62	24.78	18.72	1.07	5.77	1.07
CO2	18.81	26.71	18.90	24.08	24.89	24.09	22.12	24.54	22.14	0.97	5.72	1.02

Scenario 3

This scenario studied the impact of applying the proposed DNB-TSP controller on side roads (north-south bounds in Figure 3, with no buses), where priority was given to main roads (east-west bounds with buses). This simulation was conducted using the following parameter values: 4,525 PVs with 1 passenger, 12 buses, bus length equivalency of 3 PVs, and mean bus occupancy of 30 passengers. In the 1-hour simulation, buses were scheduled for through movements (east-west bounds only) every 15 minutes, and every 1 hour for the right and left turn movements (east-west bounds only). Table 5 shows the percent improvement in MOEs for different vehicle classes using the proposed DNB-TSP controller relative to the FP, PS, PSC and DNB controllers. Simulation results indicated significant improvements in various MOEs using the DNB-TSP controller. Specifically, the average vehicle travel time decreased by 64.5%, the average passenger travel time decreased by 64.6%, the average total delay decreased by 69.85%, the average stopped delay decreased by 80.71%, and the fuel consumption decreased by 18.15% relative to the FP controller.

Moreover, the results demonstrated that the DNB-TSP controller produced improvements in system performance relative to the other controllers. In addition, for transit vehicles the DNB-TSP controller produced reductions in average vehicle travel time of 14.74%, average passenger travel time of 15.04%, average total delay of 24.09%, average stopped delay of 76.87%, and fuel consumption of 3% over the DNB controller, with slight impacts on PVs.

Table 5. DNB-TSP Improvement (%) Over FP, PS, PSC and DNB Controllers

MOEs	DNB-TSP over FP			DNB-TSP over PS			DNB-TSP over PSC			DNB-TSP over DNB		
	PV	Bus	Avg	PV	Bus	Avg	PV	Bus	Avg	PV	Bus	Avg
Vehicle stops	10.00	12.39	10.01	10.42	18.52	10.45	10.62	13.20	10.63	-0.36	1.04	-0.36
Vehicle Travel Time	64.50	66.03	64.50	71.87	79.77	71.90	72.58	74.35	72.58	-0.98	14.74	-0.93
Passenger Travel Time	64.50	65.76	64.59	71.87	79.80	72.64	72.58	74.43	72.72	-0.98	15.04	0.36
Vehicle Total Delay	69.84	72.23	69.85	70.64	78.77	70.67	70.74	72.90	70.75	-1.83	24.09	-1.74
Vehicle Stopped Delay	80.67	95.72	80.71	80.92	96.80	80.97	80.94	95.74	80.97	-4.12	76.87	-3.92
Fuel	18.18	23.67	18.15	18.44	31.28	18.48	18.77	24.56	18.74	-0.10	2.83	-0.20
CO2	21.53	23.44	21.54	21.99	30.99	22.04	22.25	24.32	22.26	-0.20	2.82	-0.18

Figure 5 shows the average travel time results and the standard deviations over the entire simulation time for each control system, (FP, DNB, and DNB-TSP) on side-street vehicles. In addition, Table 6 shows that the DNB-TSP controller outperforms the FP controller, with slight deterioration compared to the DNB controller. The results of integrating the TSP in the DNB controller on an isolated intersection showed an improvement in all MOEs, and that the DNB-TSP controller produced significant major improvements over other state-of-the-art centralized and decentralized controllers.

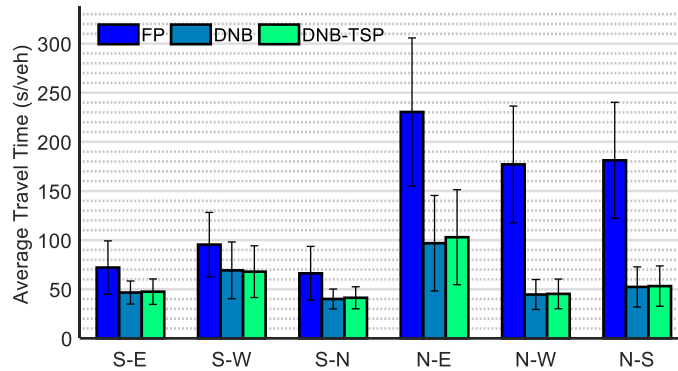


Figure 5. Average Vehicle Travel Time on Side Roads

Table 6. Average Vehicles Travel Time on Side Roads, and (%) Improvement Using DNB-TSP

	FP	DNB	DNP-TSP	DNB-TSP Imp. (%) Over FP	DNB-TSP Imp. (%) Over DNB
S-E	72.04	46.63	47.48	34.09	-1.83
S-W	95.42	69.19	67.86	28.88	1.92
S-N	66.20	40.04	41.28	37.65	-3.08

	FP	DNB	DNP-TSP	DNB-TSP Imp. (%) Over FP	DNB-TSP Imp. (%) Over DNB
N-E	230.41	96.81	102.95	55.32	-6.35
N-W	177.06	44.62	45.25	74.44	-1.43
N-S	181.21	52.31	53.18	70.65	-1.65

Arterial Network Results

The proposed controller was simulated on an arterial network located in downtown Blacksburg, VA, as shown in Figure 6. The O-D demand matrices were generated using QueensOD software, and were based on counts collected during the afternoon peak period (4–6 p.m.), at 15 minute intervals, for the year 2012 [4]. The study section includes six signalized intersections and the total distance is 0.7 miles.

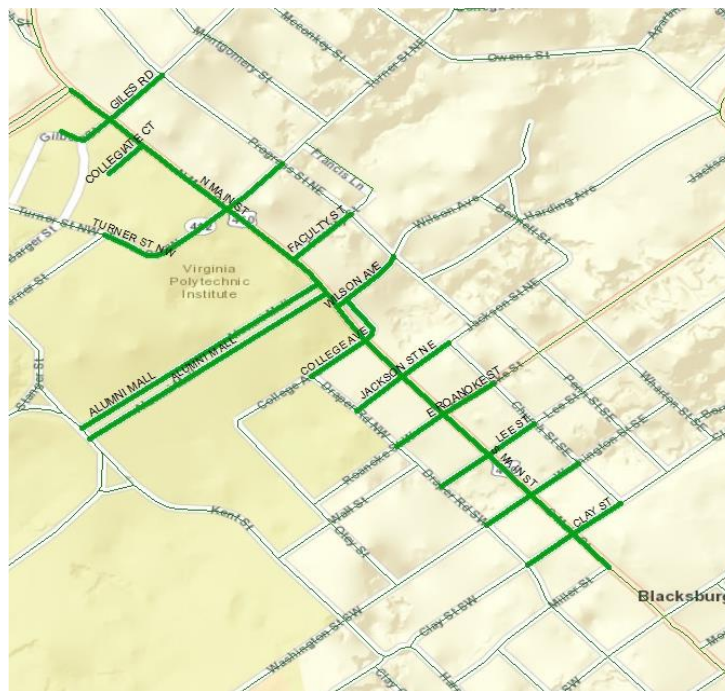


Figure 6. Downtown Blacksburg (Google Maps)

The simulations were conducted using the following parameter values: free-flow speed (40 km/h) based on the roadway speed limit, speed-at-capacity (29 km/h), jam density (160 veh/km/lane), saturation flow rate (1,800 veh/h/lane). These values were based on field measurements and typical values for arterial roadways. The FP was simulated using the observed signals' times in the field. PS and PSC were optimized every 120 s, considering a minimum cycle length of 30 s and a maximum cycle length of 120 s. The performance of the arterial network using the DNB controller was evaluated as follows: the threat points were chosen based on the number of vehicles that each phase could accommodate based on the link lengths and number of lanes, considering an updating time interval of 10 s. In the simulation, vehicles were allowed to enter the links in the first 2 hours, and the simulation ran for an extra time to guarantee that all vehicles exited the network. In the simulations, transit vehicles were simulated following Blacksburg Transit services [54] as shown in Figure 7 and Table 7. This simulation was conducted using the following parameter values: 3,036 PVs with 1 passenger, 88 buses, bus length equivalency of 3 PVs, and mean bus occupancy of 30 passengers.

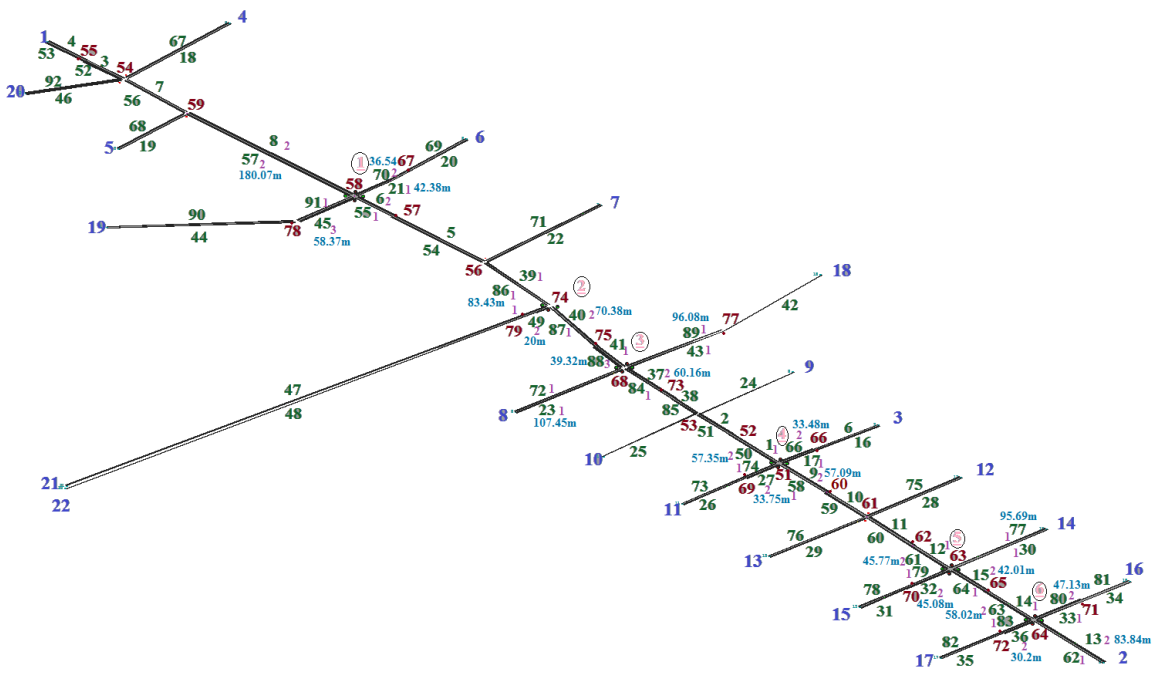


Figure 7. Downtown Blacksburg, INTEGRATION.

Table 7. Downtown Blacksburg Transit Bus Schedule

From	To	Route	Every
1	21	Patrick Henry (PHD)	15 min
1	21	Progress B (PRB)	15 min
2	21	Two Town Trolley (TTT)	60 min
1	21	Main Street South (MSS)	15 min
2	21	Main Street North (MSN)	15 min
3	21	Harding Ave. (HDG)	15 min
22	3	Harding Ave. (HDG)	15 min
22	1	Main Street North (MSN)	15 min
22	2	Main Street South (MSS)	15 min
22	2	Two Town Trolley (TTT)	60 min
22	1	Progress B (PRB)	15 min
22	1	Progress Street (PRO)	10 min

Comparing the DNB-TSP controller with DNB, the results shows an shows the percent improvement in MOEs for different vehicle classes using the proposed DNB-TSP controller relative to the FP, PS, PSC and DNB controllers. These simulation results indicate improvements in various MOEs using the DNB-TSP controller. Specifically, average vehicle travel time decreased by 6.87%, average passenger travel time decreased by 5.65%, average total delay decreased by 35%, average stopped delay decreased by 50%, and fuel consumption decreased by 6.25% relative to the PSC controller. Moreover, the results demonstrated that the DNB-TSP controller produced improvements in system performance relative to the DNB controller. Specifically, for transit vehicles, the DNB-TSP controller produced reductions in average total delay of 3.3%, average stopped delay of 14%, and fuel consumption of 1%. Comparing the DNB-TSP controller with DNB, the results shows an improvement in the MOEs for transit vehicles over PVs. Note that only slight improvements were achieved given that the downtown links of Blacksburg can accommodate only a low number of vehicles, which means that DNB controller gave an implicit priority for a bus regardless of the number of passengers, as the bus length was equivalent to 3 PVs.

Table 8. DNB-TSP Improvement (%) Over FP, PS, PSC and DNB Controllers

MOEs	DNB-TSP over FP			DNB-TSP over PS			DNB-TSP over PSC			DNB-TSP over DNB		
	PV	Bus	Avg	PV	Bus	Avg	PV	Bus	Avg	PV	Bus	Avg
Vehicle stops	0.00	13.11	14.22	5.07	3.72	5.03	23.27	16.53	23.08	0.00	-0.49	-0.82
Vehicle Travel Time	21.55	16.57	21.33	16.99	16.74	16.98	6.97	4.93	6.87	-0.15	0.37	-0.13
Passenger Travel Time	21.55	16.71	18.73	16.99	16.98	16.99	6.97	4.74	5.65	-0.15	0.41	0.18
Vehicle Total Delay	66.59	64.50	66.52	59.77	64.80	59.99	35.20	32.25	35.09	-1.12	3.28	-0.95
Vehicle Stopped Delay	82.72	88.05	82.90	78.93	88.55	79.33	49.69	60.42	50.00	-1.89	13.99	-1.46
Fuel	13.50	8.48	13.11	9.90	6.98	9.62	6.64	2.60	6.25	-0.25	0.98	-0.12
CO2	13.55	8.46	13.07	9.90	6.96	9.62	6.71	2.62	6.32	-0.16	0.99	-0.05

To evaluate the performance of the proposed controller at a higher congestion level, two simulations were conducted: one at 1.5 times the number of PVs (1.5D), and the other at 2 times the number of PVs (2D) with the same number of transit vehicles (88 buses). Table 9 shows that the DNB-TSP controller outperformed the DNB controller for different congestion levels, and shows an improvement in the MOEs for transit vehicles over PVs. In the 2D scenario, there was an improvement in the stopped delay of 19.52%, and an improvement in fuel consumption of 2.24%.

Table 9. DNB-TSP Improvement (%) Over DNB Controller at Different Congestion Levels

MOEs	DNB-TSP over DNB			DNB-TSP over DNB		
	PV (1.5 D)	Bus	Avg	PV (2 D)	Bus	Avg
Vehicle stops	0.00	0.09	-0.20	0.00	-5.83	-0.39

MOEs	DNB-TSP over DNB			DNB-TSP over DNB		
	PV (1.5 D)	Bus	Avg	PV (2 D)	Bus	Avg
Vehicle Travel Time	-0.19	0.71	-0.17	-0.13	0.64	-0.11
Passenger Travel Time	-0.19	0.77	0.29	-0.13	0.84	0.28
Vehicle Total Delay	-1.21	5.88	-1.04	-0.63	4.74	-0.54
Vehicle Stopped Delay	-2.31	17.98	-1.91	0.26	19.52	0.50
Fuel	-0.12	1.77	0.00	0.00	2.24	0.11
CO2	-0.11	1.78	0.02	-0.07	2.23	0.06

Conclusions

The study developed an advanced TSP system using cycle-free NB signal control system. The DNB-TSP solution was applied to obtain the optimal control strategy on an isolated intersection and on an arterial corridor considering a variable phasing sequence and free cycle length. The developed system was implemented and evaluated in INTEGRATION microscopic traffic assignment and simulation software. The new DNB-TSP system was compared to the operation of an optimum FP controller, a centralized adaptive PS controller, a decentralized PSC controller, and a DNB controller without TSP to evaluate the performance of the proposed DNB-TSP controller at different scenarios.

The new DNB-TSP system significantly improved various MOEs at a four-legged isolated signalized intersection. The new system improved average vehicle travel time by 64.62%, average passenger travel time by 65.09%, average total delay by 67.48%, average stopped delay by 80%, and fuel consumption by 15.68% relative to the optimized FP controller. The results also demonstrated that the DNB-TSP controller produced improvements in system performance relative to the DNB controller. Specifically, transit vehicles reduced their average vehicle travel time up to 15.6%, average passenger travel time was reduced up to 15.23%, average total delay was reduced up to 23.32%, average stopped delay was reduced up to 68.27%, and fuel consumption was reduced up to 6.17%. The study also evaluated the impacts of side-street vehicles and found that the DNB-TSP controller significantly improved side-street vehicles' travel time over the FP controller. In particular, the new TSP system reduced the travel times of side-street vehicles up to 74.4% compared to the FP controller.

The study also investigated the performance of the new DNB-TSP system at an arterial corridor. Results showed that the new system improved average vehicle travel time up to 21.33% over the FP controller, up to 16.98% versus the PS controller, and up to 6.87% over the PSC controller. The study also found that the new system reduced transit vehicle stops at intersections by up to 88.05% versus the FP controller, up to 88.55% versus the PS controller, up to 60.42% versus the PSC controller, and 13.99% versus the DNB controller.

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