University Transportation Research Center - Region 2

Final Report

Development and Evaluation of Smart Bus System

Performing Organization: New Jersey Institute of Technology (NJIT)

December 2016

Sponsor:
University Transportation Research Center - Region 2

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The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

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The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

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16. Abstract
Due to stochastic traffic conditions and fluctuated demand, transit passengers often suffer from unreliable services. Especially for buses, keeping on-time schedules is challenging as they share the right of way with non-transit traffic. With the advance of real-time interaction between passengers and operators, bus transit can be operated in a more flexible way, thereby resulting in an energy-efficient, eco-friendly, and cost-effective urban transportation mode. To improve transit system reliability under a wirelessly connected environment, this study proposes a smart bus system (SBS) enabled by two-way communication. The proposed system consists of dynamic route adjustment and smart transfer sub-systems, which can enhance bus performance via real-time operational responses not only to traffic conditions but to passenger requests. Eventually the system will encourage bus ridership, and improve the mobility and sustainability of urban transportation. The proof-of-concept simulation test is conducted in New York City SoHo area. The performance of SBS is evaluated against on-time performance, passenger travel time among others, based on predefined scenarios dealing with various factors likely affecting the effectiveness

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Abstract

Due to stochastic traffic conditions and fluctuated demand, transit passengers often suffer from unreliable services. Especially for buses, keeping on-time schedules is challenging as they share the right of way with non-transit traffic. With the advance of real-time interaction between passengers and operators, bus transit can be operated in a more flexible way, thereby resulting in an energy-efficient, eco-friendly, and cost-effective urban transportation mode. To improve transit system reliability under a wirelessly connected environment, this study proposes a smart bus system (SBS) enabled by two-way communication. The proposed system consists of dynamic route adjustment and smart transfer sub-systems, which can enhance bus performance via real-time operational responses not only to traffic conditions but to passenger requests. Eventually the system will encourage bus ridership, and improve the mobility and sustainability of urban transportation. The proof-of-concept simulation test is conducted in New York City SoHo area. The performance of SBS is evaluated against on-time performance, passenger travel time among others, based on predefined scenarios dealing with various factors likely affecting the effectiveness.

1 Introduction

1.1 Background

Public transit faces the challenge of being unreliable and underutilized. Unreliable service has great negative impacts on both passengers and operators. For passengers, extra time needs to be added in their trip planning to account for possible delays and ensure on-time arrival due to travel time variation (1). For operators, a certain amount of recovery time built into the schedules is necessary to absorb the variation of vehicle travel time, resulting in longer round-trip travel time and increased fleet size requirement.

However, conventional surface transit systems (e.g., buses), sharing the right-of-way with other vehicles, inevitably suffer from service irregularity. The bus arrival/departure time deviating from a posted schedule is often unavoidable because of various factors, such as temporal and spatial boarding/alighting demand fluctuation, traffic conditions, and irregular departure headways at the terminals/upstream stops. Especially under congested traffic conditions, it is difficult for buses to return to the driving lane after picking-up/dropping-off passengers at stops, leading to longer dwell time. Despite numerous efforts intended to improve the service quality of bus operation, such as bus signal priority and exclusive bus lane, no notable improvements that made dramatically increases in the bus ridership have been demonstrated.

One of the fundamental reasons why traditional bus operation still relies on predefined schedule and route is because no real-time information between passengers and bus operators (e.g., transit management center) are exchanged. For example, in case no boarding and alighting passengers are identified at an upcoming bus stop and the bus is behind the schedule, the bus operator would be able to skip the stop and even adjust its route. By allowing such real-time information exchange, bus operation can be more flexible, thereby resulting in an energy efficient, eco-friendly, and cost-effective urban transportation mode.

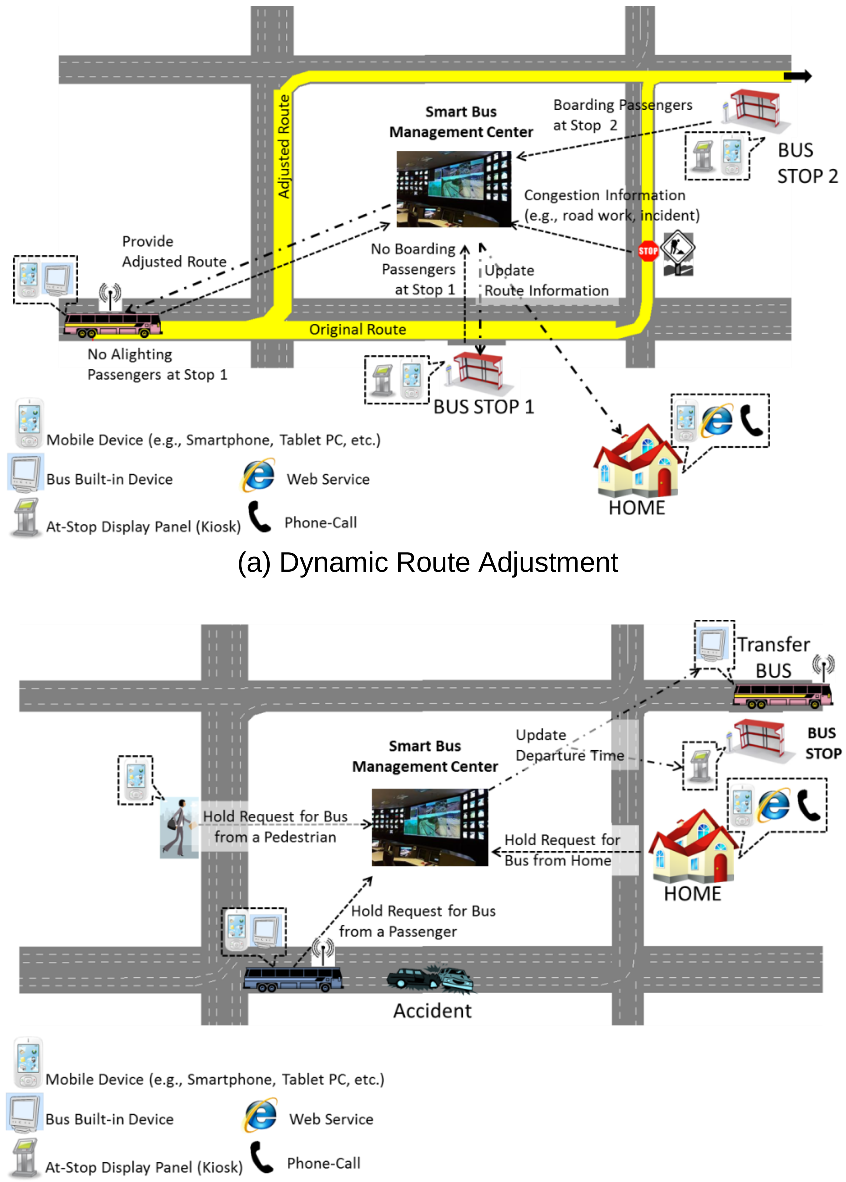
With the advancement of information and communication technologies (ICT), real-time interactions between passengers and bus operators have become easier than ever before. Particularly in recent, mobile wireless communications technologies, such as 3G, 4G/LTE, Wi-Fi, Bluetooth, have been widely spread with the rapid growth of the users of mobile wireless smart devices such as Smartphone and Tablet PC. Such smart devices enable users to access real-time information, such as traffic congestion, work zone, incident, or weather, which likely affect their decision making for travel. Obviously, under such a wirelessly connected environment, two-way communications between the bus operator and passengers are certainly possible to exchange their information on the go.

In this study, an evolutionary state-of-the-art bus operation system, namely Smart Bus System (SBS), is presented along with simulation-based evaluation results. SBS is envisioned to make bus service more flexible, energy-efficient, cost-effective and yet user-orientated. Enabled by two-way communication, SBS improves transit system reliability by the integration of a centralized bus operation system as well as a user-orientated mobile application. To increase the degree of realism and hardware complexity, a state-of-the-art hardware-in-the-loop approach for system evaluation is adopted. In this study, a microscopic simulation test bed written with VISSIM COM interface is developed, which comprises of: 1) a microscopic simulation network to mimic general traffic and bus operations; 2) a mobile application for information dissemination and reception; and 3) a virtual bus manager center for online database housing and real-time bus operational decision making.

The remainder of the study is organized as follows. In the next section, an introduction of SBS is provided with a high-level architecture for each sub-system. Relevant research efforts on bus service reliability improvement and real-time bus control is presented in the section of Literature Review. The evaluation framework to conduct the simulation-based proof-of-concept test for the smart bus system is explained in the next section, followed by Case Study to address the evaluation results. The summary of findings and further research is discussed in the last section.

2 Concept of Smart Bus System

The smart bus system is a centralized bus operation system integrating Information Technology (IT) and wireless communications environment, which consists of two major sub-system components (Figure 1): Dynamic Route Adjustment (DRA) and Smart Transfer (ST).



(a) Dynamic Route Adjustment

(b) Smart Transfer

Figure 1: Conceptual Illustration of the Smart Bus System

In the DRA system, passengers who are accessible to mobile wireless communications devices are able to share their boarding, alighting, and transferring plans. Based on real-time traffic information such as congestion, incident, and work-zone provided from a local traffic management center, the

DRA system determines the best route for the most efficient bus operation. That is, as long as no passengers who would board from and alight to bus stops located on its routes are identified and the route is under heavy congestion, the DRA system attempts to reroute to avoid the congestion.

Given the ST system, passengers are able to request holds for the next bus to make safe connection if the additional waiting time caused by the request is acceptable. Passengers send their hold requests for the next bus to the ST system through personal mobile device. The ST system gathers all the requests and estimates additional waiting time required for the safe connections. Finally, all the request messages delivered from each sub-system application are processed in a smart bus management center to find the most optimal bus operation status.

Aforementioned, the proposed smart bus system consists of the two sub-systems explained above. While each sub-system is designed to solely work as an independent application, this study focuses more on the integration of the sub-systems to leverage the synergy effects of the smart bus system.

3 Literature Review

A wide variety of innovations to improve the efficiency of bus operation have been proposed in the state-of-the arts and practice for the past decades. In this section, several highlighted research efforts with respect to the dynamic route adjustment and smart transfer applications are examined.

3.1 Route Adjustment

Route adjustment has been explored by several researchers through the application of stop-skip strategies (2-6). Stop-skip is one of transit operation techniques allowing transit vehicles to bypass a set of stops or stations along a route to improve the service quality. Particularly for the bus operation, stops to be bypassed are determined based on passenger demands. In that sense, the dynamic route adjustment application is an enhanced version of the skip-stop technique. Lin et al. (2) and Eberlein (3) proposed an optimization-based framework to design optimal bus stop-skip operation to minimize total bus travel time (2) and passenger waiting time (2-3). Fu and Liu (4) proposed a stop-skip operation strategy by minimizing costs for both bus operator and passengers by using a nonlinear binary integer programming approach. Liu and Yan (5) also proposed a nonlinear integer programing approach handling the total costs for both passengers and bus operators. To obtain the total cost, in-vehicle travel time and waiting time at stops are integrated to calculate the passenger cost while the total bus operating cost is estimated by total bus travel time.

Unlike (2-5), Sun and Hickman (6) investigated dynamic stop-skip problems that are suitable for real-time skip-stop operation. By taking into consideration the wide variety of passengers' boarding and alighting activities for each stop, the authors proposed a non-linear stochastic optimization framework to determine bypassing stops that can minimize the total travel time for both bus and passenger. Various bus controlling strategies have been applied in the previous studies for better transit performance, where simulation approaches are often applied to investigate the effectiveness of headway-based control strategies. Fu and Yang (7) simulated the scenarios of one-stop control, two-stop control, and all-stop control with predefined control points, where selected performance measures were examined (i.e., user waiting and in-vehicle time, and bus travel time). Hadas and Ceder (8) proposed an innovative public transit system enabling flexible route adjustment, namely Multi-Agent Transportation System (MATS). Comprising four major agents influencing passengers, road segment, vehicles, and transit operators, MATS enables transit operators to adjust the routes in response to transit demand.

3.2 Smart Transfer

The concept of smart transfer has been proposed by the Connection Protection (CP) application in the Dynamic Mobility Application (DMA) (9). While it is not exactly same as CP, timed transfer is one of bus operation strategy enabling smart transfer (10-14). By optimizing arrival schedules for transit vehicles at a transfer station, the timed transfer approach achieved the minimization of passenger waiting times.

Abkowitz et al. (10) examined the effectiveness of timed transfer technique through a Monte Carlo simulation method. They demonstrated the promising performance of optimized timed transfer techniques by examining two traditional transfer strategies: 1) unscheduled transfer; and 2) unscheduled transfer with a slack time. Despite the promising performance, Chung and Shalaby (11), and Ting and Schonfeld (12) addressed the deficiency of timed transfer techniques caused by the unpredictability of traffic congestion, particularly for the operation of bus which shares their right-of-way with other vehicles. To overcome this, Dessouky et al. (13) proposed a method incorporating the variability of slack time into the optimization problem for the scheduling of optimal timed transfer. The case study results showed that timed transfer with slack time achieved minimizing the total cost for both passengers and bus operators. In addition, Hadas and Ceder (14) developed a dynamic programming based approach to improve bus transfer operations to minimize unnecessary transfer waiting time in case of connecting buss being late.

With rapid advancement of Intelligent Transportation System (ITS), Hall and Dessouky (13) evaluated a dynamic timed transfer by using bus position tracking technology. Hall et al. (15) reviewed several ITS technologies that can be used for timed transfer and evaluated dispatching rules with and without ITS. Dessouky et al. (16) examined the effectiveness of real-time transfer schedule control by employing wireless communication, automated vehicle location, and in-vehicle passenger counting sensor.

For transit operator, cost is the most crucial factor for the quality of transit service. Guo and Wilson (17) assessed transfer cost considering both operator and passenger to examine the most proper ways to reduce the costs. Similar to (17), Chowdhury and Chien (18) aimed to minimize the total cost by optimizing the departure times of buses and revealed that the transfer cost is not the only indicator to evaluate transfer strategy. Hall et al. (19) proposed an optimization framework of which objective function is transfer time to seek an optimal holding time to minimize transfer delay with the consideration of both through and transfer passengers. Bookbinder et al. (20) developed a methodology focusing optimizing transfers in a transit network by employing *transfer inconvenience* for the objective function to indicate the discomfort of transfer. Daganzo (21) proposed a headway-based approach to eliminate bus bunching, where an adaptive control scheme was developed.

4 Evaluation Approach

This study proposes a hardware-in-the-loop simulation (HILS)-based evaluation approach. HILS is an advanced simulation method integrating hardware and a simulation model that is commonly used in the fields of mechanics, electrical engineering, and plant designs. In the HILS environment, the actual application of each sub-system working on a physical mobile device will be tested as if it is being operated under the actual transportation network. The entire system consists of three major components, namely a virtual management center nesting the aforementioned two modules and an online database storing bus and passenger information, a mobile application for passenger use, and a simulation network mimicking bus operations in a connected vehicle environment. Figure 2 shows the conceptual illustration of the proposed HILS approach.

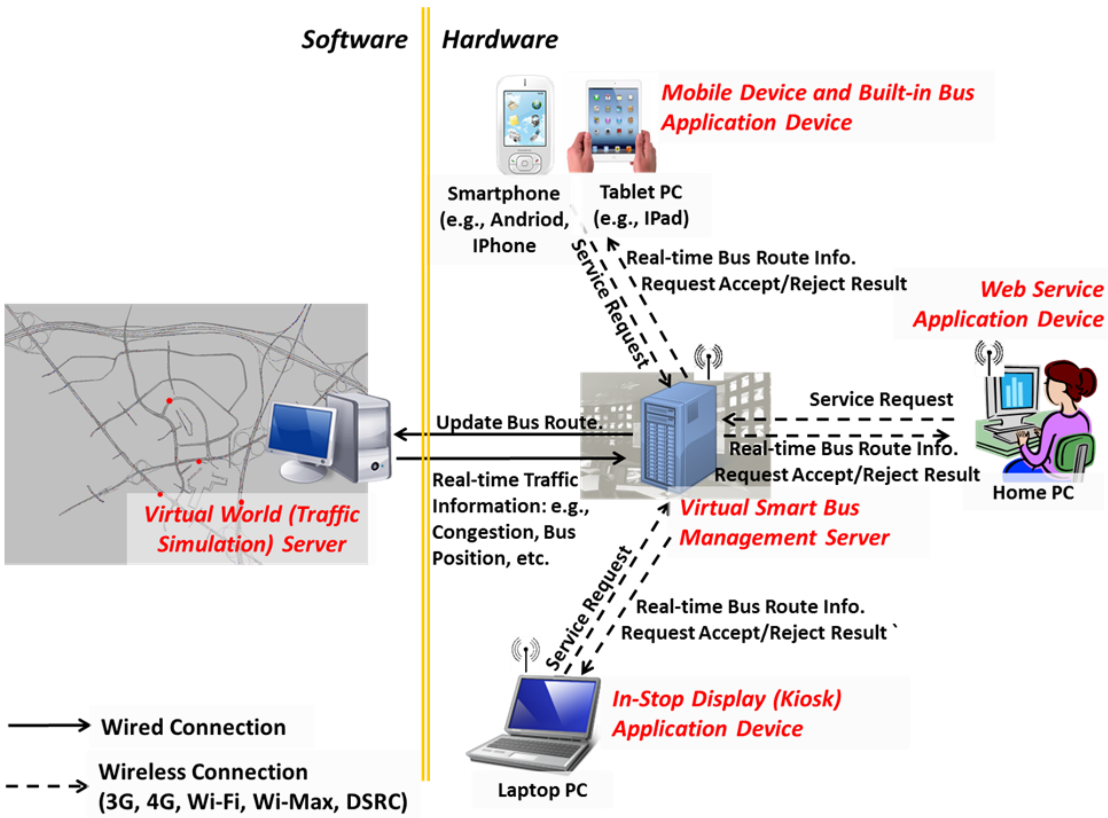


Figure 2: HILS-based Evaluation Framework

The smart bus system architecture is illustrated in Figure 3, consisting of four components: a virtual management center, an online database, a mobile application, and a VISSIM-based simulation network. First, as shown in Figure 3, the simulation network is stored and simulation computation is handler in the VISSIM layer. Second, the server (i.e., virtual management center) consists of smart transfer and dynamic routing modules to evaluate bus operations and make operational decisions based on the information retrieved from the database. Third, passengers' activities are sent to the database through mobile applications, including origin-destination information and holding requests. Meanwhile, real-time bus operating information (e.g., estimated arrival time, possible delay and detour) is received from the server. Finally, the database stores offline bus route and schedule information, as well as real-time passenger and traffic information. It connects the simulation network, the server, and the mobile application, and enables such two-way communication between passengers and buses.

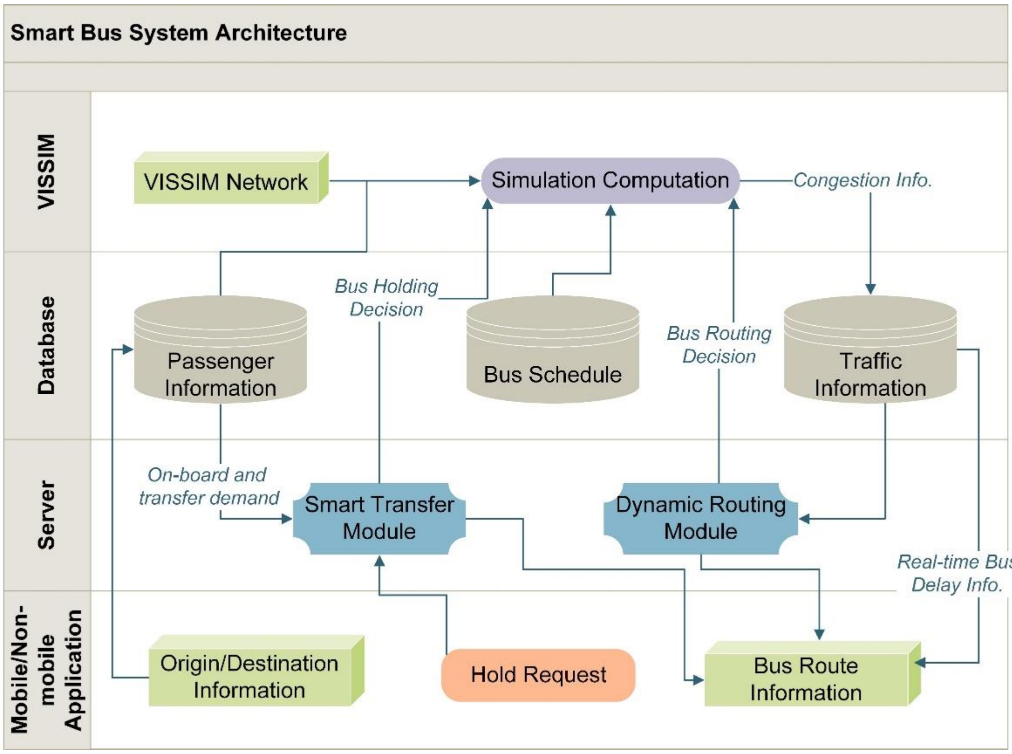


Figure 3: Smart Bus System Architecture

The step procedure and data flow of the evaluation approach is simplified in Figure 4. The system starts with checking schedules and adding a bus into the simulation network, while passengers boarding/alighting information for the dispatched bus is gathered (i.e., sent from mobile applications by users). At each stop, the system will check whether it is a transfer stop, and if any hold requests exist at the transfer stop. If there is a hold request, the smart transfer module will be triggered and a hold decision will be sent to bus and passengers sending the request. As the system runs, the management center keeps monitoring the entire network and receives real-time traffic information collected from connected vehicles. In case there is a congestion that possibly lead to a delay in bus arrival time, the center will check all the possible alternate paths for bus re-routing decision. As a result, bus route adjustment warning will also be sent to the mobile app for passenger information updates.
To summarize system inputs and outputs, the whole system receives the following inputs:

1) Street network information;
2) Bus route and schedule information;
3) Real-time traffic information collected from the simulated network;
4) Passengers' activities including boarding/alighting decisions and holding requests collected from connected mobile applications.

On the other hand, the system makes route adjustment advisory and bus holding commands for real-time bus operations, and stores bus trajectory and stop records for post-analysis of system performance.

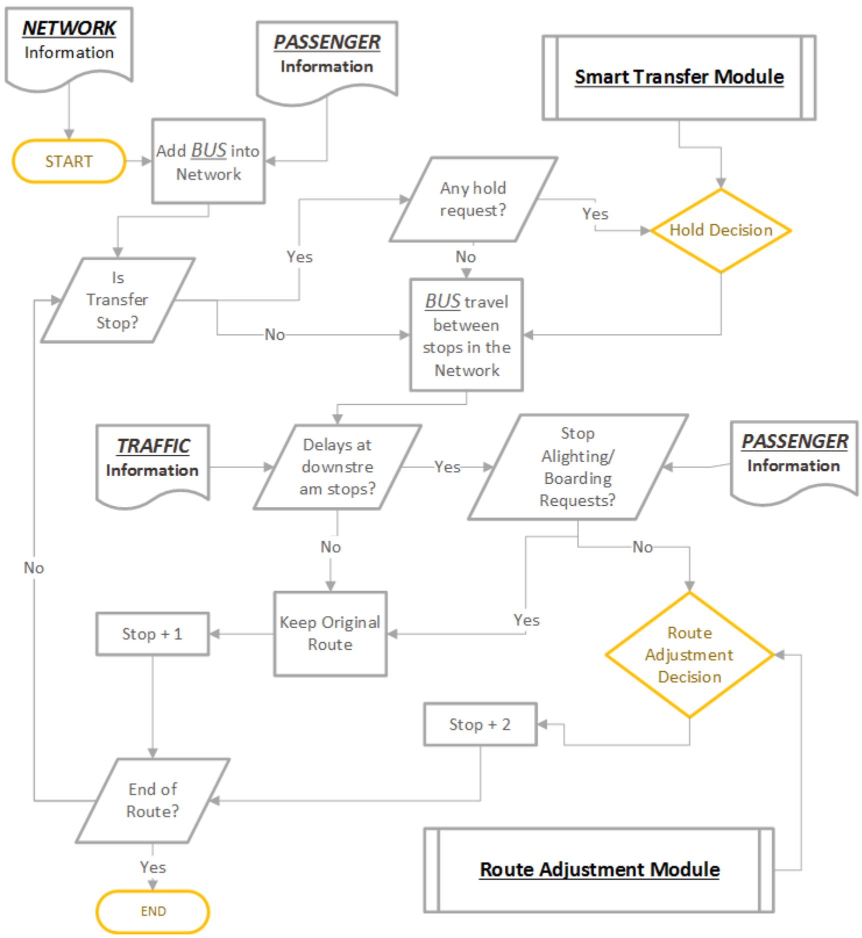


Figure 4: High-level Evaluation Framework for the Smart Bus System

Represented in Figure 5 are the screenshots for the mobile application where passengers holding a mobile application could send travel information and hold requests to the management center, and receive bus re-routing information in real-time. In the left panel is an input window, where a passenger could select his/her origin and destination stops. Once such information is received by the management center, the estimated arrival time for all the involved routes will be displayed in the screen, as shown in the middle part of the screenshot in the middle of Figure 5Figure 6. If a passenger would like to send a bus hold request at a transfer stop, a pop-up window confirms the decision and sends the request to the management center. Immediately, the center will investigate the request by evaluating total waiting time for the passenger involved in the transfer of request.

Figure 6 visualizes an integrated system that realizes these two major functions. If the incident causes delay, the coming bus will search for possible detour route, while at the same time, the hold request for the connecting bus could be sent for evaluation. Consequently, the smart bus system provides a good chance of schedule adherence and transfer success.

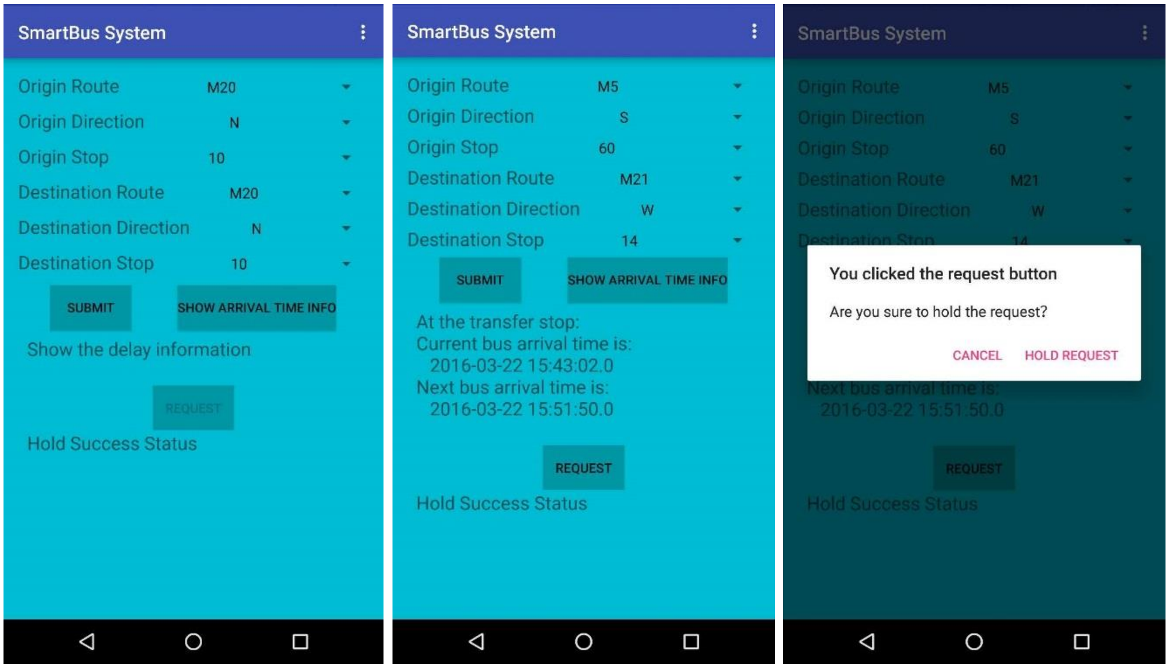


Figure 5: Smart Transfer Mobile App (Left: Main Screen; Middle: Bus Information; Right: Hold Request and Confirm)

Figure 6: Sample of the Integrated Smart Transfer and Dynamic Route Adjustment

5 Case Study

In this section, the test site is described, along with the simulation settings. Then, the simulation results are analyzed.

5.1 Simulation Test Bed

The test site is selected in New York City downtown area, where three bus routes are connected to each other (i.e., M20, M21, and M5). Due to traffic congestion condition, buses often concur delay in this area. General Transit Feed Specification (GTFS) data collected from Metropolitan Transportation Authority (MTA) is used to define bus routes, stops, and schedule information in the simulation network. Shown in Figure 7 is the configuration of study area, more than 40 intersections are present within the study boundary, and more than 25 stops are considered for test purpose.

The simulation network is created in the PTV VISSIM environment (Figure 8). According to New York City Department of Transportation (NYCDOT), several Annual Average Daily Traffic (AADT) stations exist in this area. Due to data limitation, traffic inputs are assumed and traffic signals are optimized with PTV VISTRO (22), where intersections on W Houston Street, Houston Street, and Avenue of the America are treated as coordinated. For simulation, 98% passenger cars and 2% heavy vehicles are presented in the network, and a speed limit of 25mph is adopted.

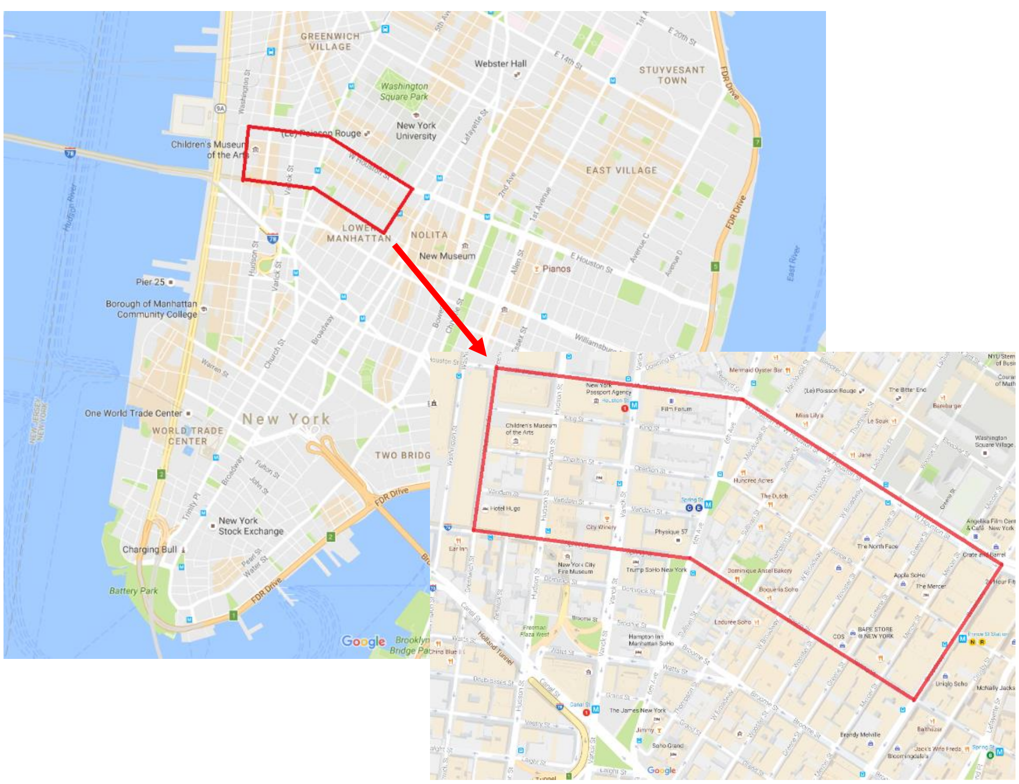


Figure 7: Study Area

Figure 8: Simulated Network in VISSIM Environment

5.2 Scenario Settings

The scenario settings under full market penetration rate are listed in Table 1 and explained below. For analysis, the afternoon peak period (16:30-17:30) is selected. 2-hour total simulation period (16:00-18:00) is set, including first half hour for warming up and last half hour for clearance. The algorithm applied for bus holding is to minimize total passenger waiting time involved at the transfer stop to be analyzed. A-star algorithm (23) is applied for finding the shortest path when necessary. The criteria to trigger the smart transfer and dynamic routing modules are:

1. Criterion for searching for bus detour route is that the estimated arrival delay exceeds pre-defined value. The route with estimated shortest travel time will be selected for detour.
2. Transfer request will be evaluated based on the total waiting time of the passengers involved in the transfer station for the request bus.

To test the transfer module, three transfer proportions are analyzed for each demand level, namely none transfers, one third, and two thirds of the total demand. Similarly, to test the route adjustment module, two artificial accidents are created in the network (represented by dotted red line in Figure 6, where all the vehicles are restricting to traverse at a very low speed (an average of 5 mph). Two bus routes (M20, M5) are directly influenced by the accidents, leading to possibly missing transfers to the other route (M21).

To investigate the effectiveness of the system under recurrent and non-recurrent congestion conditions, the scenarios completed in this quarter are listed below:

- ***Demand Level:*** Within the study area, two demand levels at 150 passenger/hr and 300 passenger/hr are assumed for analysis. The demand is randomly generated and distributed in the network within 1-hour period, and all of them are committed to using the application for sending and receiving necessary information.

    1. Base demand
    2. 100% increase of base demand

- ***Transfer Level:*** Three transfer levels are analyzed per demand level so that the differences between controlled (i.e., the proposed system) and uncontrolled bus operations (i.e., do-nothing case) can be analyzed to investigate the effectiveness of proposed smart transfer module.

    1. Zero
    2. One third of total demand
    3. Two thirds of total demand

- ***Traffic Level:*** According to VISTRO optimization results, no traffic congestion is presented in the network under base traffic level. In order to examine the system performance under recurrent congestion, two additional traffic levels are created as listed below:

    1. Base traffic volume
    2. 20% increase of base traffic volume
    3. 40% increase of base traffic volume

- ***Traffic Incident:*** Artificial incidents are created in order to test system response to non-recurrent congestion. In the simulation network, a 1-hour work area is assumed where the maximum travel speed is limited to 5 mph. Two incident locations are listed as below:

    1. Charlton St-Hudson St to King St-Hudson St, Total Length: 190ft
    2. E Houston St-Broadway to Prince St-Broadway, Total length: 310ft

- ***Market Penetration Rate (MPR):*** Market penetration rate is defined as percentage of passengers who uses the system for route and transfer management. For all the above mentioned scenarios, the system performance will be evaluated against different levels of MPR.

    1. 100% MPR
    2. 50% MPR
    3. 25% MPR

Table 1: Scenario Settings

Scenario	Group	Controlled Case No.	Uncontrolled Case No.	Demand (pass/hr)	Traffic Multiplier	Transfers (pass/hr)	Accident
1 (Base)	1	1	1001	150	1	0	No
2		2	1002	150	1	50	No
3		3	1003	150	1	100	No
4	2	4	1004	150	1.2	0	No
5		5	1005	150	1.2	50	No
6		6	1006	150	1.2	100	No
7	3	7	1007	150	1.4	0	No
8		8	1008	150	1.4	50	No
9		9	1009	150	1.4	100	No
10	4	10	1010	150	1	0	Yes
11		11	1011	150	1	50	Yes
12		12	1012	150	1	100	Yes
13	5	13	1013	300	1	0	No
14		14	1014	300	1	100	No
15		15	1015	300	1	200	No
16	6	16	1016	300	1	0	Yes
17		17	1017	300	1	100	Yes
18		18	1018	300	1	200	Yes

5.3 Result Analysis

The major objective of the proposed system is to enhance bus service performance, especially from users' point of view. Therefore, the average waiting time and average passenger travel time for all the demand in the network are selected as the primary performance measures. Additionally, to represent bus operational performance, headway adherence is also analyzed. According to Transit Capacity and Quality of Service Manual published in 2003 by Transit Cooperative Research Program (TCRP), the bus system level of service can be related to headway adherence. The manual defines six categories of LOS, each corresponding to a headway coefficient of variation (C_{vh}) bin, as shown in Table 2. Headway coefficient of variation is defined as the ratio of standard deviation of headway and average headway, as an index of relative headway adherence. Therefore, through investigating the headway adherence, system performance can be revealed.

Table 2 Level of Service vs. Headway Adherence

LOS	c_{vh}	Passenger and Operator Perspective
A	0.00 - 0.21	Service provided like clockwork
B	0.22 - 0.30	Vehicles slightly off headway
C	0.31 - 0.39	Vehicles often off headway

D	0.40 - 0.52	Irregular headways, with some bunching
E	0.53 - 0.74	Frequent bunching
F	≥ 0.75	Most vehicles bunched

Source: Transit Capacity and Quality of Service Manual (Kittelson & Associates, 2003)

For each scenario listed in Table 1 under each market penetration rate, the proposed SBS (i.e., with bus controls) and bus operations without controls are compared based on the selected performance measures. In addition, it must be noted that multiple simulation replications for the controlled and uncontrolled scenarios are conducted in the same computer. For all of the three routes, the average headway during the simulation period is 15 minutes. The simulation starts from 16:00 to 18:00 in order to include a 30-minute warming up and a 30-minute clearance period. Passenger arrival times are randomly generated between 16:30 and 17:30. Approximately 20 buses are dispatched for all three bus routes. Individual bus trajectory data are collected every 5 seconds for data analysis.

Since the simulation network covers many upstream and downstream stops without detailed street and intersection information, only those stops fall into the study boundary are selected for analysis of headways. Full records from all the passengers with mobile access to the system, regardless of boarding stops, are retrieved to estimate average waiting time and travel time.

5.3.1 Full MPR

In this section, the system performance under controlled and uncontrolled operations are compared under 100% market penetration rate, that all passengers have access and agree to use mobile applications reporting their boarding/alighting information and holding requests to the bus management center. A total of 36 scenarios is analyzed covering both controlled and uncontrolled situations. The results are organized per group and summarized below.

5.3.1.1 Scenario Group 1 – Base Condition

As indicated in Table 3, Scenario group 1 comprises three scenarios (i.e., Scenarios 1, 2, and 3), featuring base demand level, base traffic level, and no traffic incidents presented in the network. The only difference among the three scenarios within Group 1 is the transfer level, varying from zero transfers under Scenario 1 to two thirds of the total demand under Scenario 3.

Table 3: Scenario Group 1

Scenario	Group	Controlled Case No.	Uncontrolled Case No.	Demand (pass/hr)	Traffic Multiplier	Transfers (pass/hr)	Accident
1 (Base)	1	1	1001	150	1	0	No
2		2	1002	150	1	50	No
3		3	1003	150	1	100	No

Base Scenario

Scenario 1 is marked as base scenario, as base demand without transfers and base traffic level without accidents are considered. It represents bus operations under light traffic and light demand condition. To analyze headway adherence for both controlled and uncontrolled bus operations, the scheduled headways are extracted from the database for reference.

Overall, the scheduled headways for different routes during different time periods vary, according to the summarized bus schedule data (Table 4). Take M20 Northbound for instance, the average headway between 16:00 and 17:00 is 9 minutes, while the average is 15 minutes between 17:00 and 18:00.

Table 4: Scheduled Headways

Route/Direction	4 PM	5 PM	Average
M20			
N	9	15	12
M21			
E	10	20	15
W	12	20	16
M5			
N	8	9	9
S	7	12	10

Table 5 contains the comparison of controlled and uncontrolled bus operations in terms of headway, including mean, standard deviation (SD), and C_{vh}. To analyze the results, records with headways below 90th percentile are selected so that extreme values (e.g., noises due to various reasons such as detector malfunction) may not be included in the analysis for both controlled and uncontrolled cases. It should be noted that the traffic signal timing was optimized to ensure that with base traffic demand, no congestion would be present in the network. Therefore, the headway coefficient of variation is already small enough under uncontrolled operations, reflecting a LOS A for the entire system. No significant difference is found between two systems in terms of C_{vh}, except that the standard deviations of headways under controlled operations are slightly reduced.

Table 5: Headway Analysis for Base Scenario

Route	Uncontrolled			Controlled			Scheduled
	Mean	SD	C_{vh}	Mean	SD	C_{vh}	Mean
M20	14.5	1.14	0.08	14.4	1.12	0.08	14.5
M21	20.0	0.25	0.01	20.0	0.16	0.01	20.0
M5	10.9	1.24	0.11	10.9	1.22	0.11	10.9

The average passenger waiting time at the origin stops and total traveling time are computed for comparison (as shown in Table 6). In general, the proposed system reduces average waiting time especially for routes M20 and M21. Demand fluctuation and different number of stops served among routes may have an influence on the waiting time reduction magnitude. Under Scenario 1, no transfer demand is presented in the network. Therefore, the traveling time is equal to waiting time plus in-vehicle time, where in-vehicle time may be affected by passenger boarding/alighting activities at the intermediate stops. Hence, fluctuations may be expected among different routes due to randomly generated passenger origin-destination matrix.

Table 6: Passenger Waiting and Travel Time Analysis for Base Scenario

Route	Waiting Time (min)		Traveling Time (min)	
	Uncontrolled	Controlled	Uncontrolled	Controlled
M20	8.1	6.3	16.2	14.2
M21	10.1	8.6	22.5	22.6
M5	5.5	5.1	19.1	18.6

Scenario Analysis within Group 1

Overall, the results for base scenario analysis reveals a positive effect of the proposed system for the study network. Following that, the headway adherence and passenger travel time for all scenarios within scenario group 1 are investigated. Represented in Table 7 is headway analysis for all scenarios on a route basis. For both operations, the standard deviation of headways tends to be increased when transfer demand is higher, while with controlled operations, the magnitude of such increase is smaller. The reduction of SD is most significant for M21, especially for medium transfer levels (i.e., Scenario 2). Therefore, the results show that the proposed system generally works better across transfer levels in terms of headway variation control, and provides more stable bus operations when transfer demand changes.

Table 7: Headway Analysis for Scenario Group 1

Scenario	Route	Uncontrolled			Controlled		
		Mean	SD	CV	Mean	SD	CV
Scenario 1	M20	14.5	1.14	0.08	14.4	1.12	0.08
	M21	20.0	0.25	0.01	20.0	0.16	0.01
	M5	10.9	1.24	0.11	10.9	1.22	0.11
Scenario 2	M20	14.5	1.11	0.08	14.5	1.12	0.08
	M21	20.0	0.40	0.02	19.9	0.28	0.01
	M5	10.9	1.28	0.12	10.9	1.23	0.11
Scenario 3	M20	14.5	1.13	0.08	14.5	1.10	0.08
	M21	20.0	0.33	0.02	19.9	0.33	0.02
	M5	10.9	1.34	0.12	10.9	1.31	0.12

The average passenger waiting time under each scenario is shown in Figure 9. The average traveling time is also computed, but no substantial difference is observed between two operational strategies (Figure 10). Although the travelling time increases when the transfer demand increases due to additional waiting time at transfer stops, the waiting time tends to keep constant among scenarios.

Since three different routes are considered in the study and each of them travels through different parts of the study area, it is not straightforward to illustrate the effectiveness of bus controlling through analyzing the overall average traveling time. Many factors, including unbalanced traffic among streets and unbalanced bus demand among routes/stop pairs, could affect the resulted average traveling time. Therefore, to make clear and reasonable comparison among scenarios and scenario groups, the following sections only include average waiting time for analysis.

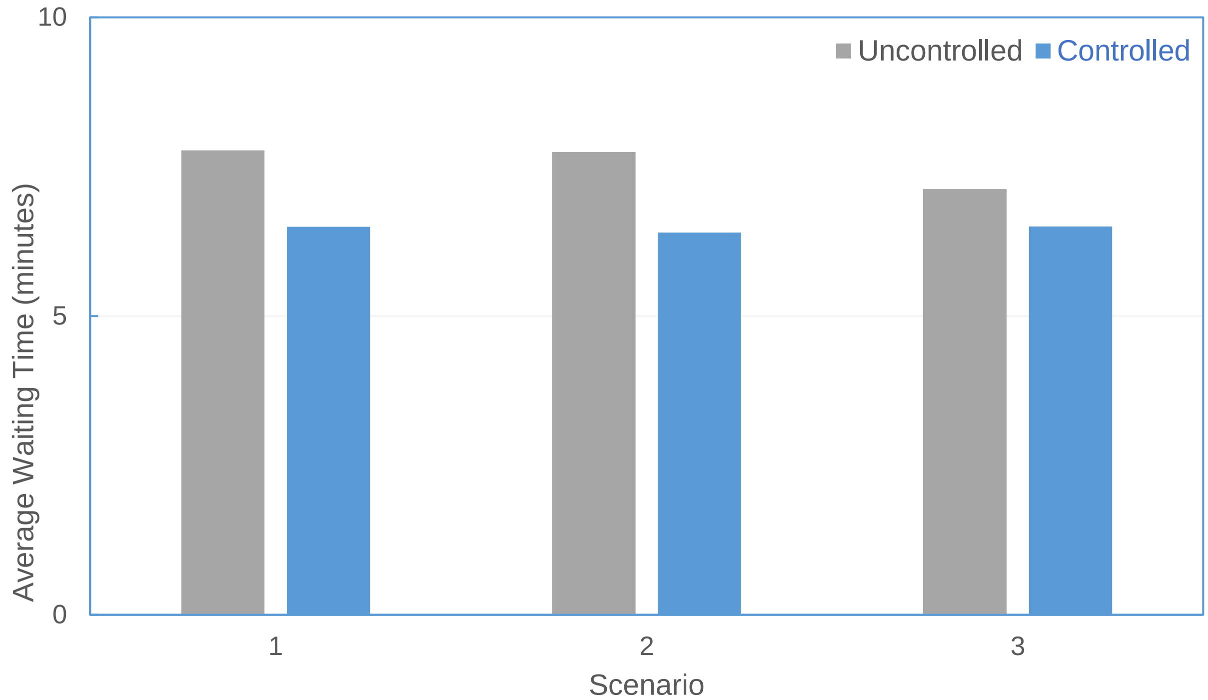


Figure 9: Comparison of Average Waiting Time for Scenario Group 1

A paired-samples t-test is conducted to compare waiting time between controlled and uncontrolled operations under each scenario in scenario group 1. With null hypothesis set as no significant difference between mean values in time, the statistics are summarized in Table 8. Significant differences in mean value of waiting time between two operating conditions are observed (with p-value smaller than or equal to 0.01), for all scenarios in Scenario Group 1. It is noted that when the transfer level increases, the difference between uncontrolled and controlled operations tends to be decreased. Although Table 5 tells that the SD for each individual route is small, the overall SD under each scenario shown in Table 8 is much higher – the reason behind may be that large difference in headways exists among bus routes.

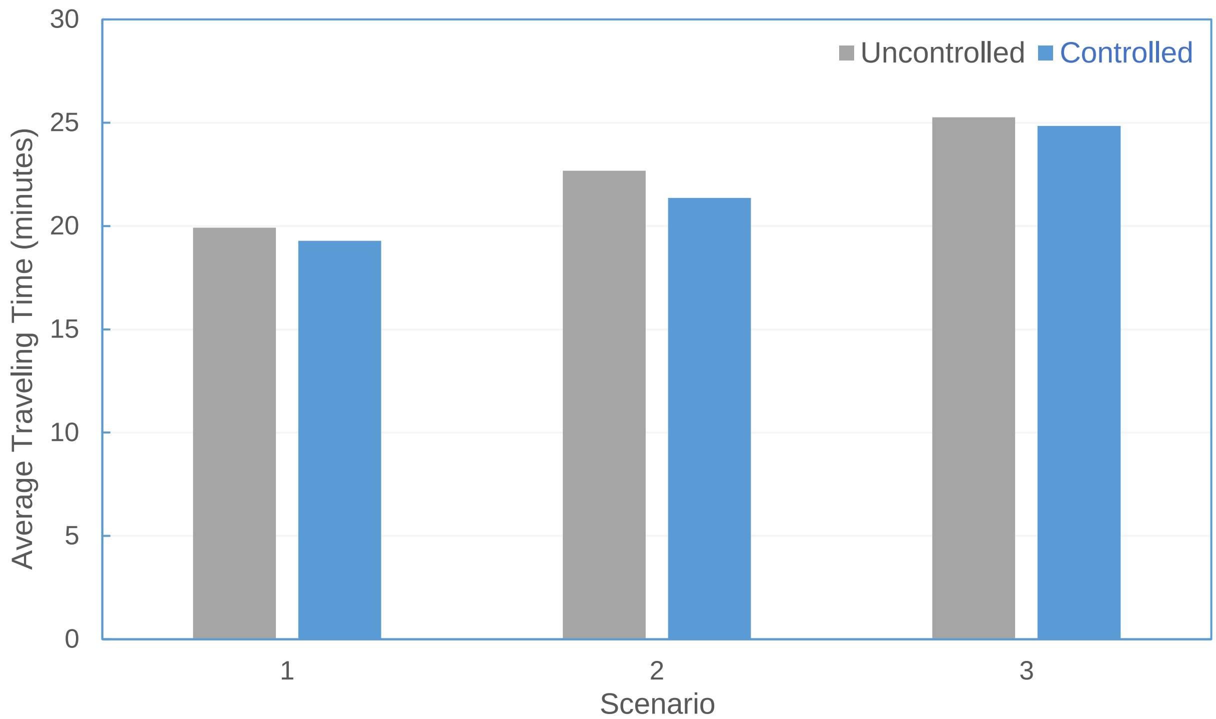


Figure 10: Comparison of Average Traveling Time for Scenario Group 1

Table 8: T-test Analysis for Average Waiting time for Scenario Group 1

Waiting Time (min)		Mean	SD	Difference in Mean	T-Value	P-Value
Scenario 1	Uncontrolled	7.8	4.7	1.4	5.82	<0.01
	Controlled	6.4	3.9			
Scenario 2	Uncontrolled	7.6	4.9	1.3	4.68	<0.01
	Controlled	6.4	3.9			
Scenario 3	Uncontrolled	7.2	4.4	0.7	2.60	0.01
	Controlled	6.5	4.0			

5.3.1.2 Sensitivity Analysis on Traffic Level - Groups 1, 2, and 3

Scenario groups 1, 2, and 3 represent bus operations under different traffic levels (Table 9): group 1 under base traffic condition, group 2 with 20% increase in traffic demand, and group 3 with 40% increase. Checking the simulated network without bus operations during the study period, it is found that 20% increase in traffic demand leads to occasionally congestion, while 40% increase leads to more often congestion, although the queue usually would not expend to two intersections.

Table 9 Scenario Settings for Groups 1, 2, and 3

Scenario	Group	Controlled Case No.	Uncontrolled Case No.	Demand (pass/hr)	Traffic Multiplier	Transfers (pass/hr)	Accident
1 (Base)	1	1	1001	150	1	0	No
2		2	1002	150	1	50	No
3		3	1003	150	1	100	No
4	2	4	1004	150	1.2	0	No
5		5	1005	150	1.2	50	No
6		6	1006	150	1.2	100	No
7	3	7	1007	150	1.4	0	No
8		8	1008	150	1.4	50	No
9		9	1009	150	1.4	100	No

The headway coefficient of variation all the scenarios from 1 to 9 are shown in Figure 11. In Figure 11, the dotted lines represent the results with uncontrolled operations, while solid lines are for controlled operations. In general, when the traffic demand increases and congestion exists in the network, bus operations are inevitably disrupted, reflected by a higher and higher headway deviation. On a route level, the fluctuation of headway coefficient of variation is apparently bigger with uncontrolled operations under traffic congestion condition (Figure 11). In contrast, with the proposed system, the increase of headway coefficient of variation is well controlled across the scenarios, and bus level of service is better especially for M21.

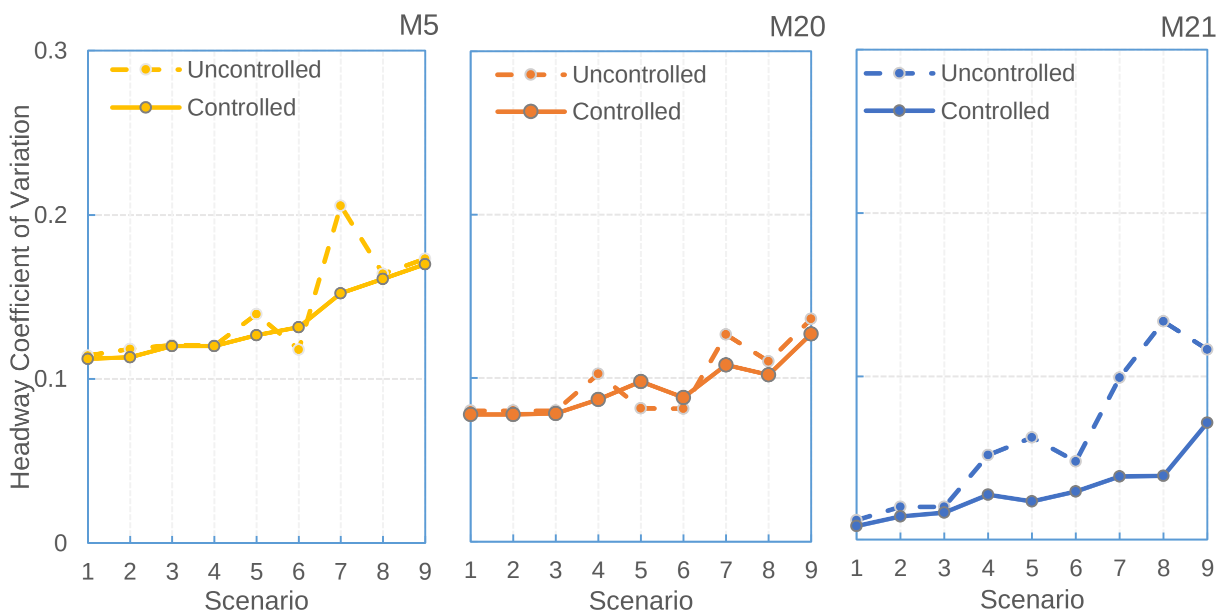


Figure 11: Headway Coefficient of Variation for Sensitivity Analysis on Traffic Level, Full MPR

Average waiting times for all passengers under different scenarios of analysis are shown in Figure 12. Overall, the controlled bus operations reduce the average waiting time for the system users; however, the advantage over the uncontrolled operations shrinks especially when congestion often occurs.

Same conclusions can be drawn through paired-samples t-test analysis as shown in Table 10: statistical difference in the mean value between controlled and uncontrolled cases gets smaller when traffic demand increases. Due to traffic congestion, some buses may be delayed. If after evaluation, the proposed system holds the delayed buses for safe transferring, the waiting time for passengers at downstream stops might be longer than usual. Therefore, it is understandable that the average waiting time may get higher under controlled operations when the transfer demand is larger (Figure 12). Considering the existence of smart transfer module, the average transfer time is also computed under each scenario for the sensitivity analysis on traffic demand level. As shown in Figure 13, the proposed system works best with the highest traffic volume in the network – reducing average transfer time by approximately 15%.

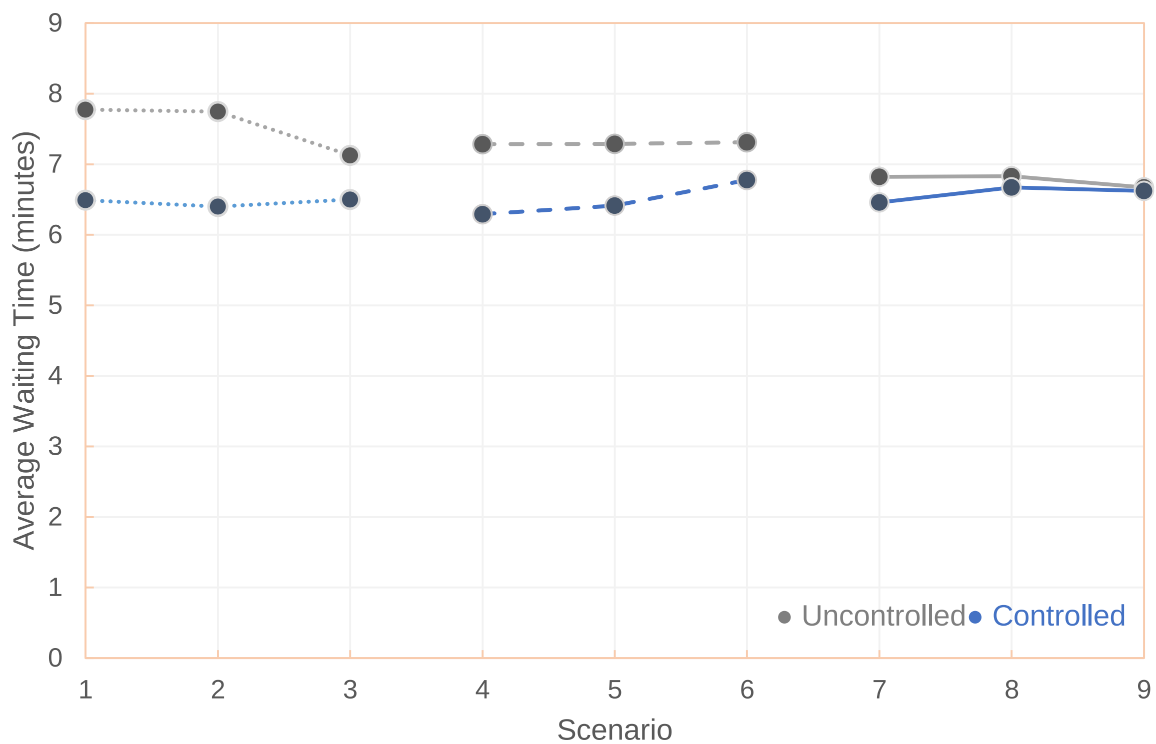


Figure 12: Average Passenger Waiting Time for Sensitivity Analysis on Traffic Level, Full MPR

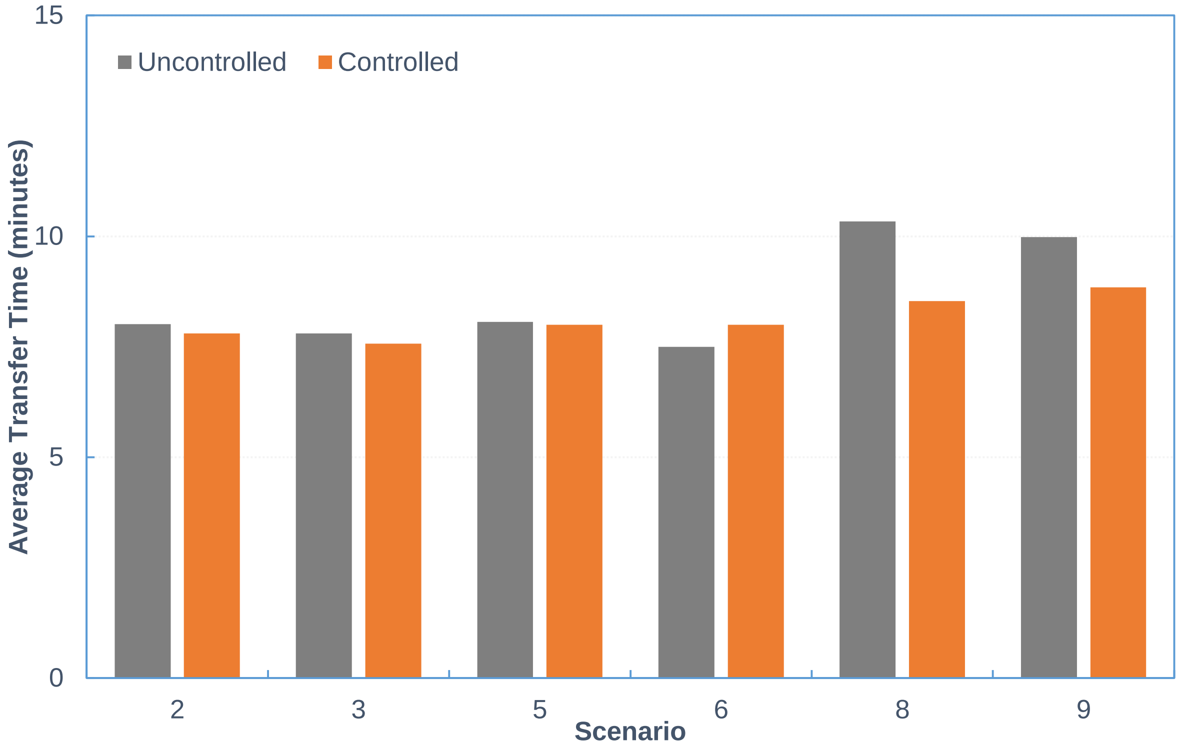


Figure 13: Average Transfer Time for Sensitivity Analysis on Traffic Level, Full MPR

Table 10: T-test Analysis for Average Waiting Time for Scenario Groups 1, 2, and 3, Full MPR

Waiting Time (min)		Mean	SD	Difference in Mean	T-Value	P-Value
Scenario 1	Uncontrolled	7.8	4.7	1.4	5.82	<0.01
	Controlled	6.4	3.9			
Scenario 2	Uncontrolled	7.6	4.9	1.3	4.68	<0.01
	Controlled	6.4	3.9			
Scenario 3	Uncontrolled	7.2	4.4	0.7	2.60	0.01
	Controlled	6.5	4.0			
Scenario 4	Uncontrolled	7.3	4.5	1.2	4.64	<0.01
	Controlled	6.0	3.6			
Scenario 5	Uncontrolled	7.3	4.6	0.9	3.26	<0.01
	Controlled	6.4	3.9			
Scenario 6	Uncontrolled	7.1	4.1	0.2	0.75	0.45
	Controlled	6.8	3.9			
Scenario 7	Uncontrolled	6.8	4.1	0.3	1.25	0.21
	Controlled	6.5	3.8			
Scenario 8	Uncontrolled	6.8	4.1	0.2	0.84	0.40
	Controlled	6.7	3.8			
Scenario 9	Uncontrolled	6.7	4.5	<0.1	0.17	0.87
	Controlled	6.6	4.0			

5.3.1.3 Sensitivity Analysis on Demand Level - Group 1 vs. Group 5

Scenario groups 1 and 5 provides a combination of different demand level scenarios (Table 11): Scenarios 1, 2, and 3 with base demand, and Scenarios 13, 14, and 15 with increased bus demand. No accidents are considered in these cases. When demand is increasing, time for buses stopping at stops to serve passengers may become longer, and it might be the situation that some stops especially downstream stops experience bus arrival/departure delays.

Table 11: Scenarios for Demand Level Sensitivity Analysis, Full MPR

Scenario	Group	Controlled Case No.	Uncontrolled Case No.	Demand (pass/hr)	Traffic Multiplier	Transfers (pass/hr)	Accident
1 (Base)	1	1	1001	150	1	0	No
2		2	1002	150	1	50	No
3		3	1003	150	1	100	No
13	5	13	1013	300	1	0	No
14		14	1014	300	1	100	No
15		15	1015	300	1	200	No

For uncontrolled operations, comparing headway coefficient of variation among scenarios (Figure 14), it is shown that increasing of demand from 150pass/hr to 300pass/hr, bus route M20 is not much affected, while the other two routes experience dropped level of service. High percentage of transfers seems to worsen the system performance in terms of headway adherence: the coefficient of variation increase significantly compared to the scenario without any transfer demand. Comparing the system performance under controlled and uncontrolled operations, it is revealed that the proposed system works better on improving system reliability with higher demand and moderate transfers.

In terms of average waiting time, when the demand level is increasing, the improvement made by controlled operation reduces a little compared to base demand condition (Figure 15). Also, the difference of average transfer time with two operational strategies is marginal (Figure 16). Overall, from the perspectives of both operators (i.e., headway adherence) and passengers (i.e., average waiting and transfer time), the advantage of the proposed system over uncontrolled operations does not become more obvious with higher demand, under full market penetration rate.

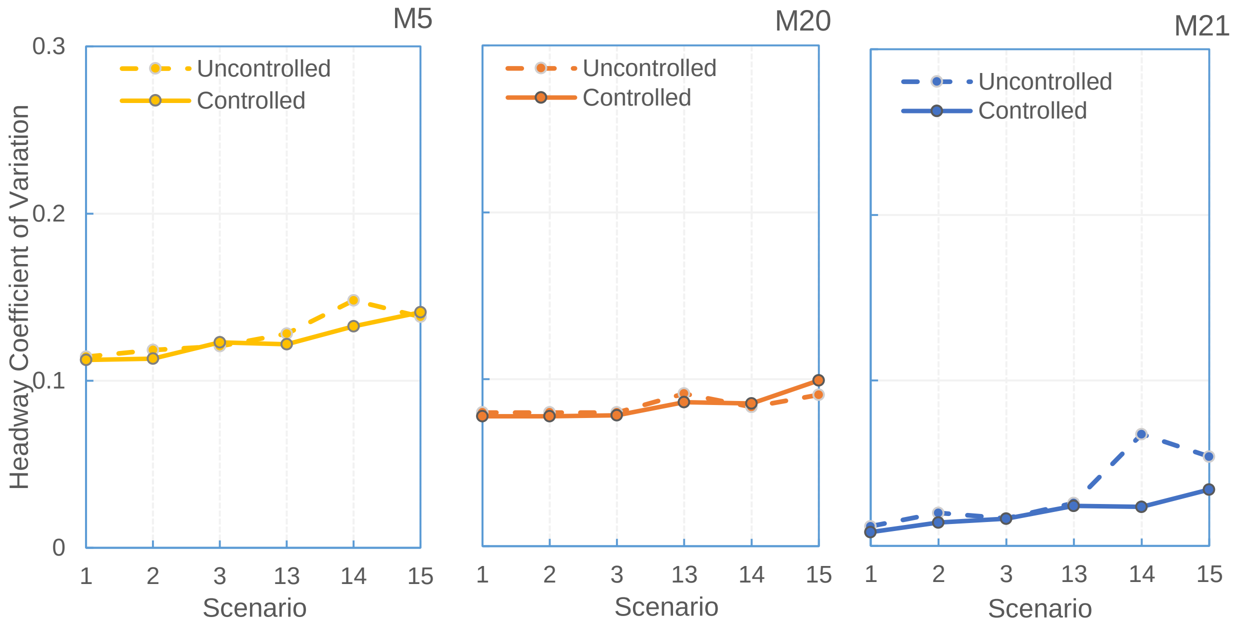


Figure 14: Headway Coefficient of Variation for Sensitivity Analysis on Demand Level, Full MPR

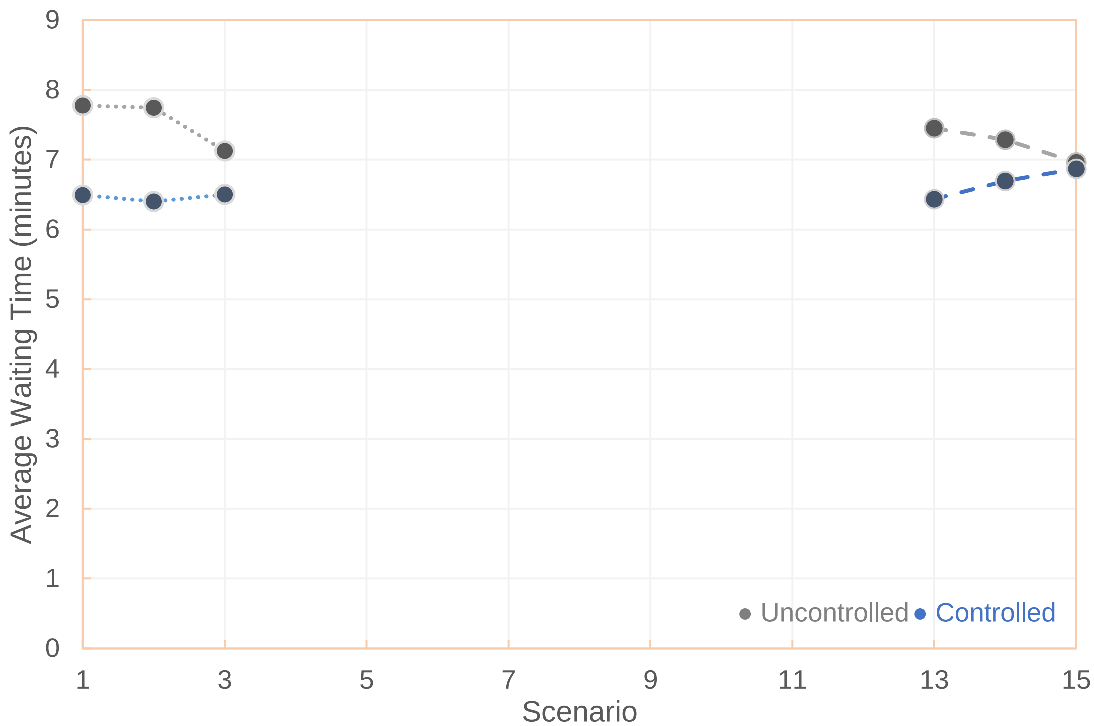


Figure 15: Average Waiting Time for Sensitivity Analysis on Demand Level, Full MPR

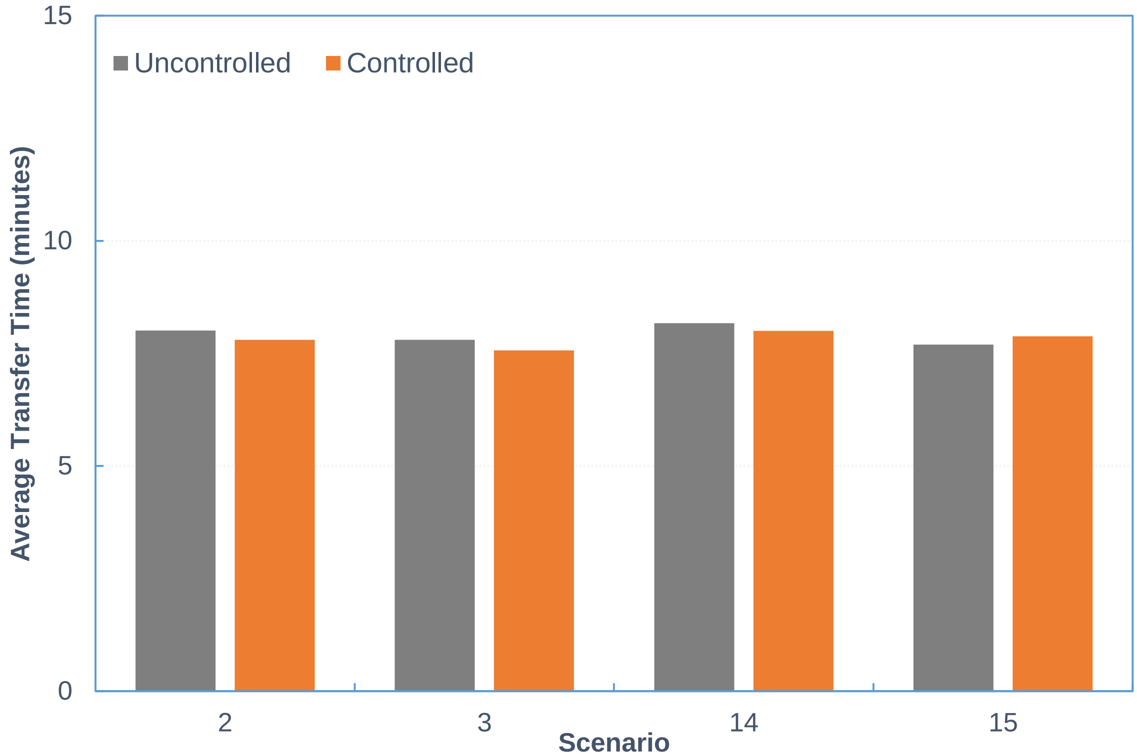


Figure 16: Average Transfer Time for Sensitivity Analysis on Demand Level, Full MPR

5.3.1.4 Sensitivity Analysis on Incident - Groups 1 and 4

When an incident is present in the network leading to traffic congestion, bus operations will be inevitability affected. It is expected that the proposed system will perform better with controlled operations. Scenario group 4 is thus created to investigate the effectiveness of the system with the same demand level of 150 passenger/hr (Table 12). With base traffic demand level, when the incidents are artificially placed in the network, headway coefficient of variation for each bus route under uncontrolled operations marginally increases compared with the network without incidents (Figure 17), indicating a slight disturbance on bus system. For route M21, whose headway adherence is more deteriorated by the incidents, larger improvements yielded by the proposed system are observed.

Similar to the changing demand scenarios, it seems that the incidents do not have much influence on both of the average waiting and transfer times on a system level (Figure 18 and Figure 19): the proposed system does lower both, but the effects are about the same level for both with and without incidents conditions.

Table 12: Scenarios for Incident Sensitivity Analysis, Full MPR

Scenario	Group	Controlled Case No.	Uncontrolled Case No.	Demand (pass/hr)	Traffic Multiplier	Transfers (pass/hr)	Accident
1 (Base)	1	1	1001	150	1	0	No
2		2	1002	150	1	50	No
3		3	1003	150	1	100	No

10	4	10	1010	150	1	0	Yes
11		11	1011	150	1	50	Yes
12		12	1012	150	1	100	Yes

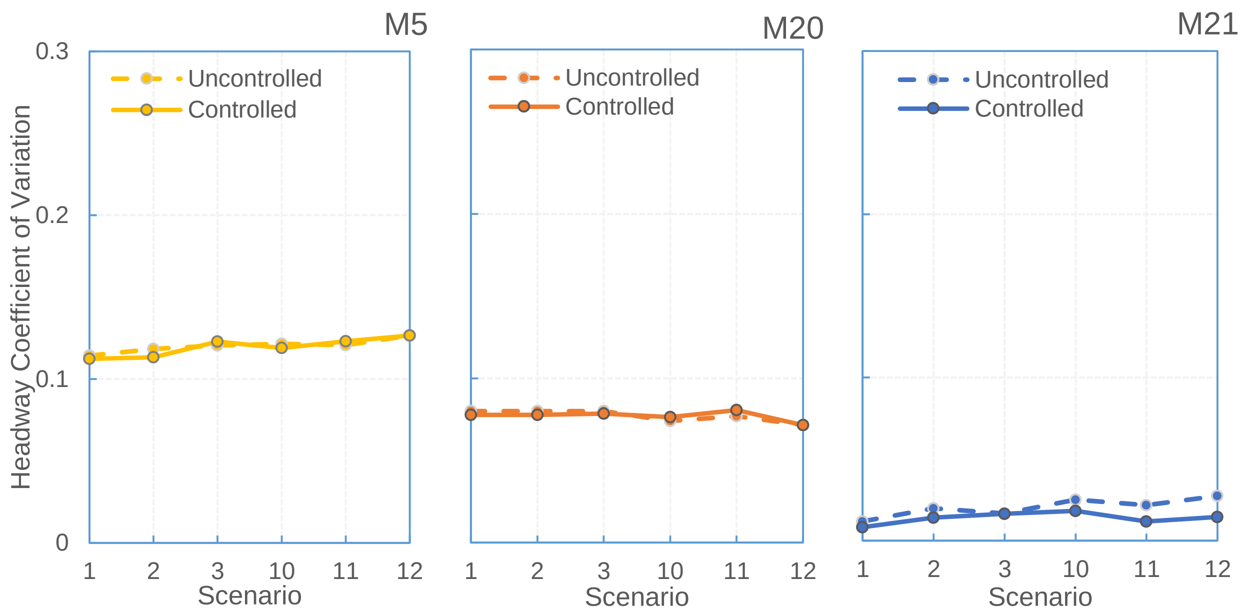


Figure 17: Headway Coefficient of Variation for Sensitivity Analysis on Incident, Full MPR

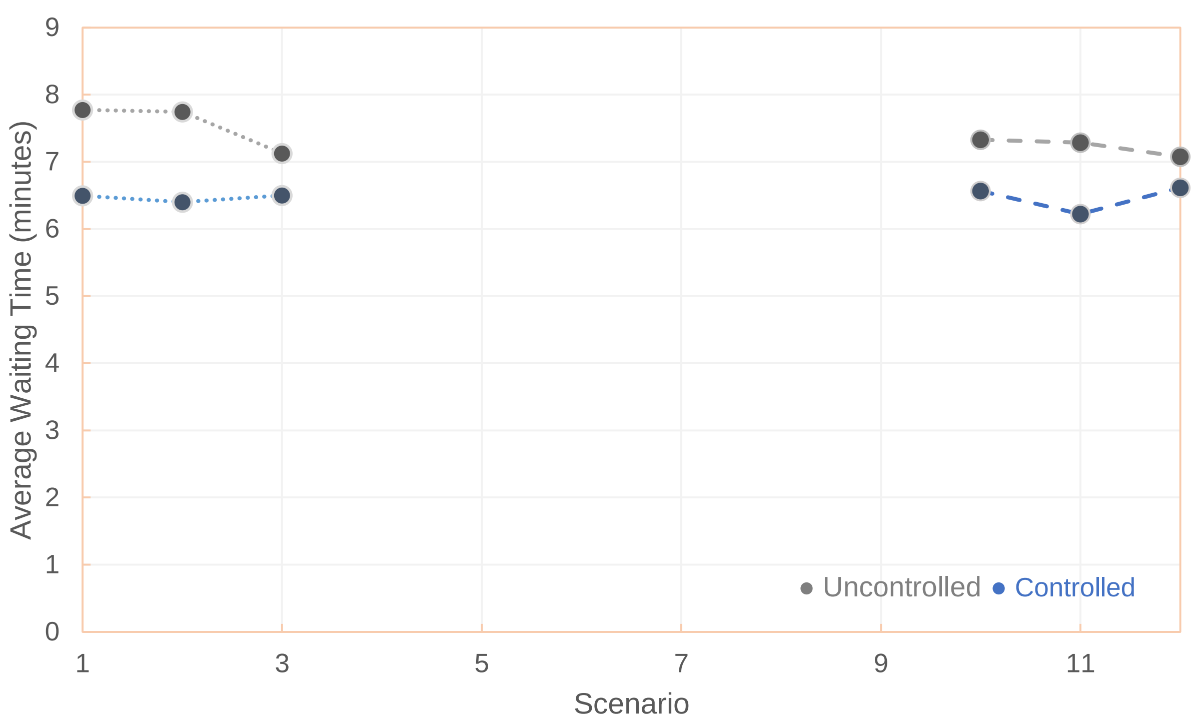


Figure 18: Average Waiting Time for Sensitivity Analysis on Incident, Full MPR

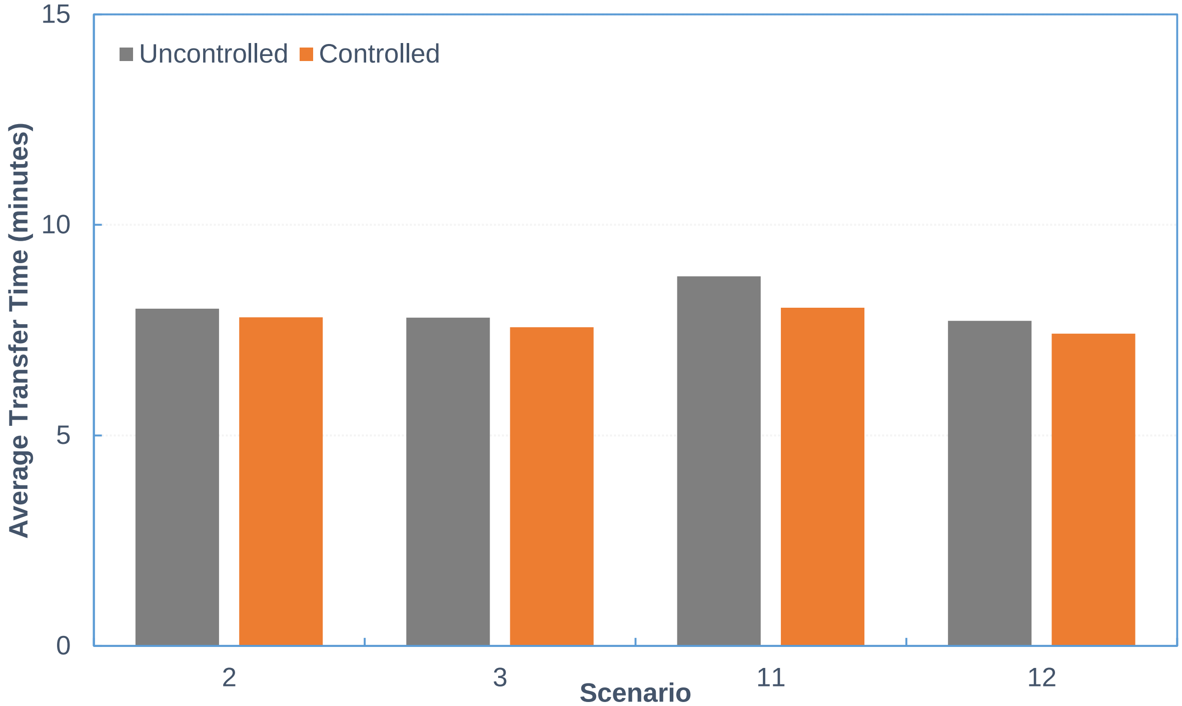


Figure 19: Average Transfer Time for Sensitivity Analysis on Incident, Full MPR

5.3.1.5 Sensitivity Analysis on Incident - Groups 5 and 6

Scenario group 6 is created to be compared to group 5 for an investigation on incident impact combined with a higher demand situation (Table 13). With higher demand, the negative impact of incidents gets larger, especially for M20, increased headway coefficient of variation is observed (Figure 20). The control over bus operations by the proposed system tends to be more effective to lower the headway variation as well as average passenger waiting and transfer times (Figure 21 and Figure 22).

Table 13: Scenarios for Incident Sensitivity Analysis, Full MPR

Scenario	Group	Controlled Case No.	Uncontrolled Case No.	Demand (pass/hr)	Traffic Multiplier	Transfers (pass/hr)	Accident
13	5	13	1013	300	1	0	No
14		14	1014	300	1	100	No
15		15	1015	300	1	200	No
16	6	16	1016	300	1	0	Yes
17		17	1017	300	1	100	Yes
18		18	1018	300	1	200	Yes

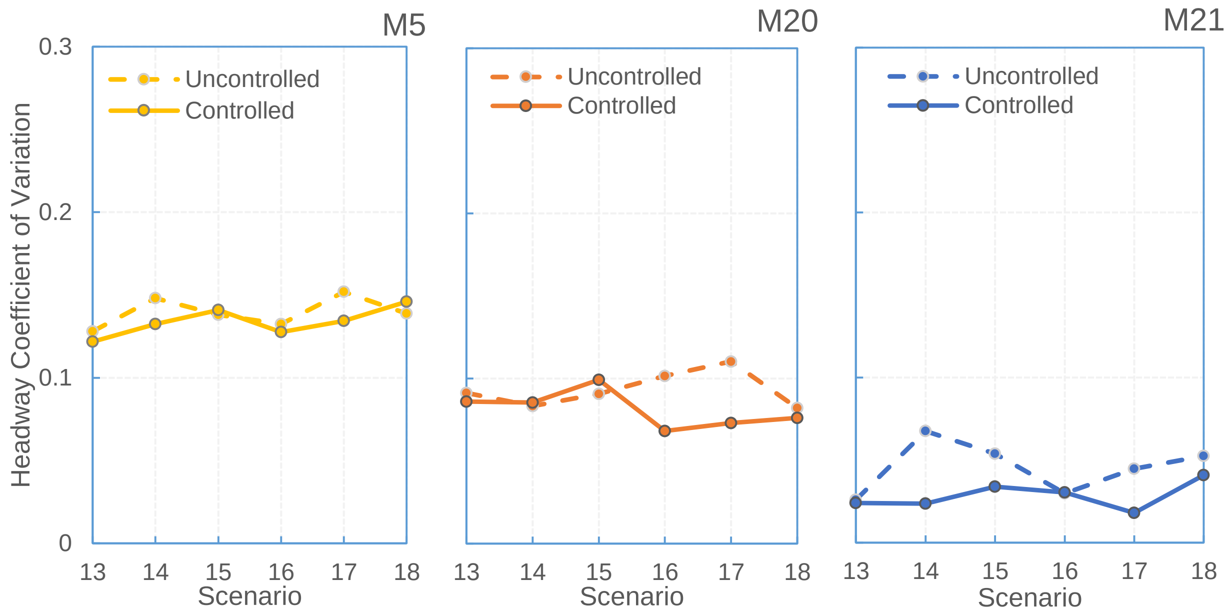


Figure 20: Average Transfer Time for Sensitivity Analysis on Incident with High Demand, Full MPR

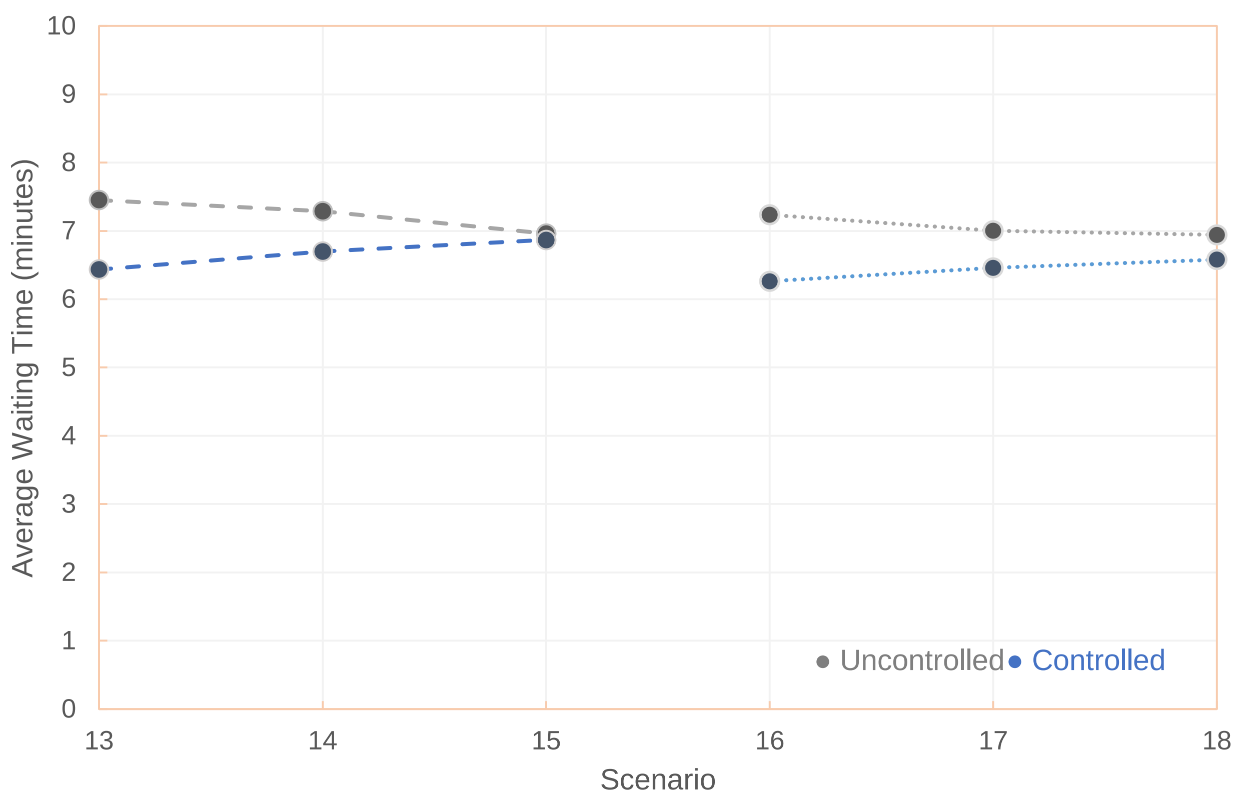


Figure 21: Average Waiting Time for Sensitivity Analysis on Incident with High Demand, Full MPR

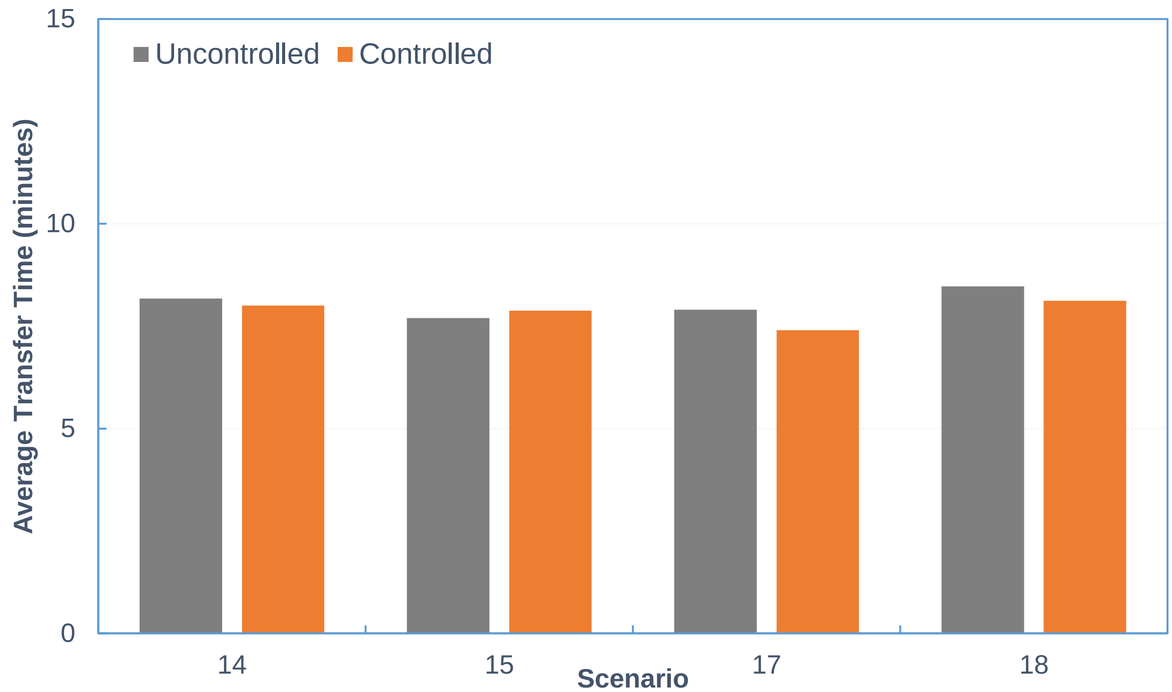


Figure 22: Average Transfer Time for Sensitivity Analysis on Incident with High Demand, Full MPR

5.3.1.6 Summary

From the above analysis on system performance under full market penetration rate, it shows that the proposed system works better when buses with higher demand are disturbed by traffic congestion. The analysis on headway coefficient of variation indicates that bus operations are more reliable under controlled situation, especially when buses run in a congested network.

5.3.2 Half MPR

To investigate the performance of the proposed system under different market penetration rates, 50% and 25% MPR are applied, with half and quarter of the total demand having access to mobile applications, respectively. In this section, same sets of scenarios with Full MPR is applied to conduct the analysis. It should be noted that the average passenger travel times (i.e., waiting, transfer time) are estimated from the mobile app users since the system only records arrival times at origin stops for this part of passengers.

5.3.2.1 Base Scenario Analysis

Compared to the full MPR scenario (Table 5), both of the standard deviation of headways are slightly increased for uncontrolled and controlled operations (Table 14). With increased passengers boarding and alighting at stops without mobile access, average travel time for the mobile app users are increased (Table 15). Similar to the full MPR scenario, the impact of the proposed system seems to be small when the bus and traffic demand are light, and no incidents exist in the network.

Table 14: Headway Analysis for Base Scenario, Half MPR

Route	Uncontrolled			Controlled			Scheduled
	Mean	SD	CV	Mean	SD	CV	Mean
M20	14.5	1.2	0.08	14.5	1.2	0.08	14.5
M21	20.0	0.6	0.03	20.0	0.5	0.02	20.0
M5	11.3	1.4	0.12	11.2	1.3	0.12	10.9

Table 15: Average Passenger Travel Time for Base Scenario, Half MPR

Route	Waiting Time (min)		Traveling Time (min)	
	Uncontrolled	Controlled	Uncontrolled	Controlled
M20	7.5	7.2	17.0	15.6
M21	8.8	8.4	23.1	21.6
M5	5.8	5.0	19.8	19.1

The same sensitivity analyses under half MPR are conducted to examine whether the proposed system would work differently with a medium MPR. In the following sections, the results for scenario groups representing changes on traffic level, demand level, and incident situation are summarized.

5.3.2.2 Sensitivity Analysis on Traffic Level - Groups 1, 2, and 3

The impacts of traffic congestion on the bus system under half market penetration rate are shown in Figure 23: if uncontrolled, when traffic level goes up, headway variation significantly increased. Although the fluctuations of headway coefficient of variation among different transfer demands make it difficult to conclude the joint effect of transfer level, it is clear that increased congestion leads to a deteriorate level of service for uncontrolled bus systems.

Figure 24 and Figure 25 represent the average waiting time and the average transfer time for scenarios 1 to 9. Whereas the reduction of average waiting time by the proposed system is smallest under scenarios 7 to 9, the average transfer time is largely shortened. Based on the magnitude of traffic congestion impact, the result combinations of decisions made by two separate modules (i.e., smart transfers and dynamic routing) might be the reason for the difference between the improvements over average waiting time and those over average transfer time.

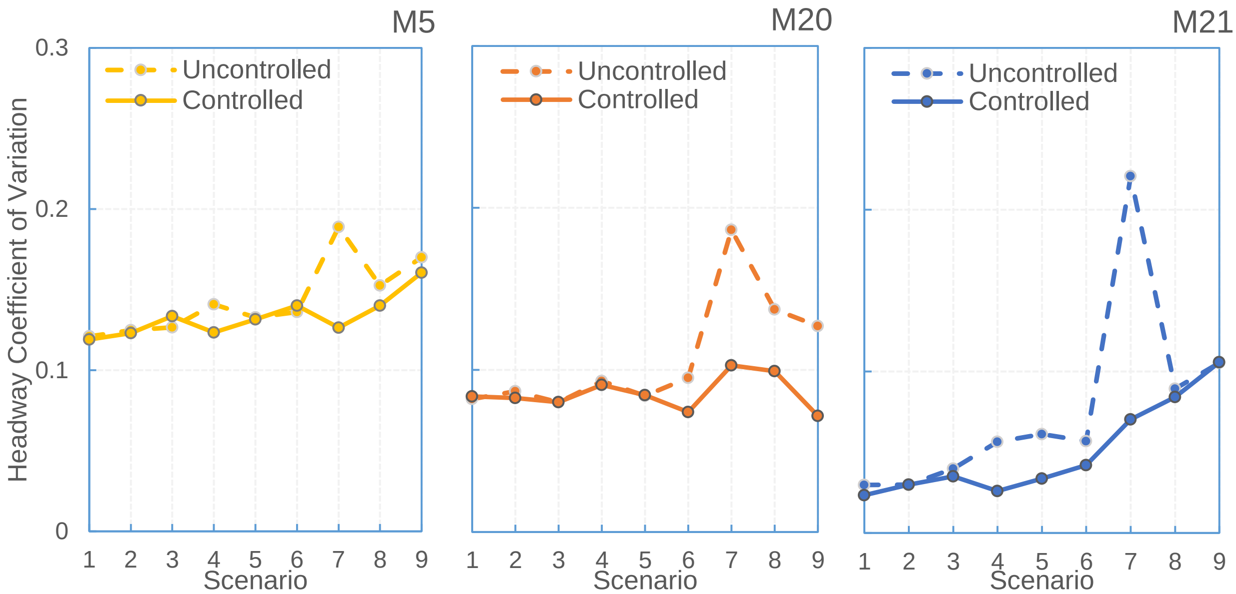


Figure 23: Headway Coefficient of Variation for Sensitivity Analysis on Traffic Level, Half MPR

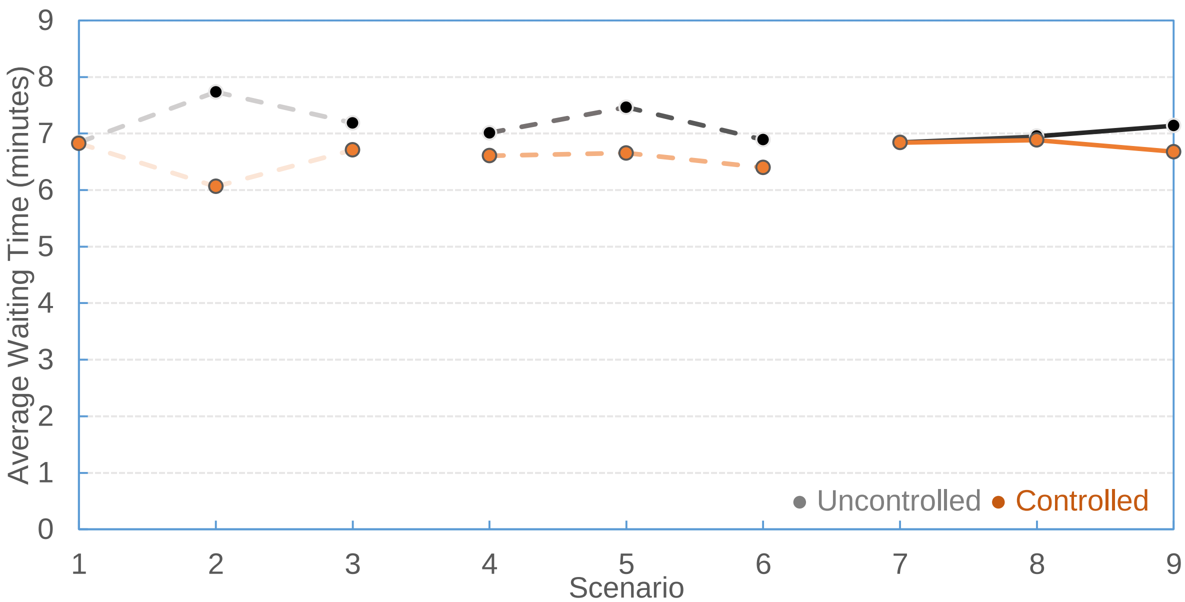


Figure 24: Average Waiting Time for Sensitivity Analysis on Traffic Level, Half MPR

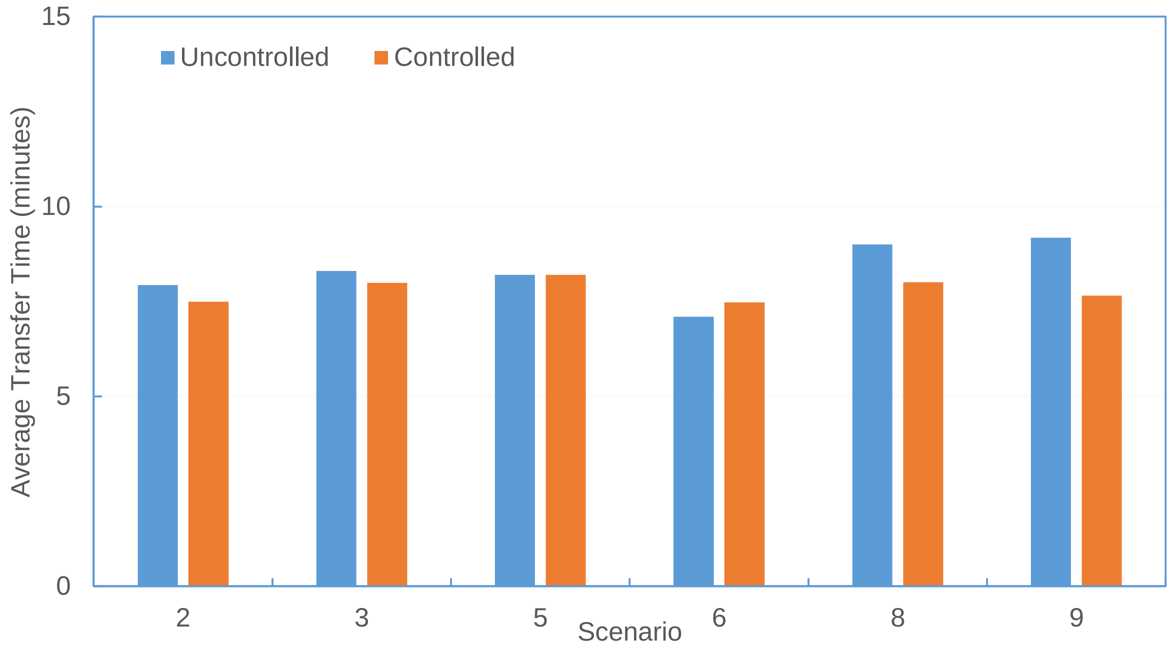


Figure 25: Average Transfer Time for Sensitivity Analysis on Traffic Level, Half MPR

5.3.2.3 Sensitivity Analysis on Demand Level - Group 1 vs. Group 5

The previous analysis on the demand level under full MPR shows 1) no significant impact of increased demand over the uncontrolled system and 2) no obvious improvement over lower demand level by the proposed system in terms of system reliability and average passenger travel times.

Same analysis is conducted under half MPR and the bus system performance is also compared between uncontrolled and controlled operations. As shown in Figure 26, the headway coefficient of variation with higher demand level tends to increase in the uncontrolled system, especially, it is still M21 that is mostly affected by the deteriorated service. Looking into the study network, it is found that M21 serves the largest amount of stops and travels across several streets. Hence, a small disturbance occurring somewhere in the route may be magnified at downstream stops. Overall, the negative impact caused by increased demand could be well reflected in M21.

Indicated in both Figure 27 and Figure 28, the advantages of the proposed system over the uncontrolled system is not enlarged because of increased demand, in terms of passenger waiting and transfer time reduction.

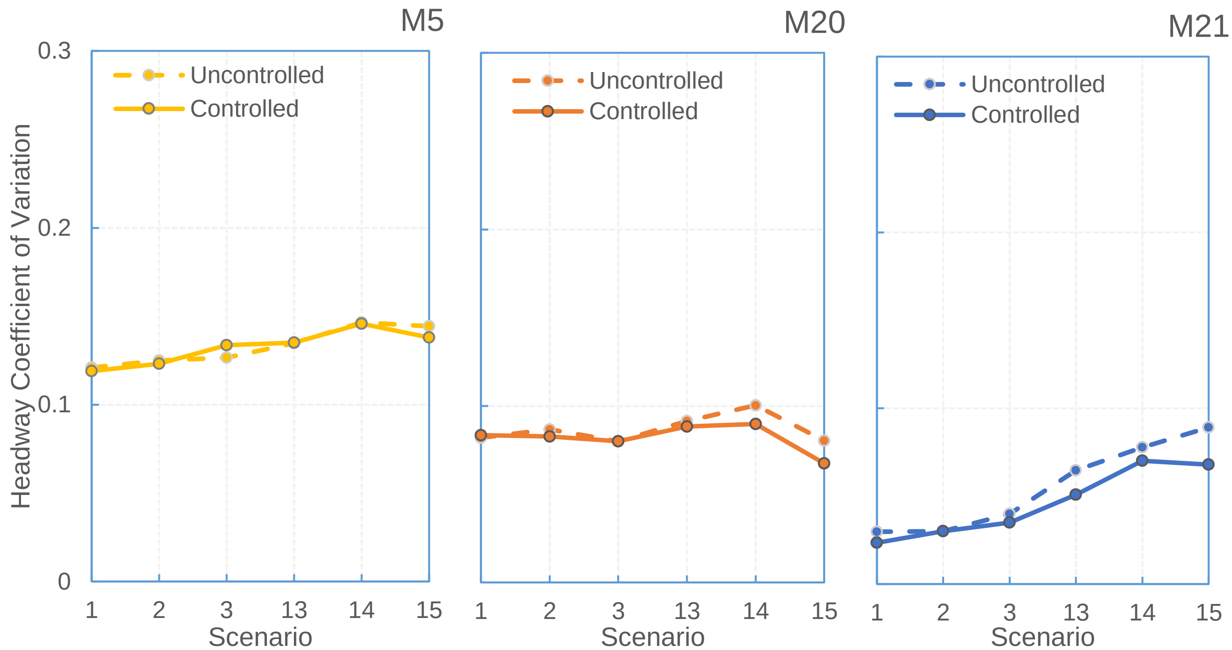


Figure 26: Headway Coefficient of Variation for Sensitivity Analysis on Demand Level, Half MPR

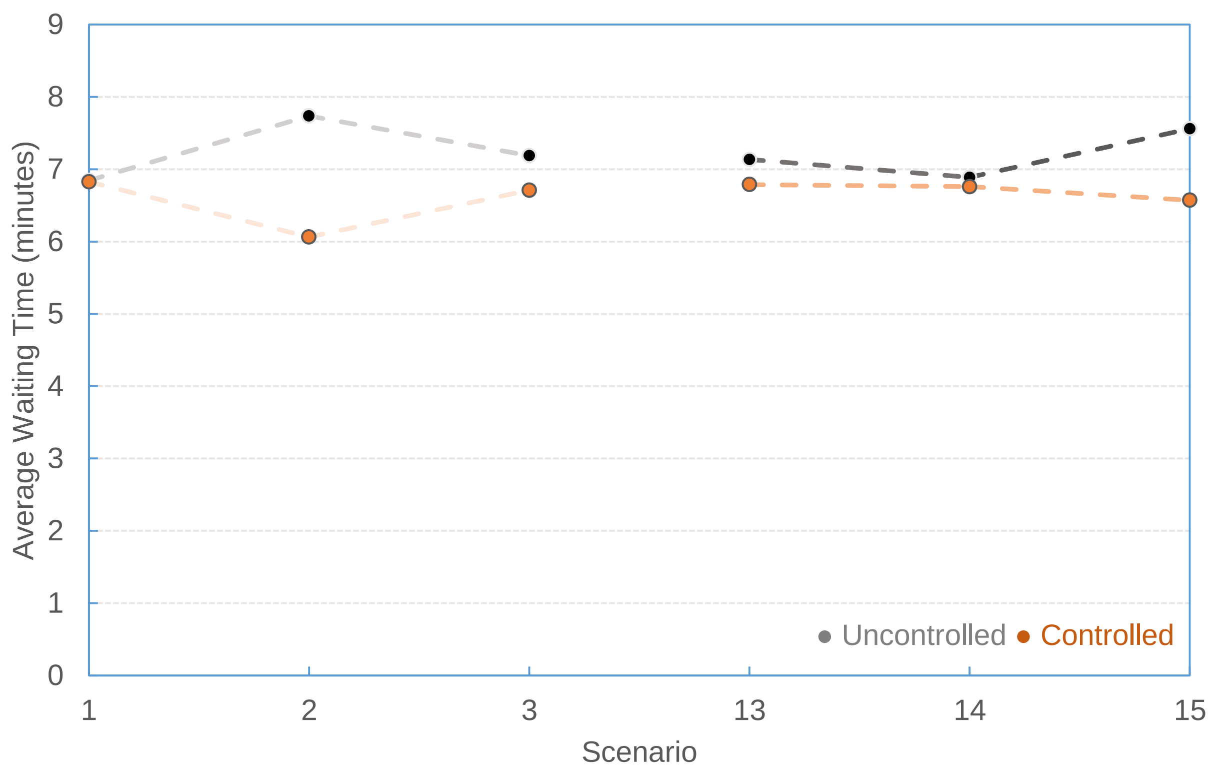


Figure 27: Average Waiting Time for Sensitivity Analysis on Demand Level, Half MPR

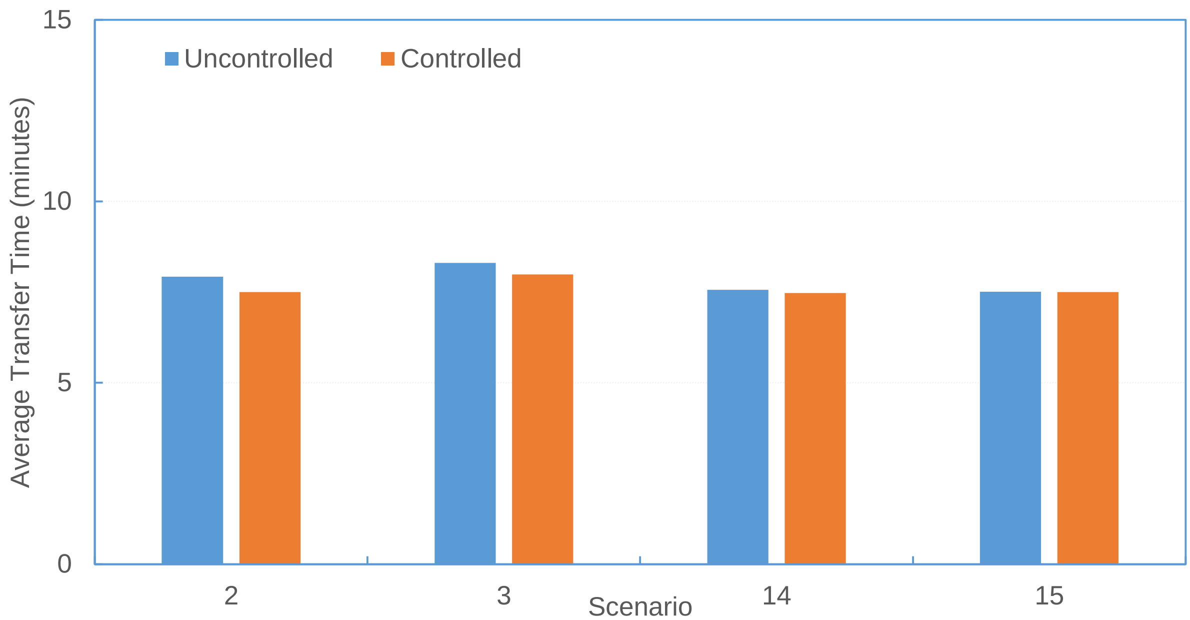


Figure 28: Average Transfer Time for Sensitivity Analysis on Demand Level, Half MPR

5.3.2.4 Sensitivity Analysis on Incident - Groups 1 and 4

Similar to the results for full MPR, the incident impact on the system under light demand and traffic condition is minor. It does show fluctuations on headway for each route (Figure 29), yet the system LOS remains the same level. Also, as shown in Figure 30 and Figure 31, system benefit from controlled operations is marginal, from passengers' perspectives: slightly reduced average waiting time, similar level of average transfer time.

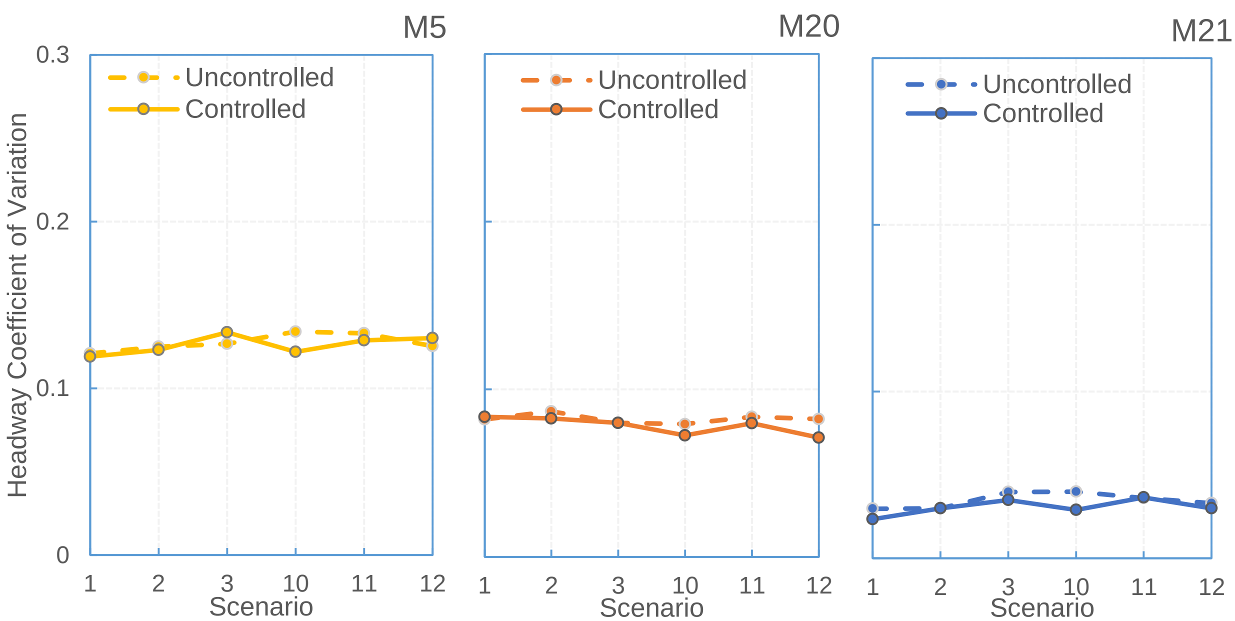


Figure 29: Headway Coefficient of Variation for Sensitivity Analysis on Incident, Half MPR

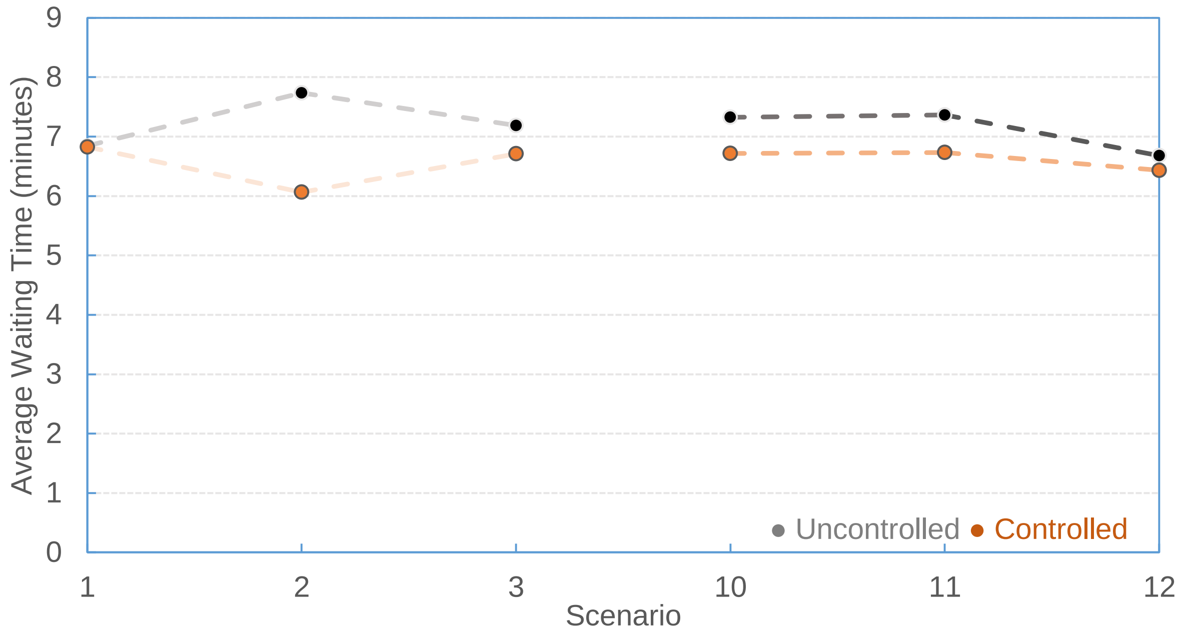


Figure 30: Average Waiting Time for Sensitivity Analysis on Incident, Half MPR

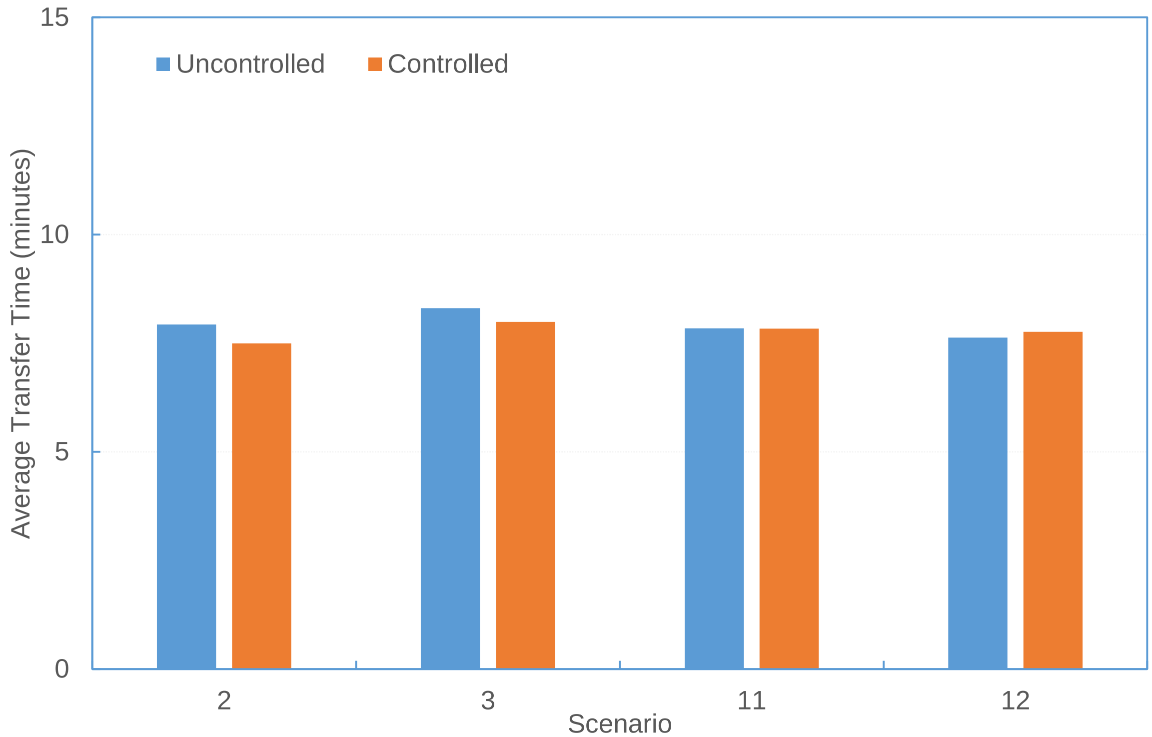


Figure 31: Average Transfer Time for Sensitivity Analysis on Incident, Half MPR

5.3.2.5 Sensitivity Analysis on Incident - Groups 5 and 6

When the bus demand is increased, the influence of the incident become larger in terms of the headway coefficient of variation, comparing scenario group 1 and 6 from Figure 29 and Figure 32. As per route, while M5 experiences the least level of service among the three routes, M21 is still the one that is mostly affected by traffic disturbance (Figure 32). From passengers' perspective, when the incidents present in the network, both of the average passenger waiting time and transfer time are increased for the uncontrolled system (Figure 33 and Figure 34). With bus controlling, both of the average waiting time and transfer time are reduced compared to both uncontrolled and no-incident scenarios.

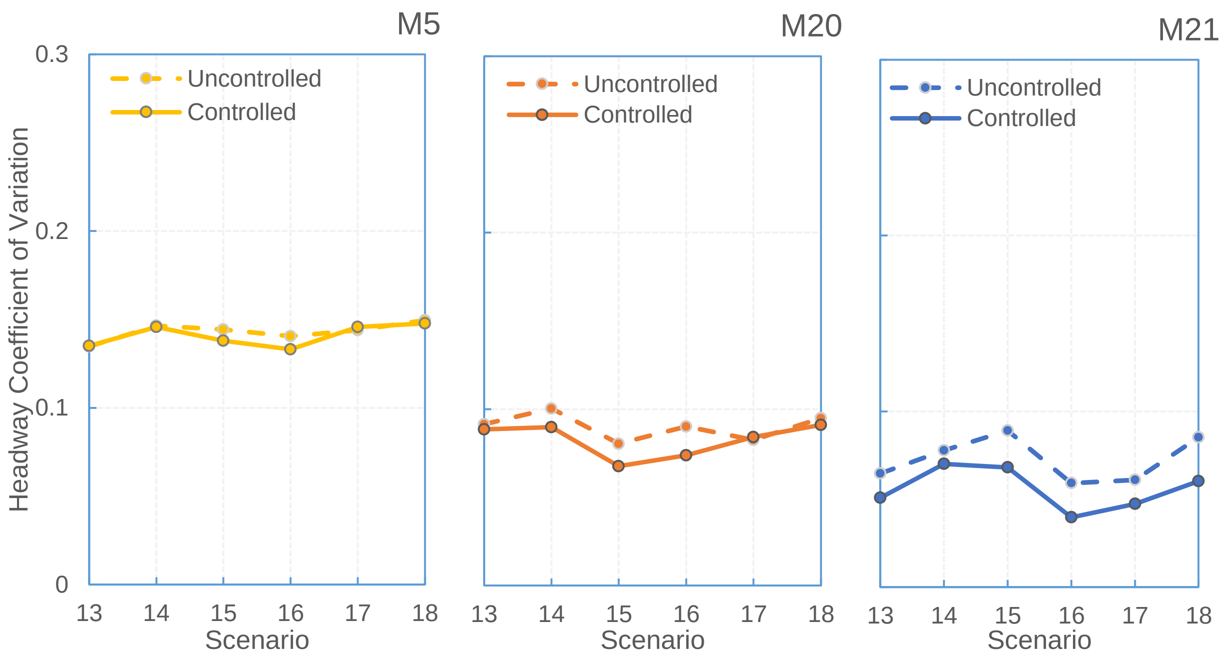


Figure 32: Headway Coefficient of Variation for Sensitivity Analysis on Incident with High Demand, Half MPR

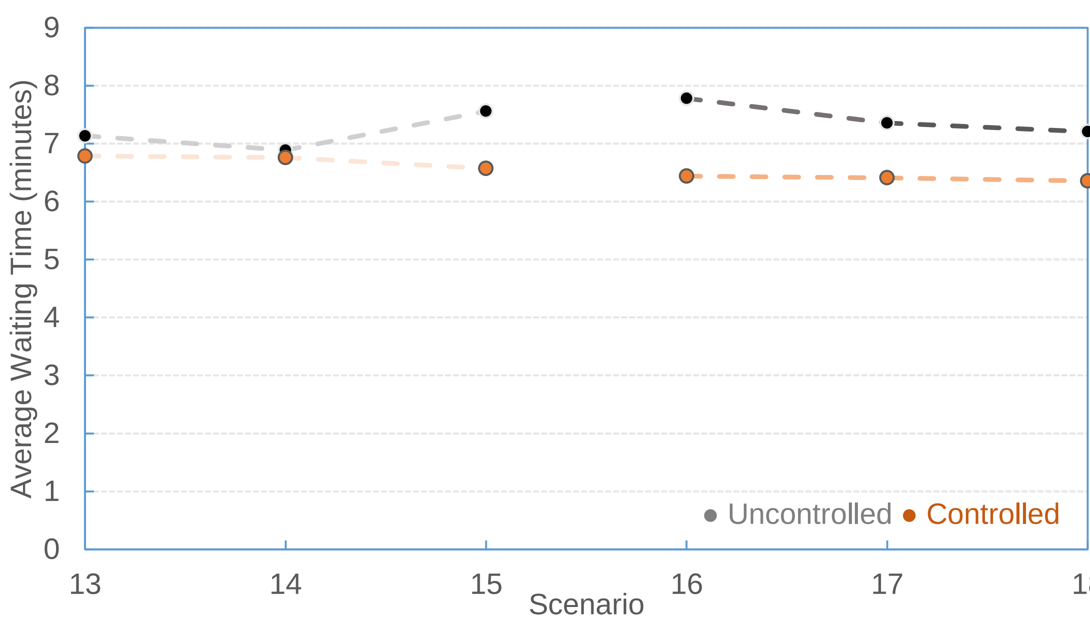


Figure 33: Average Waiting Time for Sensitivity Analysis on Incident with High Demand, Half MPR

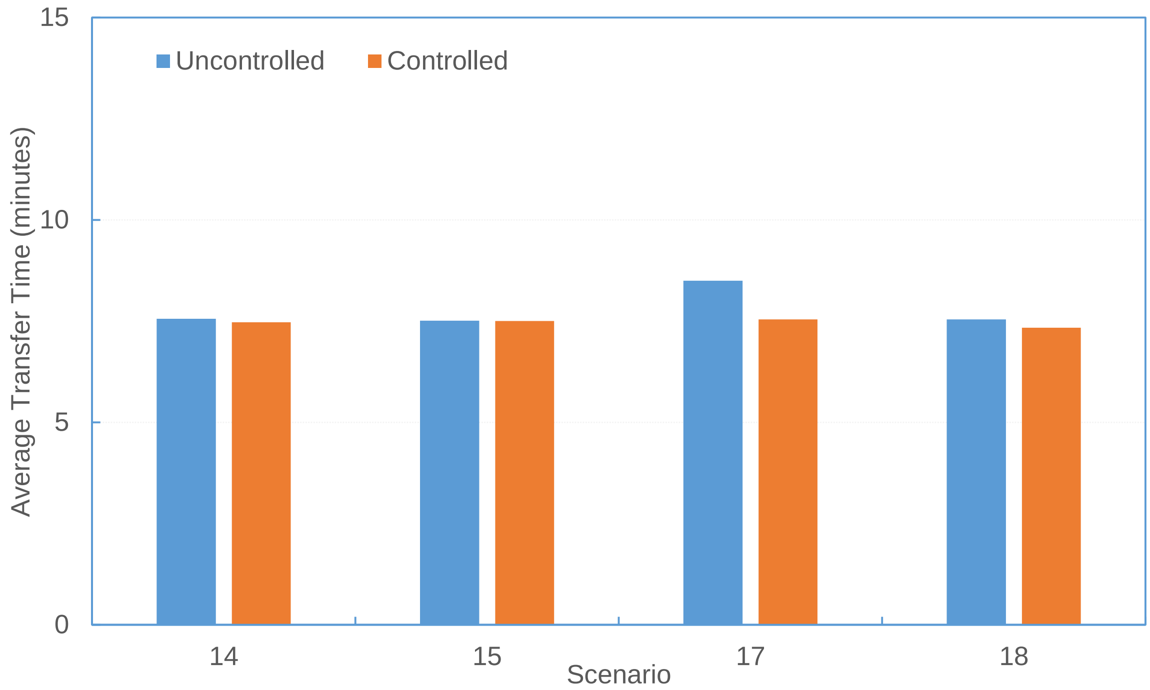


Figure 34: Average Transfer Time for Sensitivity Analysis on Incident with High Demand, Half MPR

5.3.2.6 Summary

From the above analysis on system performance under 50% market penetration rate, similar trends are found as those under full market penetration rate. However, it does show that the overall performance of the bus system is lower, and especially, the uncontrolled system is more affected by traffic congestion and demand change. The results indicate that the proposed system is slightly less effective compared to full MPR scenarios, yet it still works better when bus operations, if otherwise uncontrolled, are more disturbed by either traffic congestion or the combination of high demand and incidents.

5.3.3 Quarter MPR

Further reducing the market penetration rate to 25% leads to even smaller proportion of mobile application users in the total demand (i.e., probably lower chance of transfer holding requests from passengers, and higher chance of stop skipping). The scenario settings are the same as the first two MPR cases, and the passenger waiting and transfer time are estimated based on the information collected from mobile app users.

5.3.3.1 Base Scenario Analysis

The analysis also starts with the base scenario, where the system runs with light demand and traffic conditions without any incidents. Consider headway coefficient of variation (Table 16) for each market penetration case, bus level of service is slighted reduced. The average passenger waiting time does not change much compared to Half MPR case, however, the average travel time further increases (Table 17).

Table 16: Headway Analysis for Base Scenario, Quarter MPR

Route	Uncontrolled			Controlled			Scheduled
	Mean	SD	CV	Mean	SD	CV	Mean
M20	14.5	1.2	0.08	14.5	1.2	0.08	14.5
M21	20.0	0.4	0.02	20.0	0.4	0.02	20.0
M5	10.9	1.4	0.13	10.9	1.4	0.13	10.9

Table 17: Average Passenger Travel Time for Base Scenario, Quarter MPR

Route	Waiting Time (min)		Traveling Time (min)	
	Uncontrolled	Controlled	Uncontrolled	Controlled
M20	7.5	7.2	20.3	19.5
M21	8.8	8.4	22.2	21.3
M5	5.8	5.0	25.9	24.7

5.3.3.2 Sensitivity Analysis on Traffic Level - Groups 1, 2, and 3

The effectiveness of system in improving passengers' experience on riding the bus seems to be consistent over different market penetration rate (Figure 35), without noticeable difference for same scenario setting. However, the control over bus operations seems to be less powerful, reflected by increased headway coefficient of variation when the traffic level goes up (Figure 36).

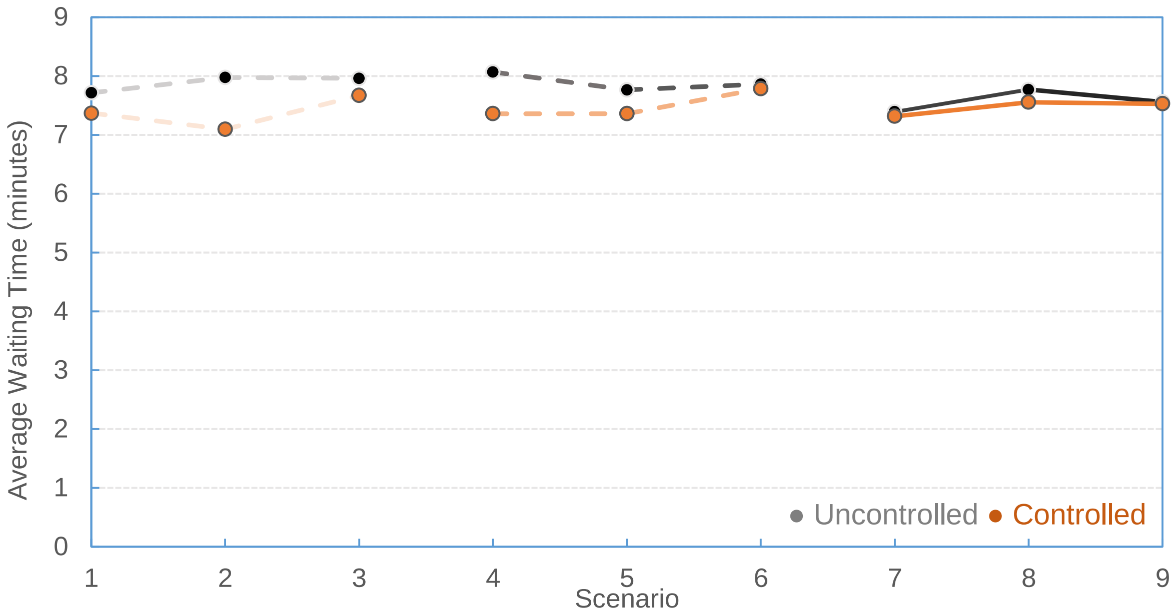


Figure 35: Average Passenger Waiting Time for Sensitivity Analysis on Traffic, Quarter MPR

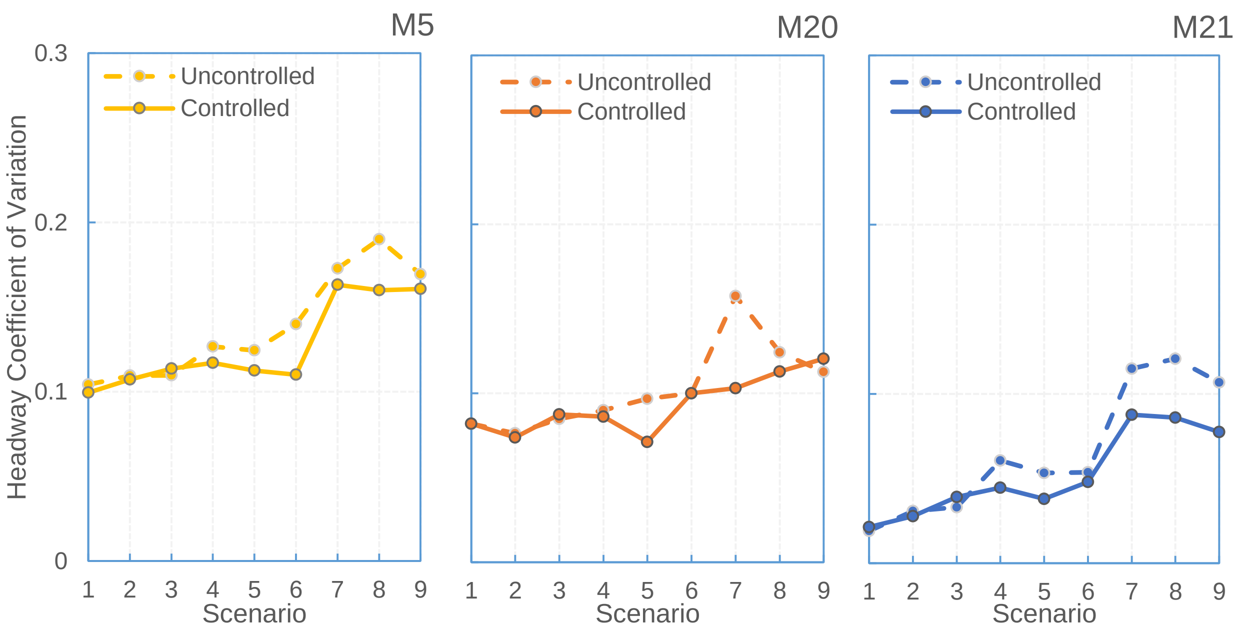


Figure 36: Headway Coefficient of Variation for Sensitivity Analysis on Traffic, Quarter MPR

5.3.3.3 Sensitivity Analysis on Demand Level - Group 1 vs. Group 5

When the number of mobile application user increases, the average passenger waiting time in an uncontrolled system tends to be increased (Figure 37). The proposed system reduces the waiting time compared to that without controls, especially when the transfer proportion in the mobile app users increases, as shown in Figure 37.

An increase in demand leads to a more fluctuated system, if uncontrolled. Shown in Figure 38, for all bus routes, the headway coefficient of variation tends to increase with higher demand. While the proposed system could slightly offset such negative influence, the level of service still drops.

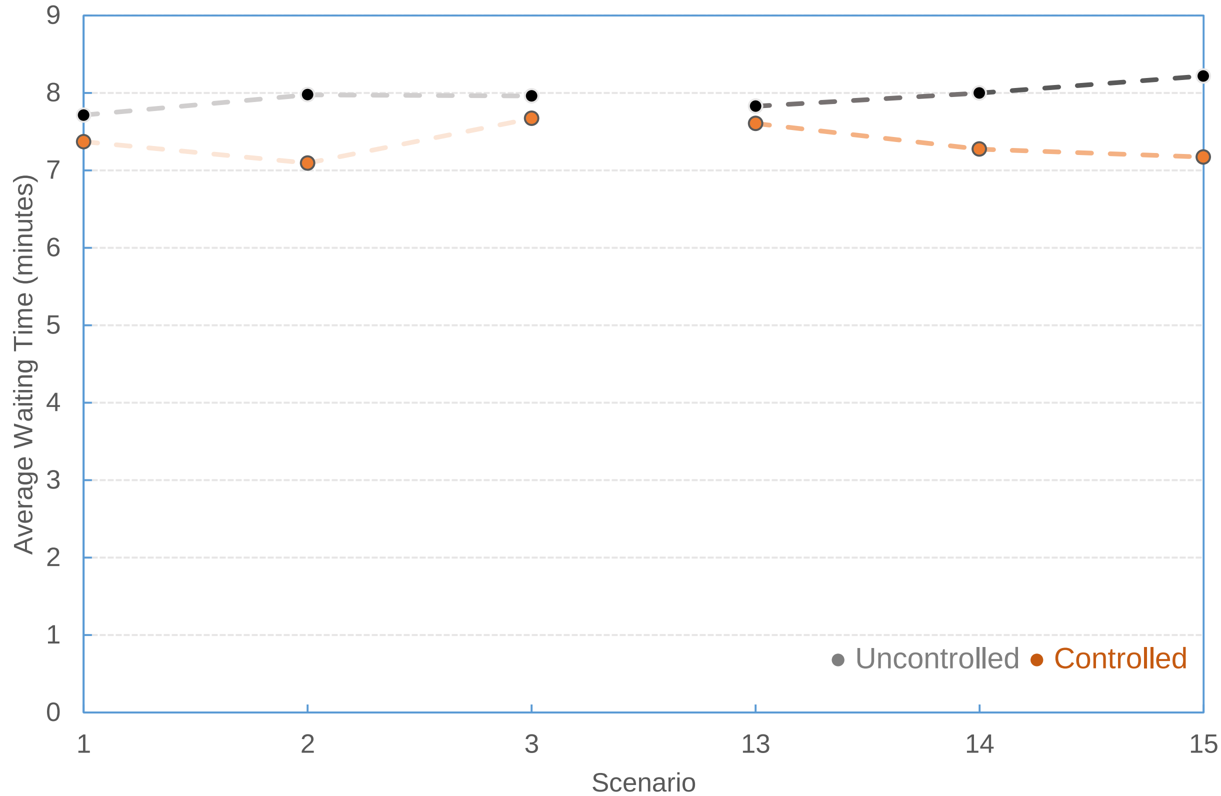


Figure 37: Average Passenger Waiting Time for Sensitivity Analysis on Demand, Quarter MPR

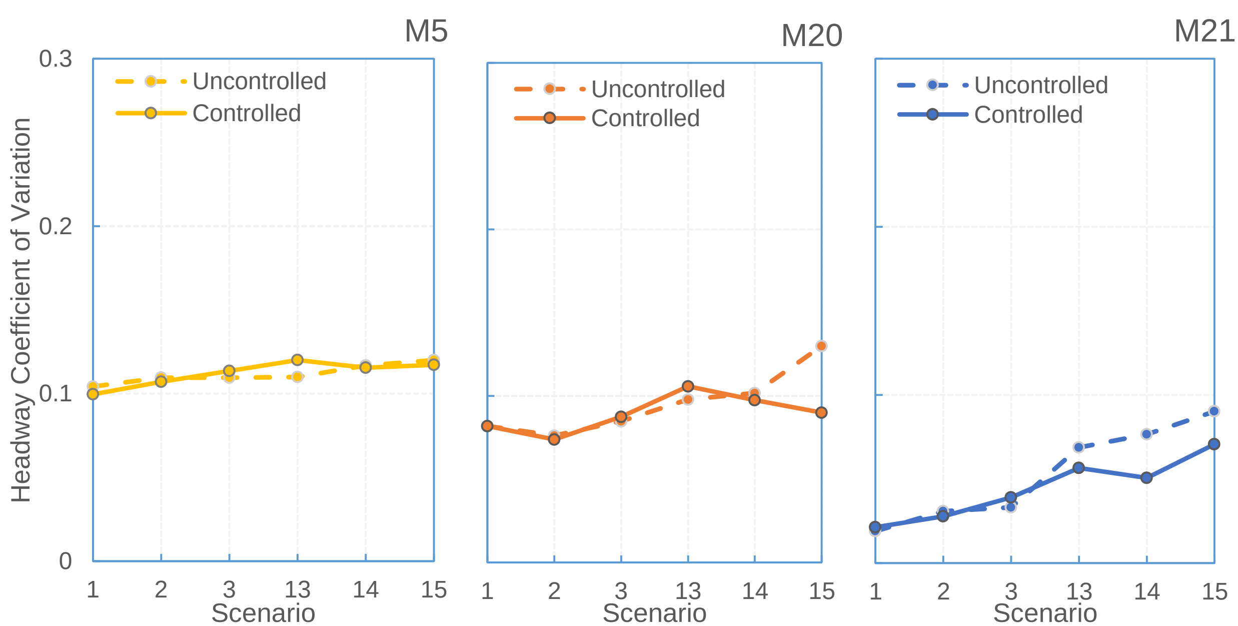


Figure 38: Headway Coefficient of Variation for Sensitivity Analysis on Demand, Quarter MPR

5.3.3.4 Sensitivity Analysis on Incident - Groups 1 and 4

Unlike previous full MPR and half MPR cases, it seems that when the incidents in the network have more impact on bus operations. Shown in Figure 39, compared to no incident scenarios, in an uncontrolled system, the average passenger waiting time is increased, especially when moderate transfers exist in the bus network. On the other hand, with bus controls, the proposed system works well in lowering waiting time for bus users. Therefore, it is indicated that benefit for passengers using the new system is enlarged when the incidents happen during the study period.

Figure 40 represents the headway coefficient of variation for both scenario groups: an increase is observed for every route with incident presenting in the network, when buses run without controls, compared to the base scenarios. M20 benefits the most from controlled operations when no transfers exist, while transfer demand increases, M5 and M21 are the two routes that get more improvement in the reliability. It makes sense that when there is no transfer demand, the only module works against the congestion is dynamic routing. It is more likely that a detour route would be selected for M20, due to relatively short detour length without skipping a stop, compared to the other two routes, where several intersections exist in possible alternate routes and stop skipping sometime is necessary for detour purpose.

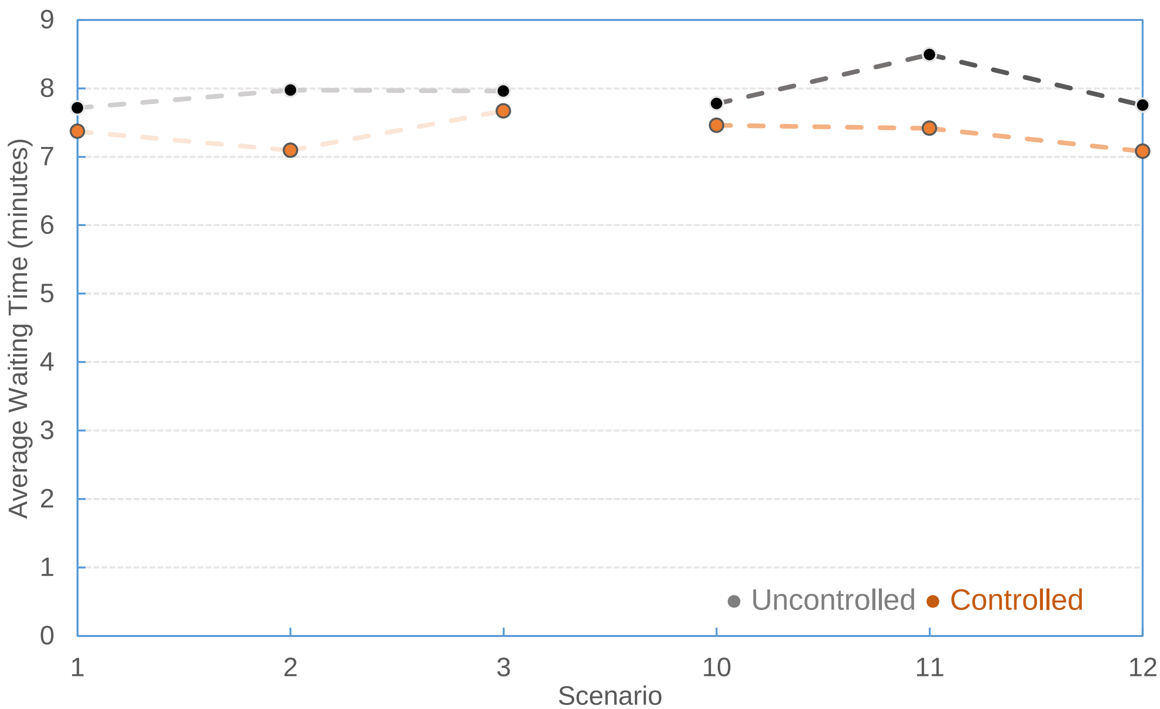


Figure 39: Average Passenger Waiting Time for Sensitivity Analysis on Incident, Quarter MPR

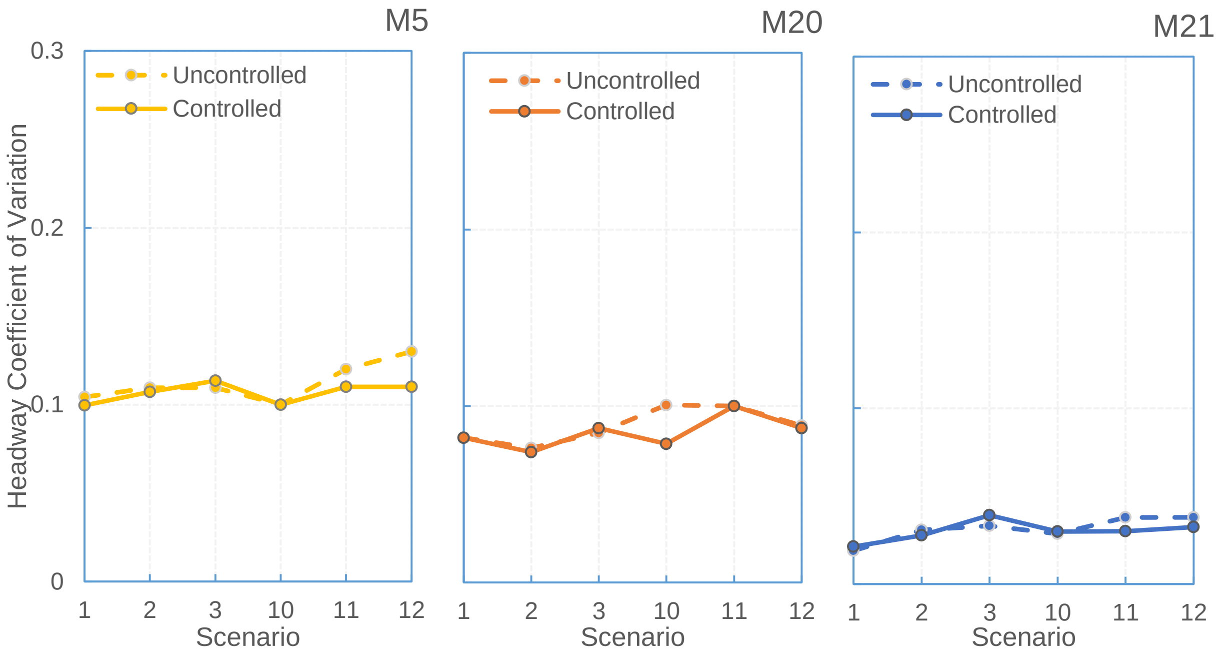


Figure 40: Headway Coefficient of Variation for Sensitivity Analysis on Incident, Quarter MPR

5.3.3.5 Sensitivity Analysis on Incident - Groups 5 and 6

As shown in Figure 41, the joint effect of incident and high demand leads to a deteriorated level of service, and it seems that the proposed system tends to be not effective in improving reliability under 25% MPR as under full MPR and 50% MPR situations. There are fluctuations in headway coefficient of variation among bus routes and different transfer levels, under controlled operations. Similar situation in the average waiting time can be observed in Figure 42, where the waiting times under controlled and uncontrolled operations are also the same under scenarios 16 through 18. Only when the transfer demand is high enough, the proposed system works to reduce average waiting time for the passengers.

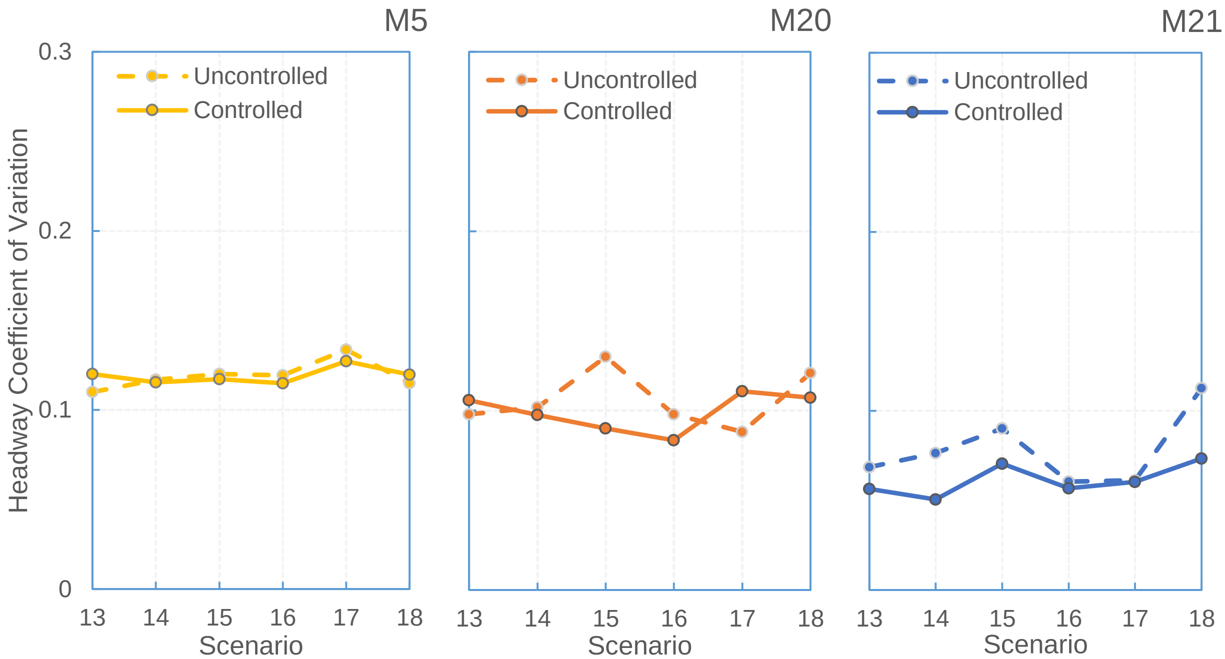


Figure 41: Headway Coefficient of Variation for Sensitivity Analysis on Incident with High Demand, Quarter MPR

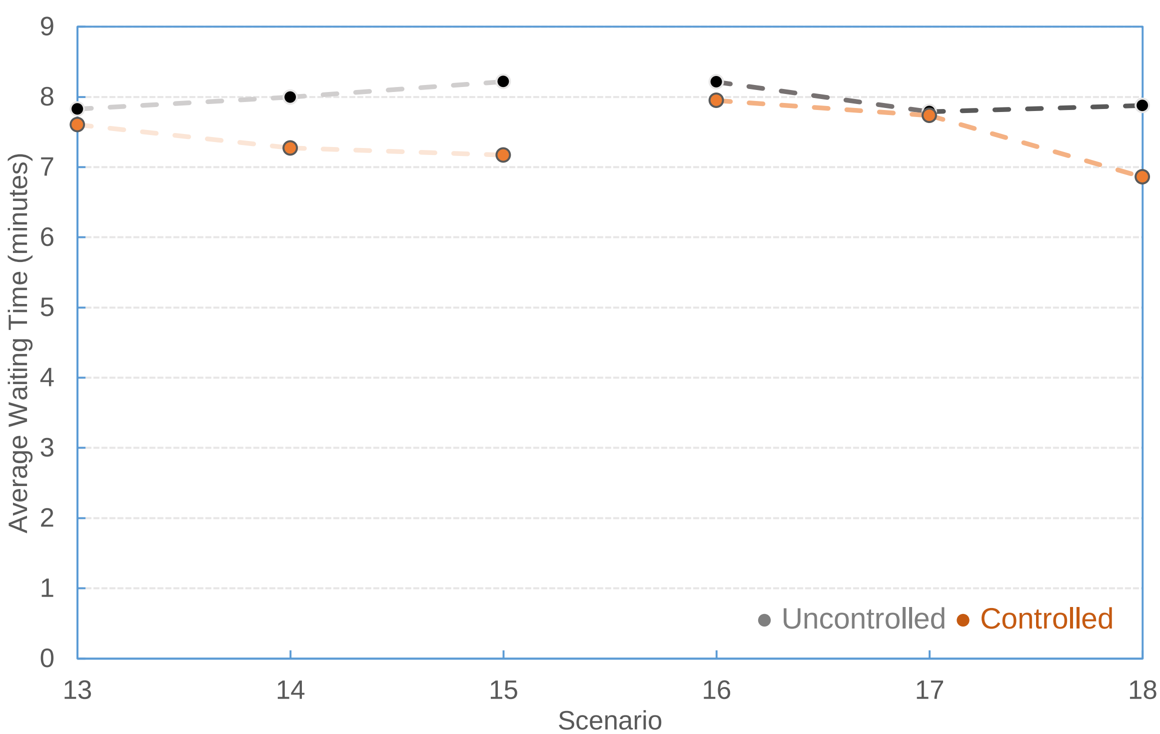


Figure 42: Average Passenger Waiting Time for Sensitivity Analysis on Incident with High Demand, Quarter MPR

6 Conclusions

This study presented a framework for smart bus management system. With the accessibility of real-time traffic information collected from connected vehicle environment, the proposed system realizes both dynamic route adjustment and smart transferring to enhance bus level of service. A simulation-based virtual test bed modeling New York City was created, and scenario analysis was conducted to examine the efficiency of the proposed system.

Observed from the case study, increasing demand have little effect on the bus system, especially if the traffic is light. Additionally, if the traffic is light, an incident may not have significant impact on the overall bus operations. However, the joint effect of high demand and an incident could have substantial influence and leads to deteriorated bus system level of service. The negative impact is enlarged when buses travels through a longer route and serves more stops.

The case study results also showed that under light demand and traffic condition, the benefit from the proposed system is marginal. However, when the traffic level increases or more demand/incident presents in the network, the positive influence of the proposed smart bus system starts to show up. Moreover, under the circumstance of traffic congestion, passengers could benefit from the proposed system by saving average transfer and waiting time, even under light demand condition. It was also discovered that holding a bus at a stop not only have an influence on the two connecting buses, but also impact the entire network, especially, if another transfer stop exists at downstream, passengers' waiting time at that downstream stop should also be considered.
The proposed system does improve the bus performance in terms of headway adherence and passenger waiting/transfer time for the majority of the studied cases. Especially, the effectiveness of the proposed system is not lowered when the market penetration shrinks. However, since the emphasis of two separate modules is slightly different (i.e., dynamic routing more on bus on-time arrivals, and smart transfers more for passengers' waiting time), differences in the effectiveness of the proposed system on passengers waiting time and transfer time are observed among various scenarios.

Considering which may enhance the performance and clarify benefits from the proposed system, the research team will continue this work with the following extensions:

- The case study will be conducted with two modules separately to identify the benefits and improvement for each of them.
- The algorithm on smart transfers should take into account the overall passengers that may be affected by a bus holding decision, to avoid any localized optimum turning into a negative impact globally.
- The criterion for dynamic routing could include the possibility of skipping stops if the number of passengers waiting at downstream stops to be skipped are substantial less than on-board passengers, so that the overall impact on passenger travel time from any congestion is minimized.
- Different thresholds for triggering dynamic routing and smart transfer modules need to be analyzed to find a best fit for the study bus network specifically.

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