PLANNING AND ASSESSMENT OF MULTIMODAL TRANSPORTATION SYSTEMS: CASE STUDIES IN SALT LAKE CITY, UT

Milan Zlatkovic, Ph.D., P.E.
University of Wyoming, Laramie, Wyoming, USA, mzlatkov@uwyo.edu

Aleksandar Stevanovic, Ph.D., P.E.
Florida Atlantic University, Boca Raton, Florida, USA, astevano@fau.edu

Sarah Zlatkovic, B.Sc.
University of Wyoming, Laramie, Wyoming, USA, szlatkov@uwyo.edu

Yu Song, M.Sc.
University of Wisconsin, Madison, Wisconsin, USA, yu.song@wisc.edu

Nikola Mitrovic, Ph.D.
Florida Atlantic University, Boca Raton, Florida, USA, nmitrovi@fau.edu

Igor Dakic, M.Sc.
ETH Zürich, Zürich, Switzerland, igor.dakic@ivt.baug.ethz.ch

DOI: 10.31075/PIS.64.04.01

Professional paper

Abstract: *The need for multimodal transportation alternatives in metropolitan areas is increasing because of the inability to build more capacities for low-occupancy vehicles. This paper describes multimodal alternative analysis and comparisons of potential improvements. The alternatives include Bus Rapid Transit (BRT), addition of bicycle lanes, implementation of Transit Signal Priority (TSP) and introduction of a streetcar line. The analysis was performed through traffic microsimulation for the target 2025 year. The implementation of upgraded transit systems and TSP has the potential to significantly improve system performance. Person-based delays decrease and transit speeds improve, with a significant increase in the offered transit productive capacities. With optimization of operations and geometry improvements, the performance of vehicular traffic is not impacted by transit-friendly solutions. In a well-balanced network, it is important to offer more travel choices through increased transit service and options for non-motorized traffic, equally considering efficiency and safety for all travel modes.*

Keywords: *Multimodal Transportation; Alternative Analysis; Person-Based Metrics; Transit Productive Capacity; Microsimulation.*

1. INTRODUCTION

As the traffic demand in metropolitan areas continues to increase, it has become clear that the big cities cannot build their way out of congestion. Therefore, there is a need among the transportation agencies to better manage the existing infrastructure and optimize the utilization of available capacities. The planning and design for transportation systems are shifting their focus from private cars, which are, in many cases, single occupancy, toward high occupancy vehicles, typically public transit, as well as active transportation modes, such as walking and biking. Innovative transportation solutions, Intelligent Transportation Systems (ITS) technologies, high-capacity rapid transit modes, advanced Transit Signal Priority (TSP) systems and similar technologies are gaining momentum, since they have the ability to increase capacities and reduce congestion of transportation facilities. These strategies are being implemented to improve the corridors' multimodal performance.

All major transportation agencies in the Salt Lake City (SLC) metropolitan area have recognized the need for integrated transportation that would facilitate all transportation modes and have begun working together to achieve this common goal. Freeway express lanes have been built, high-capacity transit modes (Bus Rapid Transit (BRT) and Light Rail Transit (LRT)) are rapidly expanding, innovative solutions (reversible lanes, innovative intersections and interchanges, and advanced signal performance metrics systems) are seeing an increase in deployment. In addition, exclusive and shared bicycle lanes are being deployed, a bicycle share (Green Bike) program is rapidly expanding, and pedestrian traffic is being facilitated in many areas, in order to improve the transportation system as a whole.

This study focuses on areas that have a high potential to improve the multimodality of the transportation system. These are the major corridors characterized by heavy traffic and transportation facilities shared by different users: State Street and a sub-area in the Downtown SLC. This study designs multimodal alternatives, based on the existing plans and future needs, and assesses the performance of different transportation modes through traffic microsimulation. The uniqueness of this paper is in performing person-based and vehicle-based analyses simultaneously, including vehicular, transit and bicycle transportation. It also preforms analyses of offered transit productive capacities, which has not been performed in the literature in such a detailed manner.

2. LITERATURE REVIEW

The lack of transportation capacities to meet future demand is recognized as the major obstacle for both passenger and freight movements, especially along urban corridors [1]. Building the way out of congestion by adding new capacities has proven an inadequate strategy. The implementation of multimodal systems, with a focus on passenger throughput rather than vehicles, has gained momentum among transportation agencies.

Until the 1970's, the private automobile was the main transportation mode in the US [2]. Shifting toward a transportation system that supports all modes of travel involves changing the focus from moving vehicles to moving people and goods [3]. Big US cities saw advances in public transportation systems in the 1970's and onward with advances in technology, rapid transit systems and ITS, as well as the creation of public agencies (transit authorities and districts) in charge of planning, design and operation of transit services [4]. Since the 1990's the transportation agencies started working together toward coordinating multimodal transportation. The overall goal of multimodal integration is to improve mobility and accessibility for all users [3, 5]. Accessibility, which is the ability of people to reach destinations and services, considers a wide range of impacts, objectives and options, and is of particular importance for multimodal operations [6]. Planning for multimodal operations needs to include all existing or expected modes within the study area (automobile, public transit, walking, cycling etc.). Different types of studies, such as traffic impact studies, local, regional or state planning, strategic planning, corridor planning, improvement plans, all depending on the scale and objectives, are typically performed within multimodal transportation assessment [7].

In a multimodal system, in addition to measuring the level of service (LOS) for automobiles, it is also required to measure the LOS for transit, pedestrian, and bicycle users [8]. The main issue is to define the meaning of LOS in the multimodal context. Therefore, researchers and practitioners are assessing the best performance measures that can be used to compare different modes, without favoring one over the other. The Florida Multimodal Mobility Performance Measures Source Book uses four dimensions of mobility to establish a multimodal performance matrix: quantity of travel, quality of travel, accessibility and utilization of transportation systems [5].

The quantity depicts the magnitude of travel on a facility, using measures such as miles traveled for vehicles, persons, passengers, freight, number of passenger trips and similar. The quality describes the travel experience, using measures such as delays, speeds, travel time reliability/variability, and percentage of miles/travel meeting LOS criteria, among others. Accessibility incorporates concepts of connectivity, modal options and time to reach destinations using measures as span of transportation service, access to transit, time spent commuting, highway adequacy, percentage of sidewalk/bike lane coverage and similar. Utilization describes the relative supply and demand of transportation facilities, which indirectly relates to the users' perception of congestion.

The measures of utilization include density, percentage of miles/travel heavily congested, hours heavily congested, and passenger trips per revenue miles, among others. In its Corridor Capacity Report, the Washington State Department of Transportation (DOT) describes and analyzes performance measures from a multimodal perspective, including automobile, transit, bicycle and walking commuting rates, as well as congestion indicators (delay, vehicle/person miles traveled, percent of congestion, throughput and reliability index) among other parameters [9]. The City of Seattle recognizes the problem of the limited street space and the inability to build new capacities, therefore turning toward multimodal solutions to make the best use of the available capacities [10].

The Washington D.C. Department of Transportation (DOT) has identified a set of performance measures for multimodal mobility, which are based on available data, and is making the metrics available to the public through a visualization tool [11]. The performance measures are classified into three main groups: intensity of usage, travel time reliability and accessibility. The intensity of usage measures include LOS, average commute times and travel time indexes, which are used to rate congestion. Travel time reliability measures variability in travel time for the same trip and is of particular importance for trip planning. Accessibility is seen in two ways: as accessibility to modes and accessibility to destinations, and mostly depends on mode availability and network configuration. San Francisco Municipal Transportation Agency (SFMTA) reports the combined performance of the transportation system with the main focus on safety, multimodal sustainable transportation, environment/quality of life and workplace [12, 13]. The Chicago area is another example of coordinated multimodal transportation systems. Currently the Chicago Metropolitan Agency for Planning (CMAP) reports on multimodal performance of the system through an interactive online tool [14]. Therefore, the major planning components for the future transportation systems include walkable communities, innovative transportation and constrained resources, in order to find sustainable solutions.

This paper presents an approach for multimodal planning, design and evaluation using two types of test-beds in Salt Lake City, UT. The evaluation was based on microsimulation models, and the results were aggregated on the person-based level. In addition to the typical performance measures used in previous studies, the analysis included transit productive capacities for the future transit service. The transit productive capacity is a dynamic measure, incorporating the capacity of the transit line and transit operating speed [15]. It shows the supply side of transit service that depends on the design and operations of both transit and street facilities and can enhance the transit planning process.

3. STUDY NETWORKS

The analysis was performed through VISSIM microsimulation on two study networks in Salt Lake City, Utah: a north-south corridor (State Street) between 500 S and 2100 S, and a portion of Downtown Salt Lake City bounded by Main Street, South Temple, 600 W and 400 S. The layouts of the networks are shown in Figure 1. Both networks are characterized by heavy peak traffic. State Street in the vicinity of the downtown area is a multi-modal corridor, with a combination of car traffic, bus transit and non-motorized modes. Downtown area is characterized by significant transit flows, including LRT lines, regular and express bus routes, pedestrian and bicyclists transportation and car traffic. The study explores the potential of the networks and their ability to incorporate multiple modes in order to meet the future transportation demand.

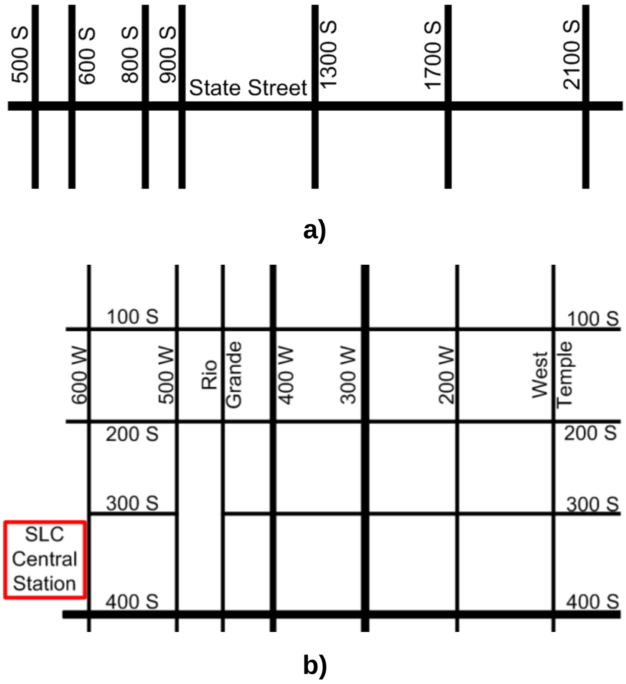


Figure 1: Network Layouts: a) State Street; b) Downtown SLC

4. METHODOLOGY AND DEVELOPMENT OF MODELS

The study analyzes the performance of the test-case network from a multimodal perspective using VISSIM microsimulation. The results presented in this paper include signalized intersection performance (throughput and delays for vehicles and persons), segment travel speeds, where a segment is defined between pairs of signalized intersections, and transit productive capacities. Intersection performance and travel speeds are presented separately for each mode: car, transit and bicycles. The result for pedestrians are not given separately in this study. The offered transit productive capacity is calculated as a product of the offered transit line capacities along a corridor (C) in spaces per hour (sps/h) and transit operating speeds (V_o) in kilometers per hour (kph) (Vuchic, 2007b):

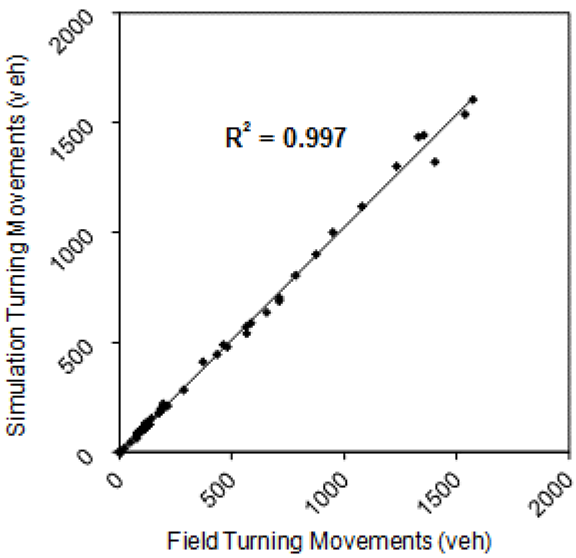
$$P_c = C \cdot V_o \quad [sps - km/h^2] \tag{1}$$

The offered transit line capacity is computed as a product of transit vehicle capacities and transit frequencies along the given corridor. In this study, vehicle capacities are taken as 40 spaces/bus for regular and express buses, 60 spaces/bus for BRT, 195 spaces/tram for streetcar, and 880 spaces/train for LRT train compositions. An LRT composition during the analyzed PM peak hour consists of four LRT cars, with a capacity of 220 spaces/car. These values are adapted according to the transit vehicle types that the Utah Transit Authority (UTA) is using in service (Gillig 40 buses for regular/express routes, Van Hool A300 for BRT, Siemens S70 Streetcar and Siemens S70 LRT for rail modes).

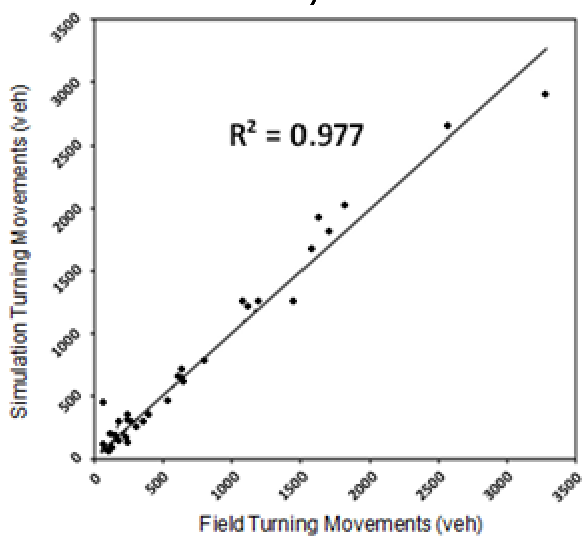
The development of the VISSIM microsimulation models was based on the actual roadway and intersection geometries and traffic and transit operations. The data used in modeling include vehicular volumes and intersection turning movements, pedestrian and bicyclist volumes, corridor travel times, transit network and ridership data, and signal timings. Traffic volume data, including bicyclists and pedestrians, as well as vehicular travel times, were collected in the field. Signal timing data were obtained from the Utah Department of Transportation (UDOT), and street views and field visits were used for a precise definition of signal heads, left turn treatment and stop bar/pedestrian crossings positions. Transit routes and stop locations were modeled according to the maps available on the UTA's official website. Transit schedules, ridership and transit travel times were obtained directly from UTA. The two test-case networks were created in separate microsimulation models. The 2015 turning movement counts for signalized intersections for each network were used for calibration, as shown in Figure 2. All base models were calibrated with R-squared values larger than 0.95. The observed corridor travel times, queueing properties and delays were used to validate the model. The research team observed actual traffic conditions and adjusted the models until satisfactory results were achieved.

Statistical analyses were performed on the obtained results to assess the statistical significance in the differences among the scenarios. The null hypothesis was that there were no significant differences between results. For the State Street corridor, a paired t-test on the 95% confidence level was used, since this corridor introduced two alternatives.

The Downtown SLC network included three alternatives, so a different statistical approach was implemented. A one-way analysis of variance (ANOVA) followed by a Dunnett's post hoc test were used to determine significant differences in performances between the alternative scenarios and the base scenario. The one-way ANOVA is used to determine if there exists a statistically significant difference in means between a group of three or more, giving an F statistic with (x, y) degrees of freedom and a p-value. Where the ANOVA found significance, the post hoc Dunnett's test was run to identify the groups that were statistically significantly different at a 95% confidence level. Dunnett's test is a multiple comparison test used to compare each alternative to the base scenario and provide a t-statistic for each comparison. The statistical analysis was performed in the SPSS software package.



a)



b)

Figure 2: Model Calibration: a) State Street; b) Downtown SLC

The analysis and comparison was performed for the 2025 target year. Sets of improvement strategies were selected for each sub-network and implemented in microsimulation as separate scenarios. The Base 2025 scenario is a Do-Nothing alternative against which the other scenarios were compared. It includes new traffic demand, as projected for 2025, with only optimization of traffic signals for the new demand levels and no other improvements. The analyzed alternatives for each sub-network are described in the next section.

5. IMPROVEMENT ALTERNATIVES

Planning for multimodal transportation was performed for the 2025 target year, taking into consideration the expected growth in transportation demand for all modes and the needs for providing sufficient capacities. Local agencies conducted earlier studies for some of these networks, and developed transportation plans to account for expected future changes in transportation needs [16 – 18]. The alternatives developed in this research are built upon the recommendations from these studies, and also present some new solutions that can be considered. In general, the following alternatives can describe the needs for future improvements for the analyzed networks:

- Exclusive transit lanes on State Street.
- Addition/upgrade of bicycle lanes.
- Enhanced bus services on State Street (BRT with consecutive bus lanes and TSP).
- Enhanced pedestrian facilities (improved mid-block crossings and signals, sidewalks) for both networks.
- Transit improvements with TSP implementation in the Downtown SLC area.
- A streetcar line in Downtown SLC.

5.1. State Street Corridor Alternatives

State Street corridor is a multimodal corridor with car traffic, transit routes with high ridership, and bicycle and pedestrian traffic, especially in the vicinity of the downtown area. Local agencies have recognized the need to improve this corridor, making it a calmer place for people to live and work [18]. The State Street corridor will undergo traffic and transit improvements in the near future, with potential BRT and TSP implementations, and operational improvements at critical locations. Therefore, it was analyzed for a center-running BRT alternative with bicycle lanes along all segments. This scenario introduces BRT operations with buses running every 15 minutes, TSP, fewer bus stops located at high-demand locations with improved pedestrian access, higher speeds and increased ridership.

The new demand was computed based on the 2.4% yearly growth rate. Synchro was used to optimize the signals for the new demand levels. The signals were re-phased for protected-only left turns because of the center BRT lanes. Ten seconds of early green/green extension TSP were incorporated into the signal timings. Additional design and operational improvements included longer storage space for turn lanes at intersections and dual left turn lanes at intersections with high left turn volumes.

5.2. Downtown SLC Alternatives

The entire downtown SLC network is a multimodal area, with heavy car traffic, high transit frequencies and ridership, and non-motorized traffic. Two improvement alternatives were studied for the Downtown SLC sub-network: a TSP scenario, and a street car implementation along 200 S/400 W [19]. The signals were optimized for the 2025 projected traffic demand. The TSP scenario incorporated 10 seconds of green extension and early green assigned to all bus routes in the network.

In the streetcar scenario, streetcar tracks were added along 400 W from 400 S to 200 S, followed by streetcar tracks along 200 S to the east. The streetcars ran on a 20-minute headway-based schedule, and preemption was implemented for all signals along the line. Streetcar stations were implemented on the far side of the intersections, in order to minimize impacts on vehicular traffic. That way the preemption did not affect the signal operation at the downstream intersection while the streetcar was stopped at the station. Additional improvements in the TSP and streetcar scenarios included minor changes in intersection geometries to allow for more storage space for left turns and updates to pedestrian and bicycle connections.

6. RESULTS AND DISCUSSION

Analyses and comparisons of State Street and Downtown SLC alternatives are performed using the developed microsimulation models. The results show the performance during the two-hour PM peak period (4:00 - 6:00 PM) for different modes. Each scenario was run for five random seeds, with a 15-minute warm-up time. Three types of evaluations are shown: intersection performance, corridor travel speeds, and the average corridor transit productive capacities. The intersection performance results include total person-based delays for the two hour PM peak period, separated by mode (car, transit and bicycles, where applicable). Travel speeds are provided on the vehicular level for each segment between pairs of signalized intersections for the three modes, where applicable. The offered transit productive capacities were computed based on the line capacities for predicted transit frequencies along the analyzed corridors, and transit operating speeds obtained from the microsimulation models.

6.1. State Street Corridor

The State Street corridor results on intersection performance, segment speeds and transit productive capacities and statistical analyses for the two scenarios in the target year are given in Tables 1 to 3. In the BRT + Bike Lane scenario, the existing Bus Route 200, running on 15-minute headways, was replaced with a center-running BRT line with updated transit operations and TSP implementation.

Table 1: 2-hr PM Peak Intersection Performance Results - State Street

Intersection	Total person delays (hrs)					
	Base 2025			**BRT + Bike Lane 2025**		
	Car	**Bus**	**Bike**	**Car**	**BRT**	**Bike**
500 S	218.1	7.28	0.14	269.0	1.33	0.12
600 S	110.9	4.01	0.24	222.9	2.88	0.28
800 S	118.6	4.73	1.48	184.7	1.45	1.77
900 S	59.4	1.68	0.23	76.0	1.94	0.36
1300 S	206.3	6.37	0.24	170.3	4.89	0.23
1700 S	204.3	4.91	0.11	163.6	2.92	0.14
2100 S	346.9	5.94	0.42	274.2	3.16	0.46
Total	**1,264**	**34.9**	**2.9**	**1,360**	**18.6**	**3.4**

The introduction of BRT and bicycle lanes increases person delays for car and bicycle modes 9% and 23%, respectively, while decreasing person delays for transit. The changes in person delays for transit and bicycle modes are statistically significant, with a p value of less than 0.001 for transit (indicating statistically highly significant difference), and a p value of 0.015 for bicycles. The person delays for transit reduced more than 50% in the BRT scenario.

The increase in car and bicycle delays is attributed to the modified intersection operations with center-running BRT lanes. All left turns along State Street had to be modified to protected-only because of conflicts with BRT. This increases delays for the left turning vehicles along the main corridor. Transit speeds significantly increase in the BRT + Bike Lane scenario ($p < 0.001$), more than 70% on average. The southbound car speeds slightly increase, while the northbound speeds significantly reduce ($p < 0.001$). Similarly, bicycle speeds reduce in both directions, with the significant difference observed only in the northbound direction ($p = 0.032$).

Table 2: 2-hr PM Peak Travel Speeds and Transit Productive Capacities - State Street

	Segment	**Base 2025**			**BRT + Bike Lane 2025**		
		Speed (kph)					
		Car	Bus	Bike	Car	BRT	Bike
Southbound	500 S - 600 S	20.5	11.4	10.6	19.7	45.9	9.8
	600 S - 700 S	44.3	30.4	17.4	45.3	17.6	16.6
	700 S - 800 S	20.3	11.4	13.3	15.8	20.0	10.9
	800 S - 900 S	31.5	18.7	13.9	35.7	44.8	12.5
	900 S - 1300 S	18.1	14.1	16.3	28.5	19.7	16.8
	1300 S - 1700 S	6.9	6.4	16.2	7.5	21.3	17.0
	1700 S - 2100 S	8.5	8.2	14.9	9.0	23.7	14.9
Northbound	2100 S - 1700 S	34.4	25.8	16.0	34.4	25.0	15.7
	1700 S - 1300 S	34.2	23.7	16.6	35.2	20.2	15.2
	1300 S - 900 S	55.5	27.0	17.4	50.9	19.2	15.7
	900 S - 800 S	41.0	14.2	12.3	17.1	49.1	12.2
	800 S - 700 S	37.1	15.2	16.0	23.8	54.9	15.2
	700 S - 600 S	13.3	11.0	13.6	5.9	10.2	9.3
	600 S - 500 S	20.2	9.4	12.6	10.4	46.7	14.9
P_c	SB	2,486 sps-km/h^2			6,632 sps-km/h^2		
	NB	2,960 sps-km/h^2			7,739 sps-km/h^2		

There is also a statistically highly significant increase in the offered transit productive capacities after the BRT introduction of 200% and 130% in the southbound and northbound direction, respectively, with p values of less than 0.001 in both cases. Although the transit frequencies are the same in both scenarios, the BRT introduces higher-capacity vehicles (50% more spaces per bus), and the operating speeds are much higher. BRT on State Street would offer a highly-competitive transportation mode to private cars and significant transit capacities, especially in the peak southbound direction.

Table 3: Statistical Analysis - State Street

Parameter	**Mode-Scenario**	**t**	**p**
Total Person Delays	Car Base	-1.284	0.208
	Car BRT + Bike		
	Bus Base	7.211	< 0.001
	Bus BRT + Bike		
	Bike Base	-2.561	0.015
	Bike BRT + Bike		
Speed SB	Car Base	-1.505	0.137
	Car BRT + Bike		
	Bus Base	-6.544	< 0.001
	Bus BRT + Bike		
	Bike Base	1.639	0.106
	Bike BRT + Bike		
Speed NB	Car Base	6.930	< 0.001
	Car BRT + Bike		
	Bus Base	-5.568	< 0.001
	Bus BRT + Bike		
	Bike Base	2.190	0.032
	Bike BRT + Bike		
Pc SB	Bus Base	-7.621	< 0.001
	Bus BRT + Bike		
Pc NB	Bus Base	-6.190	< 0.001
	Bus BRT + Bike		

6.2. Downtown SLC

The two improvement scenarios for the downtown area include the addition of TSP for all buses in the network, and an introduction of a streetcar line along 200 S and 400 W corridors. The streetcar replaces the existing bus route RT 2 which currently runs along 200 S. The simulation results for the three downtown scenarios on intersection performance, travel speeds, transit productive capacities and statistical analyses are shown in Tables 4 to 6. The intersection performance and travel speed results in are shown only for the 400 W and 200 S corridors, which are most heavily utilized from the transit perspective, including LRT, and where the future streetcar line is introduced. The statistical analysis in is provided for the overall Downtown network, where the significance is compared to the Base scenario. A separate analysis was also performed for the 400 W and 200 S corridors.

Table 4: 2-hr PM Peak Intersection Performance Results – Downtown SLC Sub-Area

	Total person delays (hrs)											
	Base 2025				**TSP 2025**				**Streetcar 2025**			
Intersection	Car	Bus	Rail	Bike	Car	Bus	Rail	Bike	Car	Bus	Rail	Bike
400 S - 500 W	77.4	0.5	0.0	0.0	83.3	0.6	0.0	0.0	82.0	0.6	0.0	0.0
400 S - 400 W	82.9	1.7	0.0	0.0	99.4	1.7	0.0	0.0	130.2	2.6	0.1	0.0
400 S - 300 W	146.8	0.7	0.0	0.0	167.0	1.6	0.0	0.0	141.3	0.7	0.0	0.0
400 S - 200 W	135.1	2.0	0.0	0.1	114.8	1.5	0.0	0.3	143.2	2.0	0.0	0.1
400 S – W. T.	198.1	2.3	0.0	0.0	213.3	1.9	0.0	0.0	194.5	2.2	0.0	0.0
200 S – W. T.	60.3	4.7	0.0	0.3	61.5	3.5	0.0	0.3	68.2	4.5	0.2	0.4
200 S - 200 W	42.7	4.7	0.0	0.6	50.1	2.9	0.0	0.5	54.6	6.2	0.4	0.7
200 S - 300 W	88.0	13.7	0.0	0.8	90.4	7.9	0.0	0.5	70.3	10.6	0.1	0.8
200 S - 400 W	79.8	14.5	1.3	0.7	76.2	10.7	1.4	0.5	82.5	14.3	1.4	0.8
200 S - 500 W	33.7	6.9	1.6	0.2	32.9	6.4	2.0	0.2	33.2	6.4	1.5	0.2
200 S - 600 W	25.0	7.8	1.3	0.4	26.0	6.7	1.3	0.5	24.5	7.7	1.3	0.5
Total	**970**	**59.5**	**4.2**	**3.1**	**1,015**	**45.4**	**4.7**	**2.8**	**1,025**	**57.8**	**5.0**	**3.5**

Table 4a: 2-hr PM Peak Travel Speeds and Transit Productive Capacities – 400 W

	Segment	**Base 2025**			**TSP 2025**			**Street Car 2025**			
		Car Speed (kph)	**Bus Speed (kph)**	**LRT Speed (kph)**	**Car Speed (kph)**	**Bus Speed (kph)**	**LRT Speed (kph)**	**Car Speed (kph)**	**Bus Speed (kph)**	**LRT Speed (kph)**	**Streetcar Speed (kph)**
Northbound	400S – 300S	49.4	27.8	N/A	49	24.8	N/A	43	24.3	N/A	13.4
	300S – 200S	16.4	22.9	N/A	16.1	16	N/A	15.4	19.1	N/A	33.9
	200S – 100S	21	N/A	9.5	21.5	N/A	10.2	20.9	N/A	9.9	N/A
	100S – S. Temp	21.9	N/A	20.3	23.3	N/A	20.2	22.8	N/A	19.4	N/A
Southbound	S. Temp – 100S	21.6	N/A	15	21.7	N/A	18.7	21.9	N/A	19.6	N/A
	100S – 200S	22.6	N/A	8.5	16.3	N/A	8.5	17.2	N/A	8.7	N/A
	200S – 300S	44.5	23.3	N/A	36.6	24.4	N/A	37.5	25.3	N/A	37.7
	300S – 400S	18.5	16.7	N/A	16.6	18.2	N/A	13.2	13.2	N/A	12.4
P_c	NB		29,387 sps-km/h^2			29,717 sps-km/h^2			35,891 sps-km/h^2		
	SB		23,299 sps-km/h^2			26,982 sps-km/h^2			35,206 sps-km/h^2		

Table 4b: 2-hr PM Peak Travel Speeds and Transit Productive Capacities – 200 S

	Segment	Base 2025			TSP 2025			Street Car 2025			
		Car Speed (kph)	Bus Speed (kph)	LRT Speed (kph)	Car Speed (kph)	Bus Speed (kph)	LRT Speed (kph)	Car Speed (kph)	Bus Speed (kph)	LRT Speed (kph)	Streetcar Speed (kph)
Eastbound	600W – 500W	21.7	15.2	8.4	22	15.9	7.8	21.3	15.7	8.5	N/A
	500W – 400W	15.7	13.6	32.5	19.2	16.1	31.5	16.5	13.6	30.8	N/A
	400W – 300W	22.7	17.5	N/A	21	20.6	N/A	21.2	14.8	N/A	36.1
	300W – 200W	34.4	14.1	N/A	22.6	18.1	N/A	20.6	12.6	N/A	13.4
	200W – W Temp	28.9	9.2	N/A	29.1	10.8	N/A	26.3	14.3	N/A	35.2
Westbound	W Temp – 200W	23.5	20.3	N/A	21.3	23.5	N/A	18.8	16.3	N/A	13.3
	200W – 300W	17.6	12.1	N/A	16.6	16.1	N/A	21.8	12.4	N/A	34.7
	300W – 400W	11.2	10.7	N/A	15.8	15.4	N/A	13.8	11.6	N/A	12.7
	400W – 500W	28.9	16.4	25.5	30	17.4	26.7	30	16.8	29.3	N/A
	500W – 600W	29.4	20.5	9.4	29.2	20.3	9.3	30	20.5	9.6	N/A
P_c	EB		47,338 sps-km/h^2			49,440 sps-km/h^2			54,467 sps-km/h^2		
	WB		45,312 sps-km/h^2			49,325 sps-km/h^2			52,339 sps-km/h^2		

On the network level, the person delay results show an average reduction of about 23% in bus person delays in the TSP scenario, and a reduction of 35% in rail person delays (which includes LRT and streetcar) in the Streetcar scenario compared to Base scenario. The TSP scenario results in the lowest bus person delays since all buses in the network benefit from TSP. Since streetcars are preempted at signals, the Streetcar scenario results in the lowest rail person delays, which is the only statistically significant difference in person delays compared to the Base scenario, with a p value of 0.019. Similarly, the speed analysis shows the only statistically significant difference in rail speeds in the Streetcar scenario ($p = 0.018$), where the average rail speed is about 26% higher than in the Base scenario. The overall offered transit productive capacities are highest in the Streetcar scenario, on average 13% higher than in Base. However, no statistically significant difference was observed in TSP or Streetcar scenarios compared to Base.

A statistically significant difference in bus person delays was found between TSP and Base scenarios along the 200 S corridor ($p = 0.019$), which is used by multiple bus routes converging to the SLC Central Station. The average decrease of bus person delays was about 27%. A slight increase in car person delays was observed in both improvement scenarios (2% and 5% for TSP and Streetcar scenarios, respectively), because they favor transit at signalized intersections. The lowest bicycle delays were recorded in the TSP scenario, and the highest in the Streetcar scenario since the new rail line interrupts bicycle traffic at several locations.

The lowest car speeds along the 400 W and 200 S corridors are recorded in the Streetcar scenario, with 11% and 6% average reduction in speeds compared to the Base scenario, respectively. However, the only statistically significant difference was found for the eastbound car speeds on 200 S ($p = 0.024$). The streetcar preemption disrupts the signal operation at intersections, causing loss in progression and therefore lower vehicular speeds. The other downtown corridors do not show considerable changes in vehicular speed in the TSP and Streetcar scenarios. Bus speeds do not show significant changes in the downtown area, although the highest speeds along most corridors are recorded in the TSP scenario. The only significant change in bus speeds exists along the 200 S corridor (p = 0.007 eastbound and p = 0.029 westbound) in the TSP scenario, which is about 20% higher than in the Base scenario. Similarly, the LRT speeds are the highest in the TSP scenario along 400 W and 200 S, although the difference is not statistically significant when compared to the Base scenario. The average streetcar speeds along the 400 W and 200 S corridors are higher than bus and LRT speeds, which is mostly due to the streetcar preemption at intersections.

Table 5: Statistical Analysis - Downtown SLC

Parameter	Mode-Scenario	F (ANOVA)	p*
Total Person Delays	Car Base	F_{calc} = 0.075 F_{crit} = 2.9957	
	Car TSP		0.933
	Car Streetcar		0.911
	Bus Base	F_{calc} = 1.342 F_{crit} = 2.9957	
	Bus TSP		0.231
	Bus Streetcar		0.976
	Rail Base	F_{calc} = 4.616 F_{crit} = 2.9957	
	Rail TSP		0.989
	Rail Streetcar		0.019
	Bike Base	F_{calc} = 0.277 F_{crit} = 2.9957	
	Bike TSP		0.773
	Bike Streetcar		0.995
Speed	Car Base	F_{calc} = 1.643 F_{crit} = 2.9957	
	Car TSP		0.188
	Car Streetcar		0.219
	Bus Base	F_{calc} = 1.799 F_{crit} = 2.9957	
	Bus TSP		0.381
	Bus Streetcar		0.722
	Rail Base	F_{calc} = 4.388 F_{crit} = 2.9957	
	Rail TSP		0.936
	Rail Streetcar		0.018
Pc	Transit Base	F_{calc} = 0.394 F_{crit} = 2.9957	
	Transit TSP		0.919
	Transit Streetcar		0.583

* Compared to the Base scenario

The offered transit productive capacities along 400 W and 200 S, that include bus, LRT and streetcar, are the highest in the Streetcar scenario, although these changes are not statistically significant on the corridor levels. Transit productive capacities in the Streetcar scenario are 35% and 15% higher along 400 W and 200 S, respectively, compared to the Base scenario. However, along the segments where the streetcar was introduced on 400 W and 200 S, the statistical analysis shows a significant difference between the Streetcar and the other two scenarios, with p values of less than 0.001 for all comparisons. Other corridors in the downtown area show highest transit productive capacities in the TSP scenario, since the line capacities remained the same, but the average bus speeds increased.

From the transit standpoint, the optimal scenario for the downtown area is the TSP scenario, which provides higher transit speeds and offered transit productive capacities with minimal or no impacts on other modes. The streetcar offers higher line capacities due to the higher capacity of the streetcar vehicles, but it also impacts other modes especially at intersections because of the preemption. An optimization of streetcar operations might improve this scenario further, making it a competitive alternative for the future.

All results obtained from the simulation and the statistical tests are available at Mendeley data (doi:10.17632/dszzkdxk4j.1). The Excel files provide intersection, travel time/speed and transit productive capacity results, while the pdf files provide the methods and results of the statistical analyses.

7. CONCLUSIONS

This paper describes the development and analysis of multimodal transportation alternatives for two sub-networks in Salt Lake City, UT: State Street and Downtown SLC. The needs for multimodal changes and improvements of these networks are recognized and documented by the local transportation agencies. This study develops a set of alternatives that include improvements for car, transit and bicycle modes, and perform operational assessment for the target 2025 year.

State Street is a multimodal corridor that is being planned for a complete overhaul in the oncoming years. Since it carries high transit ridership, a BRT implementation is proposed, so this study assessed an alternative with center-running BRT lanes accompanied by exclusive bicycle lanes. For the target year, this alternative significantly improves transit service and increases offered transit productive capacities. Transit person-delays reduce about 50%, transit speeds increase about 70%, and transit productive capacities increase up to 200%. Some impacts to cars and bicyclists are recorded, mostly at intersections, because of the modified signal operations with protected-only left turns.

Car person-delays increase about 9%, while bicycle delays increase 23%. Special attention needs to be given to bicycle traffic along this corridor because of its existing high and growing demand, especially in the vicinity of the downtown area. Therefore, fully exclusive bicycle lanes are recommended, mostly because of the safety concerns.

The two alternatives for the multimodal Downtown SLC area include improvements in transit and non-motorized traffic through an area-wide TSP implementation, and a streetcar introduction. The TSP has a potential to significantly reduce bus-person delays, 23% on the network level, and offer higher transit productive capacities within the entire network, without significant impacts to other modes. A new streetcar line, replacing one of the busiest transit routes, offers higher rail speeds (about 26%) and transit productive capacities (increase of about 13%) along its alignment, but also interrupts other traffic modes. This is caused by the signal preemption for the streetcar. With additional optimization for streetcar operations, as well as TSP implementation for buses, the streetcar scenario would be a viable transit option for Downtown SLC.

Future research should analyze additional improvement alternatives for specific segments and intersections, with a more detailed scope. Also, an area-wide analysis should be conducted to account for impacts of changes on adjacent corridors due to the potential vehicle rerouting. A parallel safety assessment should be included to perform a multi-criteria evaluation of proposed alternatives.

Acknowledgements

This study was funded by the Utah Transit Authority (UTA) and the Utah Department of Transportation (UDOT). The authors thank UTA and UDOT personnel for their assistance, comments, suggestions and data sharing.

References

[1] Cambridge Systematics, Inc. (1998). *Multimodal Corridor and Capacity Analysis Manual*. National Cooperative Highway Research Program (NCHRP), No. 399. Washington, D.C.: Transportation Research Board.

[2] Boyac, B. and Geroliminis, N. (2011). Estimation of the Network Capacity for Multimodal Urban Systems. *Procedia Social and Behavioral Sciences*, Vol. 16, pp. 803–813.

[3] Williams, K. M. and Seggerman, K. E. (2014). *Multimodal Transportation Best Practices and Model Element*. Tallahassee, FL.: Florida Department of Transportation.

[4] Vuchic, V. (2007). *Urban transit systems and technology*. Hoboken, NJ: John Willey & Sons, Inc.

[5] Florida Department of Transportation. (2016). *Multimodal Mobility Performance Measures Source Book*. Tallahassee, FL.: Florida Department of Transportation.

[6] Litman, T. (2017). *Towards More Comprehensive and Multi-modal Transport Evaluation*. Retrieved July 30, 2018, from Victoria Transport Policy Institute: http://www.vtpi.org/comp_evaluation.pdf

[7] Litman, T. (2017). *Intro to Multi-Modal Transportation Planning*. Retrieved July 30, 2018, from Victoria Transport Policy Institute: http://www.vtpi.org/multimodal_planning.pdf

[8] Dowling, R. et al. (2008). *Multimodal Level of Service Analysis for Urban Streets*. National Cooperative Highway Research Program (NCHRP), No. 616. Washington, D.C.: Transportation Research Board.

[9] Washington State Department of Transportation. (2016). *The 2016 Corridor Capacity Report*. Seattle, WA: Washington State Department of Transportation.

[10] City of Seattle. (2015). *Seattle's Comprehensive Plan: Toward a Sustainable Seattle*. Seattle, WA: City of Seattle.

[11] Dock, S., Westrom, R., Lee, K. and Cesme, B. (2017). Advancing Urban Multimodal Transportation System Performance Management. *Transportation Research Record*, No. 2646, pp. 17–27.

[12] San Francisco Municipal Transportation Agency. (2018). Performance Metrics. Retrieved July 30, 2018, from San Francisco Municipal Transportation Agency: www.sfmta.com/performance-metrics

[13] San Francisco Municipal Transportation Agency. (2018). *Strategic Plan: Performance Metrics & Targets*. San Francisco, CA: San Francisco Municipal Transportation Agency

[14] Chicago Metropolitan Agency for Planning. (2018). Mobility Visualization, Retrieved July 30, from Chicago Metropolitan Agency for Planning: www.cmap.illinois.gov/mobility/explore#/

[15] Vuchic, V. (2007). *Urban transit operations, planning and economics*. Hoboken, NJ: John Willey & Sons, Inc.

[16] Wasatch Front Regional Council. (2015). *Regional Transportation Plan 2015 – 2040*. Salt Lake City, UT: Wasatch Front Regional Council

[17] Utah Department of Transportation et al. (2015). *Utah's Unified Transportation Plan 2011 – 2040*. Salt Lake City, UT: Utah Department of Transportation

[18] The Planning Center et al (2011). . *Life on State: Our Street, Our Vision*. Salt Lake City, UT: The Planning Center

[19] Redevelopment Agency of Salt Lake City, HDR, Fehr & Peers. (2010). *Salt Lake City Downtown Streetcar: Synopsis Report*. Salt Lake City, UT: Redevelopment Agency of Salt Lake City