Research Article

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Statistical evaluation of ramp metering for a dual freeway corridor

Abstract

This study evaluates the effectiveness of ramp metering on two corridors of I-10 and I-12 in Baton Rouge, Louisiana. This is achieved by simulating both corridors with and without ramp metering. Geometric and traffic data were collected to build the network in the simulation model (VISSIM). Simulation results for travel times and delays from 25 runs were obtained for two simulation scenarios, one with and one without ramp meters. The simulation results were then analyzed statistically to investigate the impact of ramp meters on the corridors operational conditions. The comparative evaluation showed a statistically significant improvement in the corridor travel times and delays with ramp meters. Based on the simulation results, the study endorses the use of ramp metering as a successful control strategy.

Keywords: ramp metering, microscopic simulation, vissim, freeway operation, integrated corridor management

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Abbreviations: ICM, integrated corridor management; ITS, intelligent transportation systems; HERO, heuristic ramp metering coordination; SZM, stratified zone ramp metering; ARMS, advanced real-time metering system; CRPC, capital region planning commission; VAP, vehicle actuated programming

Introduction

Traffic congestion continues to escalate and spread over the surface transportation network in the U.S. Symptoms are often observed in a number of large and medium size cities across the country as travel demand continues to exceed the existing network capacity. Conventional approaches relying primarily on capacity expansion are high cost solutions that cannot meet the rising demand and limited rights of way needed for roadway widening. In the last two decades, transportation professionals recognized the need for better management of the existing network capacity as a viable alternative to capacity expansion projects. Transportation corridors may still have unused capacity on parallel routes that can be leveraged to alleviate congestion on freeways. Such concept has been referred to as Integrated Corridor Management (ICM) and successfully applied to major metropolitan areas such as Dallas, Texas, Houston, Texas, Minneapolis, Minnesota, Oakland, California, Seattle, Washington, to name a few. The city of Baton Rouge, the state capital of Louisiana, continues to grow in population and in travel demand at an alarming rate, causing severe congestion to spread over freeways and major arterials. The existing capacity of the roadway infra-structure in the city cannot sustain the rising demand, and therefore, congestion is now frequently observed over the freeway segments of I-10 and I-12, as well as the main arterials. Such congestion may be alleviated by applying integrated corridor management strategies such as ramp metering, which is the focus of this re-search study.

Under the ICM umbrella, the operation of freeways and arterials should be optimized for various functions such as traffic incident management, work zone management, planned specie vents management, and re-current day-to-day conditions. This goal ensures more sustainable and resilient transportation network under both normal and extreme (such as emergency evacuation) operating conditions. It is possible to develop an efficient integrated corridor management by developing a ramp-metering strategy, information dissemination strategy and other ITS strategies along congested corridors.

Ramp metering aims to improve the traffic conditions by regulating the inflow from the on-ramps to the free-way main stream. For fixed time metering strategies, ramp meter timings are adjusted for different time periods during the day, and therefore, do not offer the flexibility to adapt to changing traffic conditions. Traffic-responsive ramp metering strategies, on the other hand, are based on real-time measurements from sensors installed in the freeway network and can be classified as local or coordinated. Local control is a process of selecting ramp metering rates based solely on conditions present at an individual ramp, while coordinated control is a process of selecting metering rates based on conditions throughout the entire metered corridor.

Local ramp metering strategies

While numerous studies addressed various local ramp metering strategies in the open literature, this section briefly introduces the concept through a few selected studies. Masher et al.[1] Developed a demand-capacity ramp metering algorithm, which is a traffic responsive algorithm that measures the downstream occupancy. Papageorgiou et al.[2] Proposed a local responsive feedback ramp metering strategy (ALINEA), this had multiple successful field applications (Paris, Amsterdam, Glasgow, Munich). In another paper Smaragdis et al.[3] Presented several modifications and extensions of ALINEA. A zone algorithm was reported to be used at Minnesota.[4] This algorithm defines directional freeway facility "metering zones" with zones having variable lengths of three to six miles. Its basic concept of the algorithm is to balance the volume of traffic entering and leaving each zone Ghods et al.[5] Proposed an adaptive genetic fuzzy control approach to reduce peak hour congestion, along with speed limit control. Ozbay et al.[6] Developed an isolated feedback based ramp metering strategy that takes into account the ramp queue. In addition to the regulation of ramp input, the strategy calls for regulation of ramp queues by explicitly incorporating them into the model.

Coordinated ramp metering strategies

The bottleneck metering algorithm is a system of ramp control, which includes several internal adjustments of volume reduction, based on downstream bottlenecks and localized adjustments such as queue over-ride.[7] ARMS (Advanced Real-time Metering System) consists of three operational control levels within a single algorithm: free-flow control, congestion prediction, and congestion resolution.[8] Wei et al.[9] Developed a coordinated metering algorithm using artificial neural networks. Gettman et al.[10] Presented a multi-objective integrated large-scale optimized ramp metering system for freeway traffic management, seeking to address the interaction of the freeway system with the adjacent surface-street system by providing a method to trade-off queue growth at individual ramps in a freeway corridor. Zhang et al.[11] Developed a new freeway ramp control objective- minimizing total weighted (perceived) travel time by balancing efficiency and equity of ramp meters, compared to a previous metering objective, which minimizes the total absolute travel time. A ramp metering algorithm incorporating "fuzzy logic" decision support was developed at the University of Washington for a number of years.[12] The algorithm, based on fuzzy set theory, is designed to overcome some of the limitations of existing conventional ramp metering systems. A freeway traffic control system has been in place on the Hanshin Expressway near Kobe, Japan, based on the Hanshin algorithm.[13] The linear algorithm maximizes the weighted sum of ramp flows.

Another coordinated ramp metering strategies, METALINE, is a coordinated generalization (using lists of multiple values, or columnar vectors, in place of single values) of ALINEA.[14] The metering rate of each ramp is computed based on the change in measured occupancy of each freeway segment and the deviation of occupancy from critical occupancy for each segment that has a controlled on-ramp. Chang et al.[15] Proposed a metering model for non-recurrent congestion. This algorithm uses a two-segment linear flow density model. As the successor of the zone metering algorithm, the Stratified Zone Ramp Metering (SZM) Strategy has been developed and deployed in the Minneapolis/Saint Paul area.[16] The SZM strategy aims to maximize freeway throughput while keeping ramp waiting times below a predetermined threshold. In a recent study Papamichail et al.[17] Developed a traffic- response feedback control strategy, HERO (Heuristic Ramp Metering Coordination) to coordinate local ramp metering actions in freeway networks Wang et al.[18] Proposed an area-wide ramp metering system to improve the coordination of ramp meters for system-wide optimization and on-ramp overflow minimization. In summary, coordinated ramp metering strategies have been suggested as more effective measures than local ramp metering when there are multiple congestion bottlenecks on the freeway, excessive ramp delays, and when the optimization of freeway and on-ramp performances requires the metering of several ramps.

Study objectives

This study applies ramp metering strategies on the two corridors of I-10 and I-12 within the city of Baton Rouge in order to determine their effectiveness. This is achieved by simulating both corridors with and without ramp metering at the microscopic level using the forecasted traffic demand in the year 2012.The specific objectives of this research are to: (1) review the state of the practice of ramp metering strategies and their application in other metropolitan areas in order to learn from similar experiences and identify the various strategies used thus far, as well as their points of strengths and weaknesses, (2) identify the data requirements for developing a simulation model for the two corridors of I-10 and I-12 in Baton Rouge and estimate the forecasted travel demand is used for the year 2012, (3) select a microscopic simulation platform (VISSIM) and build the simulation network for the study area, and (4) evaluate the effectiveness of ramp metering by comparing selected network performance measures with and without the implementation of ramp meters. It is anticipated that meeting these objectives will lay a foundation for the application and implementation of ICM strategies to reduce congestion on the freeway and arterial systems in Baton Rouge.

Data collection

Traffic data was collected from the Capital Region Planning Commission (CRPC) to reflect the forecasted origins and destinations for all on and off ramps along the 7 mile corridor of I-10 and the 4 mile corridor of I-12in Baton Rouge, Louisiana; see Figure 1. The two corridors currently experience heavy recurrent congestion during the morning and evening peak periods. Geometric data was collected to build the study area network in the simulation model. The planning-level network was provided in the form of a Trans CAD file, based on the Baton Rouge Metropolitan Transportation Plan Update of December 2007.The morning interval was defined from 6:30-9:30 AM and the evening interval from 3:30-6:00 PM. With this data, a Friction Factor Matrix was created in order to determine the origin-destination flows for the morning peak period only between on- and off-ramps as origins and destinations, respectively. The gravity model was then applied to synthesize an Origin-Destination (O/D) matrix based on the estimated friction factor matrix. Table 1 shows the non-zero values of the friction factor matrix for the 25 origins (on-ramps) and 25 destinations (off-ramps), as well as the corresponding values of the O/D matrix after the first iteration and the final O/D matrix. The friction factors were inversely proportional to the distances between the origins and destinations along both corridors. A total of 14 iterations were required to reduce all errors in the attractions to 1% or less. The final O/D matrix was then used in the simulation model to predict the network performance with and without ramp metering strategies in the target year.

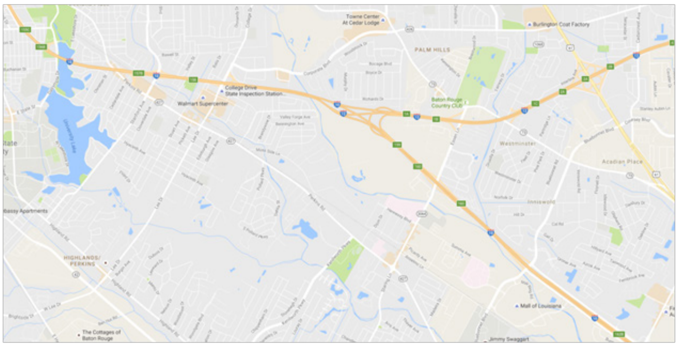

Figure 1 Study Network for I-10 and I-12; Baton Rouge, LA.

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Table 1 Friction factor matrix, first iteration and final origin/destination matrix

O Labels	D Labels	Friction Factor	First Iteration	Final Value	O Labels	D Labels	Friction Factor	First Iteration	Final Value	O Labels	D Labels	Friction Factor	First Iteration	Final Value	O Labels	D Labels	Friction Factor	First Iteration	Final Value
A1	Off1	100	2792	2537	On3	Off6	50	1097	747	On19	Off20	40	143	50	A72	Off6	50	2105	657
	Off2	90	934	862		Off7E	40	268	172		Off22	30	220	68		Off7E	40	515	152
	Off3	80	1362	1412		Off8E	30	132	113		Off24	20	10	4		Off8E	30	253	99
	Off4	70	137	162		Off9E	20	229	294		A60	10	244	155		Off9E	20	439	259
	Off5	60	751	731		A23	10	319	610		Off10	60	602	802		A23	10	612	537
	Off6	50	2281	1617		Off20	40	254	219		Off9W	50	628	424		Off9W	50	2143	1617
	Off7E	40	558	373		Off22	30	390	197		Off8w	40	554	448		Off8w	40	1888	1711
	Off8E	30	274	245		Off24	20	17	17		Off7a	30	207	191		Off7a	30	706	728
	Off9E	20	475	637		A60	10	433	671		Off7W	20	45	56		Off7W	20	152	215
	A23	10	663	1322	On4	Off7E	40	604	309		A24	10	386	839		A24	10	1315	3200
	Off20	40	529	474		Off8E	30	297	203	On18	Off20	40	8	3		Off17	80	1911	2319
	Off22	30	811	643		Off9E	20	515	527		Off22	30	12	4		Off15a	70	943	1173
	Off24	20	36	37		A23	10	718	1094		Off24	20	1	0		Off15	60	943	1257
	A60	10	901	1453	On5	A23	10	545	545		A60	10	13	8	On27	Off6	50	233	75
On1	Off2	90	91	82	On6	A23	10	995	995		Off10	60	32	43		Off7E	40	57	17
	Off3	80	132	134	On13E	Off22	30	1009	655		Off9W	50	34	23		Off8E	30	28	11
	Off4	70	13	15		Off24	20	44	38		Off8w	40	30	24		Off9E	20	49	30
	Off5	60	73	69		A60	10	1121	1481		Off7a	30	11	10		A23	10	68	62
	Off6	50	222	153	On13a	Off22	30	267	173		Off7W	20	2	3		Off9W	50	237	185
	Off7E	40	54	35		Off24	20	12	10		A24	10	21	45		Off8w	40	209	196
	Off8E	30	27	23		A60	10	296	391	On17	Off20	40	79	28		Off7a	30	78	83
	Off9E	20	46	60	On13b	Off24	20	31	20		Off22	30	121	38		Off7W	20	17	25
	A23	10	65	125		A60	10	793	804		Off24	20	5	2		A24	10	146	367
	Off20	40	51	56	On14E	A60	10	1827	1827		A60	10	134	85		Off15a	70	104	134
	Off22	30	79	61	A48	Off20	40	411	128		Off10	60	331	441		Off15	60	104	144
	Off24	20	4	3		Off22	30	630	174		Off9W	50	345	233	On26	Off6	50	195	65
	A60	10	88	138		Off24	20	28	10		Off8w	40	304	246		Off7E	40	48	15
On2	Off5	60	358	336		A60	10	700	393		Off7a	30	114	105		Off8E	30	23	10
	Off6	50	1086	744		Off12	80	1174	1690		Off7W	20	24	31		Off9E	20	41	25
	Off7E	40	266	172		Off11	70	764	1257		A24	10	212	461		A23	10	57	53
	Off8E	30	131	113		Off10	60	1729	2035	On16	Off20	40	82	31		Off9W	50	199	159
	Off9E	20	226	294		Off9W	50	1803	1075		Off22	30	125	42		Off8w	40	175	168
	A23	10	316	610		Off8w	40	1589	1138		Off24	20	5	2		Off7a	30	65	72
	Off20	40	252	219		Off7a	30	594	485		A60	10	139	96		Off7W	20	14	21
	Off22	30	386	297		Off7W	20	128	143		Off9W	50	258	263		A24	10	122	315
	Off24	20	17	17		A24	10	1107	2129		Off8w	40	315	278		Off15	60	87	124
	A60	10	429	671	On14W	Off7a	30	167	90		Off7a	30	118	118	On25	Off6	50	213	73
On15	Off8w	40	286	180		Off7W	20	36	27		Off7W	20	25	35		Off7E	40	52	17
	Off7a	30	107	77		A24	10	311	396		A24	10	220	520		Off8E	30	26	11
	Off7W	20	23	23	On13W	Off7a	30	445	241	On11	Off7W	20	106	65		Off9E	20	44	29
	A24	10	200	337		Off7W	20	96	71		A24	10	922	963		A23	10	62	60
						A24	10	829	1057	On10	A24	10	1771	1771		Off9W	50	216	180
																Off8w	40	190	191
																Off7a	30	71	81
																Off7W	20	15	24
																A24	10	132	357

Methodology

Network description

VISSIM is a behavior based microscopic simulation model that was adopted in this study. The freeway corridors of I-10 and I-12 were coded in VISSIM using links and nodes. Figure 2 shows a snapshot of both corridors as coded in VISSIM. Routes were created from every specific entrance point (on-ramp) to all possible exit points (off-ramps) for both eastbound and westbound directions within the simulation model. Each route began at a routing decision point and ended at one or more destination points. For each designated route, a number of trips were as-signed based on the final O/D matrix explained earlier.

Simulation experiments

Two simulation scenarios were created, one with ramp meters and one without ramp meters. For the ramp meter scenario, a ramp meter controller was added for each on-ramp along both corridors in both directions. Also, signal heads were installed at every on ramp to represent each ramp meter. A set of detectors was also attached to each signal head. One detector was placed at the location of the signal head and another one shortly be-hind signal head. Other detectors were added on each lane of the mainline to adjust the ramp meter flow rate based on the current lane occupancy detected on the mainline. Each set of detectors was identified with its reference signal head by a two-digit number system where the tens digit was the signal controller and the ones digit was the detector numbers. For the control corridor, no signal heads or detectors were created, as no ramp meters would be used. Vehicle Actuated Programming (VAP) was used as the signal state generator. With this setting, user controlled signal logic was actuated.

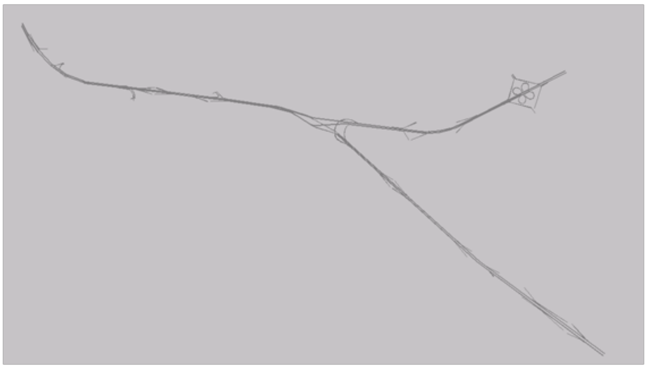

Figure 2 VISSIM Coded Network for I-10 and I-12.

Simulation runs

In order to account for randomness in driving behavior, a total of 25 simulation runs were generated for each of the two scenarios. The network was simulated for one hour, in addition to a 15-minute warm up period. A set of network-level performance measures was also identified as follows:

- Average delay time per vehicle [s]
- Total travel time [h]

Statistical analysis

This section presents the statistical analysis used to compare the traffic performance for metered and non-metered traffic on the study section. Basic descriptive statistics is presented first, followed by tests of hypothesis. All tests were performed in SAS®.

Descriptive statistics

The basic descriptive statistics for metered and non-metered scenarios is shown in Table 2. The statistics include the sample size, and the mean, standard deviation, and minimum and maximum values for the two performance measures. The table shows that when metering is implemented, the average delay per vehicle was reduced from 496 to 452 seconds. Same applies to the average travel time which was reduced from 6066 to 5292veh. h. This indicates that the ramp metering improves the travel conditions in the corridor.

Table 2 Basic descriptive statistics for metered corridors

Metered corridors					
Variable	**N**	**Mean**	**Std dev**	**Min**	**Max**
Average Delay Time per Vehicle [s]	24	452	7.8	442	463
Travel Time [veh.h]	24	5292	33	5246	5346
Non-metered corridors					
Average Delay Time per vehicle [s]	24	496	5.3	484	502
Travel Time [veh.h]	24	6066	43	5959	6118

Tests of hypothesis

The statistical tool used for the analyses of results was the Student's t-test for two independent population means with unknown variances. The population variances were first tested to confirm whether they were equal or not; so as to determine whether to perform a pooled t-test or Satterthwaite t-test, respectively. The test results for the average delay time per vehicle and total travel time are presented in the following sub-sections.

Average delay time per vehicle: If μ_i and μ_j denote the average delay time in seconds per vehicle for the metered and non-metered corridors respectively, the following hypotheses were tested:

$$H_0 : \mu_i - \mu_j = 0 \text{ (no difference exists)}$$

$$H_1 : \mu_i - \mu_j \neq 0 \text{ (difference exists)}$$

A test of variances concluded that both populations have equal variances. Therefore, a pooled t-test analysis was performed on the population means. This resulted in a p-value of <0.0001, which is less than the 0.05 level of significance used. It can therefore be concluded that at the 0.05 level of significance a difference exists between the average delay time between the metered and non-metered corridors. In particular, since $\mu_i = 452.26$ and $\mu_j = 496.93$, it can be concluded that the average delay time in seconds is greater for the non-metered corridor than that for the metered corridor. In other words, implementing ramp metering led to a statistically significant reduction in the average delay per vehicle.

Total travel time: If μ_i and μ_j denoted the total travel time in vehicle hours for the metered and non-metered corridors, respectively, the following hypotheses were tested:

$$H_0 : \mu_i - \mu_j = 0 \qquad \text{(no difference exists)}$$

$$H_1 : \mu_i - \mu_j \neq 0 \qquad \text{(difference exists)}$$

Similar to the average delay analysis, the test of variances concluded that both populations shaves equal variances, and therefore, the pooled t-test analysis was performed on the total travel time too. The test resulted in a p-value of <0.0001, which is less than the 0.05 level of significance used. It can therefore be concluded that at the 0.05 level of significance a difference exists between the total travel time for the metered and non-metered corridors. In particular, since $\mu_i = 5,292$ and $\mu_j = 6066$, it can be concluded that the total travel time in vehicle hours is greater for the non-metered corridor than that for the metered corridor. In other words, the reduction in the total travel time resulted when implementing ramp metering is statistically significant.

Conclusion

The comparative evaluation of two scenarios (with and without ramp metering) showed a statistically significant improvement in the corridor performance when ramp metering strategies were implemented. The statistical analysis using the Student's t-test for two independent samples with unknown variances showed consistently that the means were significantly different at 95% confidence level. A test of variances was also con-ducted and concluded that both populations had equal variances, and therefore, a pooled t-test analysis was conducted. More specifically, the statistical analysis shows that (a) the average delay time in seconds is greater for the non-metered corridor than that for the metered corridor; and (b) the total delay travel time in hours is greater for the non-metered corridor than that

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None.

Conflict of interest

The author declares no conflict of interest.

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