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Connected Vehicles Versus Conventional Traffic Congestion Mitigation Measures: An Operational Economic Analysis

Mutasem Alzoubaidi[1], Adli Al-Balbissi[2], Abdel Rahman Alzoubaidi[3], Amr Alzoubaidi[4], Baha Azzeh[5], Ahmed Al-Mansour[6], Ahmed Farid[7]

[1] University of Wyoming, USA, malzouba@uwyo.edu
[2] The University of Jordan, Jordan, balbissi@ju.edu.jo
[3] Eastern Washington University, USA, aalzoubaidi@ewu.edu
[4] Al-Sendyan Engineering Office, Jordan, amralzoubaidi@gmail.com
[5] Omrania & Associates Architecture & Engineering Consultants, Jordan, bahaa.azzeh@omrania.com.jo
[6] The University of Jordan, Jordan, eng.ahmedalmansour@hotmail.com
[7] California Polytechnic State University, USA, afarid@uwyo.edu

*Correspondence: Mutasem Alzoubaidi, University of Wyoming, USA. Email: malzouba@uwyo.edu

Abstract

This paper conducted an operational, economic analysis to assess alternative solutions to traffic congestion. They involved integrating adaptive traffic signal control (ATSC) with connected vehicle technology (ATSC-CV) and the application of various conventional and unconventional solutions. The studied conventional scenarios include signal timing optimization, signal actuation, and upgrading existing intersections to interchanges. There were unconventional scenarios involving converting two intersections to interchanges and the third to a continuous green-T intersection (CGTI). Different unconventional alternatives involved deploying ATSC-CV-based systems assuming varying market penetration rates (MPRs). The operational performance of each alternative was analyzed using VISSIM microsimulation software. To model the driving behavior of CVs, Python programming language was used through the COM interface in VISSIM. One-way analysis of variance (ANOVA) and post-hoc testing results indicate that implementing any suggested alternative would substantially decrease the mean vehicular travel time compared to the fixed signal control strategy currently implemented. Specifically, the ATSC-CV-based systems yielded notable travel time reductions ranging from 9.5% to 21.3%. Also, ANOVA results revealed that the highest benefit-to-cost ratio among all alternatives belonged to scenarios in which the MPRs of CVs were 100%. It was also found that ATSC-CV-based systems with MPRs of 25% and 50% would be as feasible as converting signalized intersections to underpass interchanges.

Keywords: Connected vehicles, Adaptive traffic signal control, Traffic operations, Benefit-to-Cost ratio, Microsimulation, VISSIM.

1. Introduction

Traffic congestion instigates frustration among motorists and incurs substantial costs on the economy. According to the Greater Amman Municipality (GAM), the cost of traffic congestion in Amman, the capital of Jordan, is estimated to be over 570 million Jordanian Dinars (JOD), which is roughly $800 million (Gharaibeh, A. A., Zu'bi, A., Esra'a, M., & Abuhassan, L. B., 2019). Besides the tremendous increase in automobile ownership, other factors contributing to traffic congestion include the inability of the infrastructure to accommodate the increasing traffic demand, inefficient traffic signal control strategies, and inefficient public transportation.

A considerable proportion of signalized intersections in Amman are pre-timed traffic signals, also known as fixed time traffic signals, programmed based on historical data leading to significant traffic congestion and long travel times (Gharaibeh, A. A., Zu'bi, A., Esra'a, M., & Abuhassan, L. B., 2019). On the other hand, adaptive traffic signal control (ATSC) based systems, which rely on real-time traffic data, were demonstrated to reduce traffic congestion, cut fuel consumption, and improve travel time reliability (Martin, P. T., Perrin, J., Chilukuri, B. R., Jhaveri, C., & Feng, Y., 2003; Gradinescu, V., Gorgorin, C., Diaconescu, R., Cristea, V., & Iftode, L., 2007, April).

Present-day ATSC-based systems rely wholly on infrastructure-based sensors, including video or in-pavement loop detectors, for data collection. However, loop detectors have drawbacks. For instance, many detectors are needed to provide the necessary data for signal timing optimization, leading to high installation and maintenance costs. Also, the detectors are susceptible to environmental effects and cannot measure the vehicles' particularities (such as speeds, positions, and accelerations). Furthermore, the performance of adaptive signal control systems might be notably degraded if one of the detectors malfunctions. However, these shortcomings are no longer a challenge with the connected vehicle (CV) technologies that feed the required input data to a single infrastructure device interfaced with the ATSC-based systems. This leads to substantially less expensive installation and maintenance costs (Feng, Y., Head, K. L., Khoshmagham, S., & Zamanipour, M., 2015). Connected vehicles operate using advanced equipment, such as wireless communication devices, on-board computer processing units, vehicle sensors, global positioning system (GPS) navigation devices, and intelligent infrastructure devices. The communication between connected vehicles and ATSC-based systems was demonstrated to reduce delays. This also led to reductions in fuel consumption. Furthermore, the assessment of traffic conditions involving connected vehicles communicating with ATSC-based systems yielded more reliable results than traffic conditions comprising legacy (non-CV) vehicles served by non-ATSC-based signals (Gradinescu, V., Gorgorin, C., Diaconescu, R., Cristea, V., & Iftode, L., 2007, April; Agbolosu-Amison, S. J., Park, B., & Center, M. A. U. T., 2008; Khan, S. M., 2015).

This paper compares the benefit-to-cost (B/C) ratio of implementing ATSC-based systems while adopting CV technologies with the benefits of implementing multiple scenarios selected among various traffic congestion mitigation measures. The benefits refer to the improvements in traffic flow efficiency, while the costs refer to construction and life cycle costs. The study site, a major urban arterial in Amman, Jordan, comprises three closely spaced signalized intersections under the pre-timed control scheme. Conventional and unconventional scenarios were compared in terms of their B/C ratios. The studied conventional scenarios include signal timing optimization, signal actuation, and upgrading two of the intersections to underpass interchanges. When it comes to the unconventional scenarios, one included upgrading two of the intersections to underpass interchanges and the third to a continuous green T intersection (CGTI). This is since unconventional intersection and interchange designs have been efficient in improving the operational performance and alleviation congestion considerably, according to previous studies (Alzoubaidi, M., Molan, A. M., & Ksaibati, K., 2021; Hughes, W., Jagannathan, R., Sengupta, D., & Hummer, J., 2010). Another unconventional set of scenarios involved the deployment of Adaptive Traffic Signal Control-Connected Vehicle (ATSC-CV) based systems assuming varying market penetration rates (MPRs) without implementing any geometric design changes.

This paper is organized as follows. The studies related to the operational aspects of ATSC-CV-based systems and traffic operations' economic analyses are discussed in the following section. The data collection, simulation modeling, and analysis methodology are described in the subsequent section and followed by a section dedicated to presenting and discussing the analysis results. Finally, the conclusions and future work are discussed.

2. Literature Review

The Sydney Coordinated Adaptive Traffic System (SCATS), developed in Sydney, Australia, in the 1970s, and the Split Cycle and Offset Optimization Technique (SCOOT) system are among the earliest examples of ATSC-based systems. Both systems rely on infrastructure-based sensors to manipulate individual settings of a timing plan, such as those of cycle lengths, splits, and offsets. Deployments of SCOOT systems at early stages showed improvements as high as 53% in delay and 26% in travel time relative to the case of pre-timed signal control (Martin, P. T., Perrin, J., Chilukuri, B. R., Jhaveri, C., & Feng, Y., 2003; Sims, A. G., & Dobinson, K. W., 1980; Bretherton, D., Wood, K., & Raha, N., 1998). (Mudigonda, S., Ozbay, K., & Doshi, H., 2008) developed their prototypes of the SCOOT, SCATS, and Optimization Policies for Adaptive Control (OPAC). They renamed them SCOOT-like, SCATS-like, and OPAC-like. The research team modeled their developed prototypes in major arterials in New Jersey via traffic simulations. The simulations showed that a reduction in travel time by 8.2%, 10.2%, and 12.91% could be achieved by deploying the SCATS-like, SCOOT-like, and OPAC-like systems. The study also showed that the B/C ratio was 79.37 for the SCOOT-like system and 1.23 for the OPAC-like system.

Another example of ATSC-based systems is the InSync system, recently deployed in various locations around the United States. In a study by Stevanovic and Zlatkovic (2013), the InSync system plan was compared to conventional time-of-day (TOD) plans of signalized intersections along a multilane highway in Florida VISSIM microsimulation software. The InSync plan showed 2 to 20% improvements depending on the operational performance metrics. Hu et al. (2016) tested the performance of the InSync system in six corridors in Virginia. The study results indicated that InSync was capable of reducing delays by nearly 25% and improving travel time reliability by an estimated 16%. Additionally, the B/C ratio of the InSync system was estimated as 3.74 for the first analysis year.

ATSC systems alleviate traffic congestion and curtail travel time for various conditions. The conditions are geometric network characteristics and traffic demands. ATSC systems also offer a great return on investment (Jagannathan, R., & Khan, A. M., 2001; Stallard, C., & Owen, L. E., 1998, December).

Gradinescu et al. (2007) examined the ability of an ATSC-based system to reconfigure the signal timing plans depending on data fed from incoming vehicles. The authors conducted simulations of vehicles with Vehicular Ad-hoc NETwork (VANET) communication devices for the study. According to the results, the ATSC-based system outperformed the pre-timed signal control strategy with up to 28.3% savings in total delay and 6.5% savings in fuel consumption. Agbolosu-Amison and Park (2008) developed an algorithm permitting traffic signals to utilize CV data to predict vehicle arrival patterns in the gap-out stage during which no vehicles were anticipated to arrive. When no vehicles were predicted, the algorithm could shorten the signal phase at the beginning of the gap-out stage instead of at the end, reducing the signal's cycle length. This algorithm has improved 12.5% in delay when tested via simulations using an optimized timing plan on a hypothetical four-legged intersection.

Khan (2015) proposed a method to ascertain traffic density using real-time data collected from vehicle on-board units on a portion of Interstate-26 in South Carolina. The data were processed using the support vector machine and case-based reasoning artificial intelligence algorithms. That was in order to improve the accuracy of density estimations in real-time. The author compared the accuracy of the proposed method to that of the conventional one in which loop detector data were processed to estimate the traffic density. The results showed that the proposed method offered more accurate results. Other researchers have relied on cloud computing to achieve improved performance, greater efficiency, availability, and security (Liu, C., & Ke, L., 2022; Alzoubaidi, A., M. Alzoubaidi, et al., 2021; Alzoubaidi, A. R., 2016; Alzoubaidi, A. R., 2016). Olia et al. (2016) modeled the impact of communications and the sharing of travel time data among CVs using PARAMICS traffic microsimulation tool. The research team interpreted that CVs could transmit and receive real-time data. Therefore, CVs could select the optimal route from multiple routes, which leads to improved mobility. The study also showed that CV technologies have the potential to mitigate traffic congestion by reducing travel time by as much as 37%, reducing emissions by 30%, and curtailing crash risk by 45%. Bagheri (2017) processed CV data across different market penetration rates to suggest the needed data inputs for ATSC-based systems. The results showed that the CV data could estimate queue lengths, saturation flow rates, and temporally varying saturation flow rates in response to changing network conditions and free-flow speeds.

Moreover, it was indicated that such metrics could be estimated at acceptable tolerance levels even at low CV market penetration rates. Islam et al. (2021) compared several mobility performance metrics of ATSC-CV-based systems and ATSC systems with only loop detectors. It was found that a minimum of 40% CV MPR is required so that ATSC-CV-based systems would outperform ATSC with only loop detectors. Similarly, Wang et al. (2021) have reported that the ATSC-CV-based systems can outperform conventional traffic signal control strategies by up to 15.67% in operational metrics.

Researchers have investigated the effects of CVs on travel time, safety, and fuel consumption, among other measures. However, to the best of the authors' knowledge, feasibility studies related to implementing ATSC-CV-based systems were not conducted. Hence, this study contributes to the literature by comparing the B/C ratio of adopting ATSC-CV-based systems to applying various alternative solutions to traffic congestion.

3. Data and Methods

3.1. Data and Modeling Methodology

For this study, traffic data, including traffic signal timing, traffic volumes, and traffic composition, were obtained from GAM. The peak hour was found to be from 5:00 to 6:00 PM. Based on the data, the percentage of heavy vehicles simulated for this study was 8%. The geometric design data, including the number of lanes, lane widths, link lengths, and lane configurations, were manually collected from Google Earth. The underpass interchanges and CGTI were designed in Autodesk AutoCAD Civil 3D (25) according to the American Association of State Highway and Transportation Officials (AASHTO's) A Policy on Geometric Design of Highways and Streets, 2018 (26).

The study site comprised three highly congested signalized intersections along Mecca St., a major urban arterial in Amman, Jordan. The study area into three zones, as depicted in Figure 1. Mecca St. intersects with Kindi St., and their intersection was coded as MK. Mecca St. also intersects with Saed Ben Abi Waqqas St. and Naim Abdul Hadi St. Their intersection was coded as MSN. The third intersection is Mecca St.

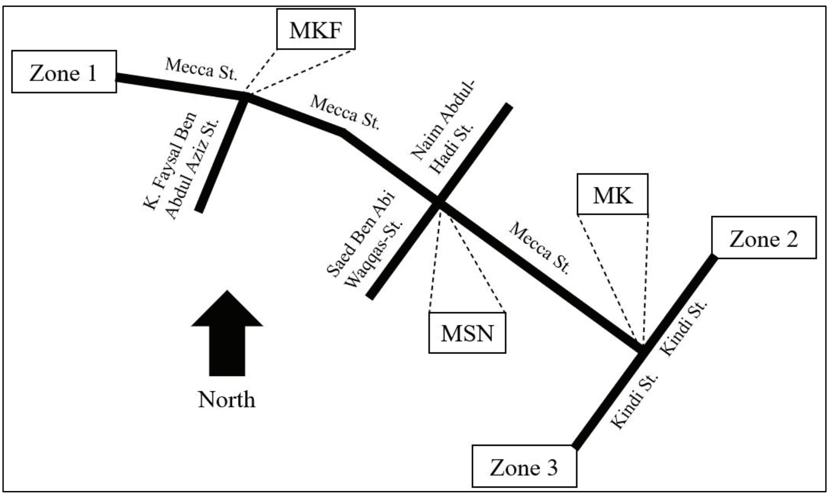

Fig. 1. Study area along Mecca St.

with King Faysal Ben Abdul Aziz St., coded as MKF as shown in the figure. Intersections MK, MSN, and MKF are currently operating under the pre-timed control scheme. Alternative solutions were suggested; namely, alternatives A through E. Table 1 lists the description of each alternative.

Koonce et al. (2008) suggested retiming and optimizing signal timings once every three to five years and more frequently if there are considerable fluctuations in traffic patterns or changes to the geometric design configurations. Although alternative A entailed optimizing the signal timing plans for all intersections over the entire study period (2021-2041), it represented the do-nothing alternative. The fifth alternative (alternative E) involved implementing ATSC-CV-based systems at all intersections, assuming varying MPRs.

The models were built using VISSIM microsimulation software version 9 (28). Initially, version 8 of Synchro, a traffic analysis, optimization, and simulation tool (29), was used to optimize the traffic signal timings. The optimal timings obtained from Synchro were then input in VISSIM. Python programming language was used through the COM interface in VISSIM to model CVs' driving behavior accurately. Fifty simulation runs were conducted for each simulation scenario. The random seeds were reserved to ensure that the outputted results were reproducible.

Table 1. Description of Alternative Scenarios

Alternative	Alternative Description
A	Do nothing (includes the routine optimization of signal timing plans for all intersections)
B	Signal actuation for all intersections
C	Constructing an underpass interchange at intersection MSN, serving them through movements of both directions of Mecca St., and another underpass interchange at intersection MK, serving the left-turn movements from Kindi St. to Mecca St.
D	Constructing an underpass interchange at intersection MSN, serving them through movements of both directions of Mecca St., another underpass interchange at intersection MK, serving the left-turn movements from Kindi St. to Mecca St., and a CGTI at intersection MK, serving the northeast-bound through movements on Kindi St.
E1	Deploying ATSC-CV-based systems at intersections MK, MSN, and MKF at 0% MPR of CVs.
E2	Deploying ATSC-CV-based systems at intersections MK, MSN, and MKF at 25% MPR of CVs.
E3	Deploying ATSC-CV-based systems at intersections MK, MSN, and MKF at 50% MPR of CVs.
E4	Deploying ATSC-CV-based systems at intersections MK, MSN, and MKF at 75% MPR of CVs.
E5	Deploying ATSC-CV-based systems at intersections MK, MSN, and MKF at 100% MPR of CVs.

3.2. VISSIM Calibration and Validation

The VISSIM simulation models of this study were developed, calibrated, and validated for the traffic conditions of 2021, 2031, and 2041. The calibration results are depicted in Figure 2, where the traffic volumes provided by GAM are plotted against those generated by the simulations. The R2 value of 0.98 indicates a strong correlation between the field-collected data and the simulation results. Note that the term “turning movements” in Figure 2 refers to all traffic movements at the intersection approaches.

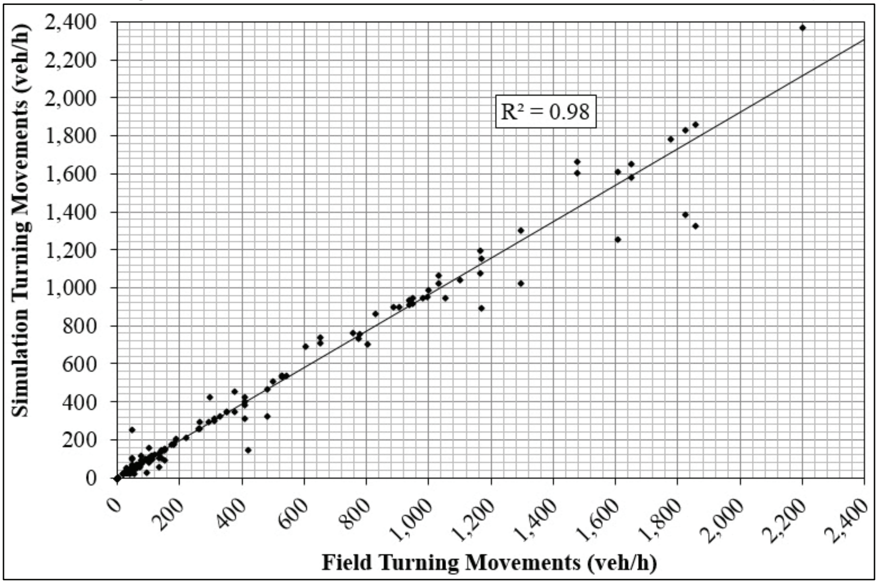

Fig. 2. Field and simulated traffic volumes’ scatterplot.

3.3. Cost Calculation Methodology

Vital cost data were obtained from the United States Department of Transportation’s (USDOT’s) Intelligent Transportation Systems Joint Program Office (1) and the standards of the Ministry of Public Works and Housing (2020). Note that Autodesk AutoCAD Civil 3D (2) was used to compute the material quantities needed to upgrade intersections of alternatives C and D to interchanges to estimate the alternatives' costs.

The following equations (3) were used in the cost computations. In the equations, the variables P, F, A, i, and n are the present value of money, future value of money, annualized value of money, interest rate, and the number of years during which payments are dispensed.

$$P = \frac{F}{(1+i)^n} \quad (1)$$

$$P = A\,\frac{(1+\mathrm{i})^n - 1}{\mathrm{i}(1+\mathrm{i})^n} \quad (2)$$

$$A = F\,\frac{\mathrm{i}}{(1+\mathrm{i})^n - 1} \quad (3)$$

4. Results and Discussion

4.1. Travel Time Empirical Results and Discussion

The vehicular travel times were extracted from VISSIM's modeling results for all alternatives. The analysis covers the 20 years between 2021 and 2041. The traffic volumes were assumed to increase by a growth rate of 3% per year as per GAM (1). The vehicular travel times of each alternative are presented in Table 2.

Table 2: Inter-Zonal Mean Vehicular Travel Times

Alternative	From Zone - To Zone Mean Travel Time over the 20 years (s/veh)						Total (s/veh)
	1-2	1-3	2-1	2-3	3-1	3-2	
A	692	695	383	90	386	39	2,285
B	636	647	370	85	449	37	2,224
C	164	156	172	52	197	34	775
D	161	156	183	52	199	22	773
E1	623	624	356	82	347	37	2,069
E2	594	595	340	78	330	35	1,972
E3	580	581	333	76	323	34	1,927
E4	547	548	314	72	304	32	1,817
E5	541	542	311	71	301	32	1,798

4.2. Benefit-Cost Analysis of Alternative Scenarios

The total inter-zonal vehicular travel time for alternative A was subtracted from the total inter-zonal vehicular travel times of each of the other alternatives. The difference was then multiplied by the number of vehicles traveling between each zonal pair over the 20 years (2021-2041). This yielded a per alternative total change in vehicular travel time for 20 years relative to the current situation (alternative A). Abojaradeh et al. (2014) used 1.5 JOD/hr (2.12 $/h) as the minimum hourly salary per capita in Jordan in a similar economic analysis. In this study, the total change in vehicular travel time over the analysis period was multiplied by 1.5 for each alternative to estimate the monetary gains resulting from savings in travel times for the alternative. Table 3 lists the costs, benefits, and B/C ratios for the considered alternatives. The alternatives in Table 3 were sorted based on their B/C ratios in descending order.

Table 3: Costs, Benefits and B/C Ratio of Alternatives

Alternative	Cost (JOD)[b]	Benefit (JOD)	B/C
E5	955,572 ($1,347,791)	24,739,281 ($34,893,643)	25.89
E4	955,572 ($1,347,791)	23,804,502 ($33,575,179)	24.91
E3	955,572 ($1,347,791)	17,981,467 ($25,362,050)	18.82

C	4,005,297 ($5,649,291)	71,640,181 ($101,045,252)	17.89
D	4,026,494 ($5,679,189)	71,749,486 ($101,199,421)	17.82
E2	955,572 ($1,347,791)	15,611,893 ($22,019,873)	16.34
E1	955,572 ($1,347,791)	10,512,659 ($14,827,633)	11
B	324,829 ($458,157)	1,564,858 ($2,207,162)	4.82
A	193,912 ($273,504)	0[a]	0[a]

B/C: Benefit to cost ratio; JOD: Jordanian Dinar = $1.41

[a]Alternative A entailed routine signal timing optimization throughout the years and represented the reference alternative. Hence, it did not yield any benefits relative to itself.

[b]Costs items include the following where applicable: technicians and labor, signals' operations, maintenance and replacement, routine signal controller upgrade, routine signal timing updates, inductive loops, and inductive loops maintenance, ATSC, ATSC maintenance, DSRC and backhauling, excavation and earthwork, flexible pavement, steel reinforcement, concrete, curbstones, merging lanes.

4.3. Statistical Analysis Results

Each alternative's estimated vehicular travel time and B/C ratio were compared with the others'. The comparisons were made via analysis of variance (ANOVA) and post-hoc testing using IBM SPSS 26 software (34). Table 4 lists the ANOVA and post-hoc analyses results for the average inter-zonal vehicular travel time. In addition, Table 5 presents the alternatives' B/C ratios ANOVA and post hoc analyses results. The 95th percentile confidence interval was used to infer the results.

For the analyzed 20-year period, alternatives C (converting two intersections to underpass interchanges) and D (converting two intersections to underpass interchanges and the third to a CGTI) had the least mean vehicular travel times. They were followed by alternatives E5 through E1 (deployment of ATSC-CV-based systems), as shown in Table 2. Implementing alternatives D and C would result in approximately 66.2% and 66.1% savings in travel time. On the other hand, selecting alternative E results in a 9.5% to a 21.3% reduction in travel time, depending on the MPR of CVs. Alternative B (signal actuation) had the most negligible influence on travel time savings at only 2.6%. It should be noted that alternative A, which entailed routine signal timing optimization throughout the years and represented the reference alternative, did not yield any benefits relative to itself.

The ANOVA test results confirmed that implementing alternative D significantly reduced travel time instead of other alternatives except for alternative C. The ANOVA pairwise comparison test results have shown that the mean difference between alternatives C and D vehicular travel times was statistically insignificant at the 95th percen-

Table 4: Inter-Zonal Vehicular Travel Time ANOVA and Post-Hoc Analyses Results

Alternative		Travel Time Mean Difference (I-J) (s/veh)	P-Value	Alternative		Travel Time Mean Difference (I-J) (s/veh)	P-Value	Alternative		Travel Time Mean Difference (I-J) (s/veh)	P-Value	Alternative		Travel Time Mean Difference (I-J) (s/veh)	P-Value
I	J			I	J			I	J			I	J		
A	B	61	< 0.001	B	A	-61	< 0.001	C	A	-1,510	< 0.001	D	A	-1,512	< 0.001
	C	1,510	< 0.001		C	1,449	< 0.001		B	-1,449	< 0.001		B	-1,451	< 0.001
	D	1,512	< 0.001		D	1,451	< 0.001		D	2	0.317#		C	-2	0.317#
	E1	216	< 0.001		E1	155	< 0.001		E1	-1,294	< 0.001		E1	-1,296	< 0.001
	E2	313	< 0.001		E2	252	< 0.001		E2	-1,197	< 0.001		E2	-1,199	< 0.001
	E3	358	< 0.001		E3	297	< 0.001		E3	-1,152	< 0.001		E3	-1,154	< 0.001
	E4	468	< 0.001		E4	407	< 0.001		E4	-1,042	< 0.001		E4	-1,044	< 0.001
	E5	487	< 0.001		E5	426	< 0.001		E5	-1,023	< 0.001		E5	-1,025	< 0.001
E1	A	-216	< 0.001	E2	A	-313	< 0.001	E3	A	-358	< 0.001	E4	A	-468	< 0.001
	B	-155	< 0.001		B	-252	< 0.001		B	-297	< 0.001		B	-407	< 0.001
	C	1,294	< 0.001		C	1,197	< 0.001		C	1,152	< 0.001		C	1,042	< 0.001
	D	1,296	< 0.001		D	1,199	< 0.001		D	1,154	< 0.001		D	1,044	< 0.001
	E2	97	< 0.001		E1	-97	< 0.001		E1	-142	< 0.001		E1	-252	< 0.001
	E3	142	< 0.001		E3	45	< 0.001		E2	-45	< 0.001		E2	-155	< 0.001
	E4	252	< 0.001		E4	155	< 0.001		E4	110	< 0.001		E3	-110	< 0.001
	E5	271	< 0.001		E5	174	< 0.001		E5	129	< 0.001		E5	19	< 0.001
E5	A	-487	< 0.001												
	B	-426	< 0.001												
	C	1,023	< 0.001												
	D	1,025	< 0.001												
	E1	-271	< 0.001												
	E2	-174	< 0.001												
	E3	-129	< 0.001												
	E4	-19	< 0.001												

#: The mean difference is statistically insignificant at the 95th percentile level; s/veh: seconds per vehicle.

Table 5: B/C Ratio ANOVA and Post-Hoc Analyses Results

Alternative I	Alternative J	B/C Ratio Mean Difference (I-J)	P-Value	Alternative I	Alternative J	B/C Ratio Mean Difference (I-J)	P-Value	Alternative I	Alternative J	B/C Ratio Mean Difference (I-J)	P-Value	Alternative I	Alternative J	B/C Ratio Mean Difference (I-J)	P-Value
A	B	-4.82	< 0.001	B	A	4.82	< 0.001	C	A	17.89	< 0.001	D	A	17.82	< 0.001
	C	-17.89	< 0.001		C	-13.07	< 0.001		B	13.07	< 0.001		B	13.00	< 0.001
	D	-17.82	< 0.001		D	-13.00	< 0.001		D	0.07	1.000#		C	-0.07	1.000#
	E1	-11.00	< 0.001		E1	-6.18	< 0.001		E1	6.89	< 0.001		E1	6.82	< 0.001
	E2	-16.34	< 0.001		E2	-11.52	< 0.001		E2	1.55	0.623#		E2	1.48	0.674#
	E3	-18.82	< 0.001		E3	-14.00	< 0.001		E3	-0.93	0.960#		E3	-1.00	0.940#
	E4	-24.91	< 0.001		E4	-20.09	< 0.001		E4	-7.02	< 0.001		E4	-7.09	< 0.001
	E5	-25.89	< 0.001		E5	-21.07	< 0.001		E5	-8.00	< 0.001		E5	-8.07	< 0.001
E1	A	11.00	< 0.001	E2	A	16.34	< 0.001	E3	A	18.82	< 0.001	E4	A	24.91	< 0.001
	B	6.18	< 0.001		B	11.52	< 0.001		B	14.00	< 0.001		B	20.09	< 0.001
	C	-6.89	< 0.001		C	-1.55	0.623#		C	0.93	0.960#		C	7.02	< 0.001
	D	-6.82	< 0.001		D	-1.48	0.674#		D	1.00	0.940#		D	7.09	< 0.001
	E2	-5.34	< 0.001		E1	5.34	< 0.001		E1	7.82	< 0.001		E1	13.91	< 0.001
	E3	-7.82	< 0.001		E3	-2.48	0.120#		E2	2.48	0.120#		E2	8.57	< 0.001
	E4	-13.91	< 0.001		E4	-8.57	< 0.001		E4	-6.09	< 0.001		E3	6.09	< 0.001
	E5	-14.89	< 0.001		E5	-9.55	< 0.001		E5	-7.07	< 0.001		E5	-0.98	0.946#
E5	A	25.89	< 0.001												
	B	21.07	< 0.001												
	C	8.00	< 0.001												
	D	8.07	< 0.001												
	E1	14.89	< 0.001												
	E2	9.55	< 0.001												
	E3	7.07	< 0.001												
	E4	0.98	0.946#												

#: The difference in mean B/C ratios is statistically insignificant at the 95th percentile level.

tile confidence level. ANOVA results suggested that opting for any of the proposed alternatives would considerably decrease the mean vehicular travel time compared to selecting alternative A (i.e., the current situation).

As shown in Table 3, alternative A had the lowest cost of only JOD 193,912 ($273,504), compared to JOD 324,829 ($458,157) for alternative B. On the other hand, alternatives E1 through E5 would cost JOD 955,572 ($1,347,791). Alternatives C and D would have the highest costs, with alternative C being slightly less expensive than D. This is because the only difference between the two alternatives in the surface works required to construct the additional CGTI in alternative D. Alternatives C and D would cost 4,005,297 ($5,649,291), 4,026,494 ($5,679,189), respectively. The highest benefit was that of alternative E5, with an estimated return on investment of 25.89 to 1, followed by alternatives E4, E3, C, D, E2, E1, and B, respectively. These results indicate that, despite their high benefits in travel time savings, the return on investment of underpass interchanges is lower than that of ATSC-CV-based systems when MPRs are at 50%, 75%, and 100%.

Furthermore, it was confirmed from the ANOVA test results, listed in Table 5, that alternative E5 (ATSC-CV at 100% CV MPR) had a B/C ratio that was substantially greater than those of all the other alternatives except that of alternative E4 (ATSC-CV at 75% CV MPR). The ANOVA pairwise comparison test results have shown that the mean difference between B/C ratios of alternatives E4 and E5 was statistically insignificant at the 95th percentile confidence level. ANOVA results indicated that ATSC-CV-based systems with CV MPRs of 25% and 50% would be as feasible as converting signalized intersections to underpass interchanges.

5. Conclusions and Future Work

This paper aimed to compare the benefit-to-cost (B/C) ratio of implementing ATSC-based systems while adopting CV technologies to implement multiple scenarios selected among various traffic congestion mitigation measures. Conventional and unconventional scenarios were compared in terms of vehicular travel time and B/C ratios. The studied conventional scenarios include signal timing optimization, signal actuation, and upgrading two of the intersections to underpass interchanges. Regarding the studied unconventional scenarios, one included upgrading two of the intersections to underpass interchanges and the third to a continuous green T intersection (CGTI). Another unconventional set of scenarios involved the deployment of Adaptive Traffic Signal Control-Connected Vehicle (ATSC-CV) based systems assuming varying market penetration rates (MPRs) without implementing any geometric design changes.

According to this study's results, selecting any of the suggested alternatives would considerably decrease the mean vehicular travel time compared to alternative A (i.e., the current situation). Alternative D, however, which involved converting two of the intersections to underpass interchanges and the third to a CGTI, significantly outperformed all the other suggested alternatives in terms of vehicular travel times except for alternative C. Alternative C involved the upgrading of two of the intersections to underpass interchanges. It was estimated that alternative D reduced vehicular travel times by as much as 66.2%. On the other hand, Alternative B had the lowest travel time reduction of only 2.6%.

When it comes to the feasibilities of the alternatives, ANOVA test results indicated that alternative E5 (deploying ATSC-CV based systems at a 100% CV MPR) had a B/C ratio that was remarkably higher than all other alternatives considered for this study except alternative E4. The ANOVA pairwise comparison test results have shown that the mean difference between B/C ratios of alternatives E4 and E5 was statistically insignificant at the 95th percentile confidence level. More importantly, it was interpreted that ATSC-CV-based systems with CV MPRs of 25% and 50% would be as feasible as converting signalized intersections to underpass interchanges.

Before implementing the ATSC-CV-based systems in this study's site, GAM undertook a large-scale feasibility assessment on the area encompassing Mecca St. The assessment would also incorporate the safety aspect into the study. This encompasses comparing the different alternative solutions in terms of operational performance measures and surrogate safety measures, such as vehicle-vehicle conflicts and time to collision (Msallam, M., 2014). Thus, the B/C ratios, which are the decisive factors used for comparing the alternatives, would be dependent on the results of both operational and safety performance measures.

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