Identifying and Prototyping Integrated Corridor Management (ICM) Strategies for Application in Virginia

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Abstract:

Highway congestion is a major problem in urban transportation, and the search for feasible mitigation measures continues to evolve with advancement in technology and better understanding of traveler behavior. Due to institutional barriers and traditional practices, individual subsystems within a "corridor"—for example, arterial signal control systems and transit systems—have been operated independently, in isolation from each other. This management approach often leads to improving the performance of one subsystem at the expense of others. A more efficient approach that has the potential to improve corridor-wide mobility is to coordinate the management of the individual transportation subsystems in order to make them operate collaboratively. This holistic approach is referred to as integrated corridor management (ICM).

In order to explore and demonstrate the potential for ICM application in Virginia, an investigation into the factors that are critical to its successful implementation and operation was conducted. Critical success factors were identified from the eight ICM "pioneer" sites sponsored by a U.S. Department of Transportation ICM initiative. The three most critical factors identified include (1) a robust Intelligent Transportation Systems (ITS) infrastructure; (2) the need for stakeholder partnerships and development of institutional frameworks within which ICM will be implemented and operated; and (3) the need to adopt standards and protocols through which information will be disseminated.

Additionally, the potential effectiveness of ICM as a congestion mitigation measure in Virginia was explored by prototyping the application of a set of ICM strategies in a simulation environment using a segment of the I-95/I-395 corridor (between mile marker 152 and mile marker 163) as a test bed. The strategies implemented include variable speed limits; ramp metering; transit signal priority; financial incentives (reduction in transit and parking fees); high occupancy toll (HOT)/high occupancy vehicle (HOV) lanes and HOV bypass; and increased transit and parking capacity. Analysis of the simulation results revealed that corridor person flow per hour had the potential to be increased by 14% under non-incident traffic conditions, compared to 38% during incident conditions. In terms of average travel time, the I-95 general purpose lanes could potentially experience a reduction of 48% and 58% under non-incident and incident traffic conditions, respectively. Whereas the average travel time on the HOV lanes remained essentially unchanged, average travel times on the primary arterial (U.S. 1N) improved by 29% under both non-incident and incident conditions. Additionally, the amount of fuel usage was reduced by 34% and 33% during non-incident and incident conditions, respectively. Although the cost of ICM implementation is high, benefit-cost ratios of 4:1 and 6:1were obtained for non-incident and incident conditions, respectively.

Based on the analysis results, it is recommended that variable speed limits, increased transit and parking capacities, HOV bypass lanes, and HOV/HOT lanes be considered the most promising for future ICM implementation in Virginia.

FINAL REPORT

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DISCLAIMER

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ABSTRACT

Highway congestion is a major problem in urban transportation, and the search for feasible mitigation measures continues to evolve with advancement in technology and better understanding of traveler behavior. Due to institutional barriers and traditional practices, individual subsystems within a "corridor"—for example, arterial signal control systems and transit systems—have been operated independently, in isolation from each other. This management approach often leads to improving the performance of one subsystem at the expense of others. A more efficient approach that has the potential to improve corridor-wide mobility is to coordinate the management of the individual transportation subsystems in order to make them operate collaboratively. This holistic approach is referred to as integrated corridor management (ICM).

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INTRODUCTION

Highway congestion has been a major problem in traffic operations and management, and the search for feasible mitigation measures continues to evolve with advances in technology and better understanding of traveler behavior. According to the *2012 Urban Mobility Report*,[1] in calendar year 2011, travel delay per commuter was 38 hours, total delay was 5.52 billion hours, and total fuel wasted was 2.88 billion gallons, amounting to $121.2 billion for the entire United States. According to the same report, the total cost of congestion in the Virginia–District of Columbia–Maryland metropolitan area was $3.771 million in 2011. These costs are likely to increase in the future as a result of population and car ownership growth.

Currently, most individual transportation facilities within a corridor are operated independently; therefore, any mitigating measures are geared toward improving a specific facility. This may result in inefficiencies at network junctions and reduce the potential benefits of such mitigation measures on the entire transportation system. For example, improving freeway operations by using dynamic message signs (DMS) to divert traffic to parallel arterials without knowing the existing operating conditions on those arterials might have little system-wide benefits. Essentially, the freeway's traffic conditions will be improved at the expense of the arterials. Therefore, there is a need to operate transportation facilities (which are usually managed by different agencies) within a corridor as a single system in order to maximize the system-wide benefits of traffic management strategies. This management approach is referred to as ICM. ICM can be best described as the coordination of the day-to-day activities of distinct transportation networks/facilities within a clearly defined geographical region (corridor), with the aim of improving the mobility, safety, and efficiency of the overall transportation system.

Transportation corridors often contain under-utilized capacity in the form of parallel routes (freeways, arterials, and HOV lanes), single occupant vehicles (SOV), and transit systems operating below capacity that could be tapped to help reduce congestion.[2] ICM provides the opportunity for system-wide improvement in traffic operations in which all facilities and modes

are considered. The system that provides the platform to operate the ICM concept is referred to as the Integrated Corridor Management System (ICMS).

PURPOSE AND SCOPE

The purpose of this study was to explore and demonstrate the potential for ICM application in Virginia and identify applicable ICM strategies that hold high potential for mitigating congestion. These strategies were prototyped in a microscopic simulation model in order to evaluate the benefits associated with ICM.

This study will provide the Virginia Department of Transportation (VDOT) with information that will allow the agency to make sound decisions on the existing and future applications of ICM strategies.

METHODS

In order to achieve the study objectives, the project was divided into eight main tasks:

1. Literature review on ICM
2. Selection of site to test prototype ICM strategies
3. Identification of best practices and potential ICM strategies
4. Development of ICM evaluation methodology
5. Development and validation of simulation network
6. Evaluation of proposed ICM strategies
7. Analysis of results
8. Development of recommendations.

Literature Review

The research team conducted a comprehensive literature review on ICM-related policies and strategies, implementations, and evaluations. Since there are no existing fully operational U.S. or international ICM systems, the main focus of the literature review was on the eight pioneer ICM sites adopted by the U.S. Department of Transportation (U.S. DOT) as part of its seven-year ICM development initiative.

Sources for the literature review included the VDOT Research Library, Transportation Research Information Service (TRIS), University of Virginia engineering databases, and U.S. DOT–dedicated website on ICM.

Selection of Test Site

The Northern Virginia (NOVA) VDOT district initiated an ICM project in late 2011 along I-95/I-395, and a final concept of operations document is scheduled to be released later this year.[3] The potential to coordinate this research with that of NOVA motivated the research team to change its initial choice of study areas (I-264/U.S. 58 corridor Virginia Beach and I-66 corridor in NOVA) and focus on the I-95/I-395 corridor instead. The description and potential application of ICM to the corridor are discussed next.

I-95/I-395 Corridor Description

The I-95/I-395 corridor is a major north-south corridor located in the Northern region of Virginia and connects downtown Washington, D.C., to many of the suburban cities south of Washington, D.C. The corridor begins at the intersection of U.S. 1 and I-95 at Spotsylvania (mile marker [MM] 126), terminating at the intersection of the 14th Street Bridge and I-395 in Washington, D.C. (MM 10). The corridor is composed of three segments:

1. U.S. 1/17 to Route 610 (MM 126-144)
2. Route 610 to Interstate 495 (MM 144-170)
3. Interstate 495 to 14th Street (I-395[MM0-10]).

The corridor is composed of freeways (I-95 and I-395); a primary arterial (U.S. 1); commuter rail (Virginia Railway Express [VRE]) along the entire length of the corridor (but some segments lie far from I-95); Metrorail from Franconia to Washington, D.C.; bus services (e.g., Fairfax Connector, Potomac and Rappahannock Transportation Commission [PRTC] buses); and park-and-ride facilities. The freeways are made up of six to eight general purpose (GP) lanes and two reversible HOV lanes (expansion to three in the future for high HOT operation). The primary arterial, U.S. 1, is a relatively convenient alternate route for transportation between Spotsylvania and Woodbridge. Additionally, the corridor operation includes transportation demand management strategies such as vanpooling, carpooling, "slugging," and real-time ride sharing (pilot). About 40,771 spaces are available at the park-and-ride facilities in the corridor and 3,000 more have been proposed for construction by 2015.[3]

Currently, the operating conditions along the corridor deteriorate as one travels north. Volume to capacity (V/C) ratios on I-95 exceed 1:0 near and inside I-495, with operating speeds ranging from 20% to 25% of free flow speeds during the morning peak (northbound) and 14% to 23% of free flow speeds during the evening peak (southbound). Similarly, the number of crashes is also higher at the northern end of the corridor.   Table 1 shows a list of hot spots along the corridor and their operating conditions.

Table 1. I-95/I-395 Corridor Hot Spots

Hot Spot Location	Volume/Capacity		% of Operating Speed to Free Flow Speed		Crashes
	AM (NB/SB)	PM (NB/SB)	AM (NB/SB)	PM (NB/SB)	
Route 17 (MM 134-136)	0.8/0.9	0.92/0.88	70/60	48/65	165
Routes 619-234 (MM 151-153)	0.88/0.8	0.93/0.88	62/73	49/66	276
Route 123 (MM 157-161)	1.0/0.82	0.92/1.02	25/67	53/21	390
Route 7100 (MM 166-170)	1.1/0.93	0.94/1.04	20/30	27/23	644
I-495-Route 236 (MM 0-3)	1.04/0.8	1.05/1.15	20/56	25/14	388

Source: Virginia Department of Transportation, Northern Virginia District. *I-95/I-395 Corridor Assessment and Project Scoping Workshop*. Fairfax, December 16, 2011.

In order to test as many ICM strategies as possible in the simulation environment, a northbound segment of the corridor beginning at MM 152 (exit 152 on I-95N) and ending at MM 163 (intersection of I-95 N and Lorton Road) was selected as the analysis segment as shown in Figure 1.

A key consideration in selecting this segment was the relative proximity of I-95N to the primary arterial, U.S. 1N, as well as the VRE commuter line. On average, the distance between the freeway and the arterial along the entire length of this segment is 1.5 miles, making it a desirable alternative route should a traveler choose to change routes. Also, a shorter segment of the entire I-95/I-395 corridor was used as a result of the computational limitations of the adopted microscopic simulation software (VISSIM).
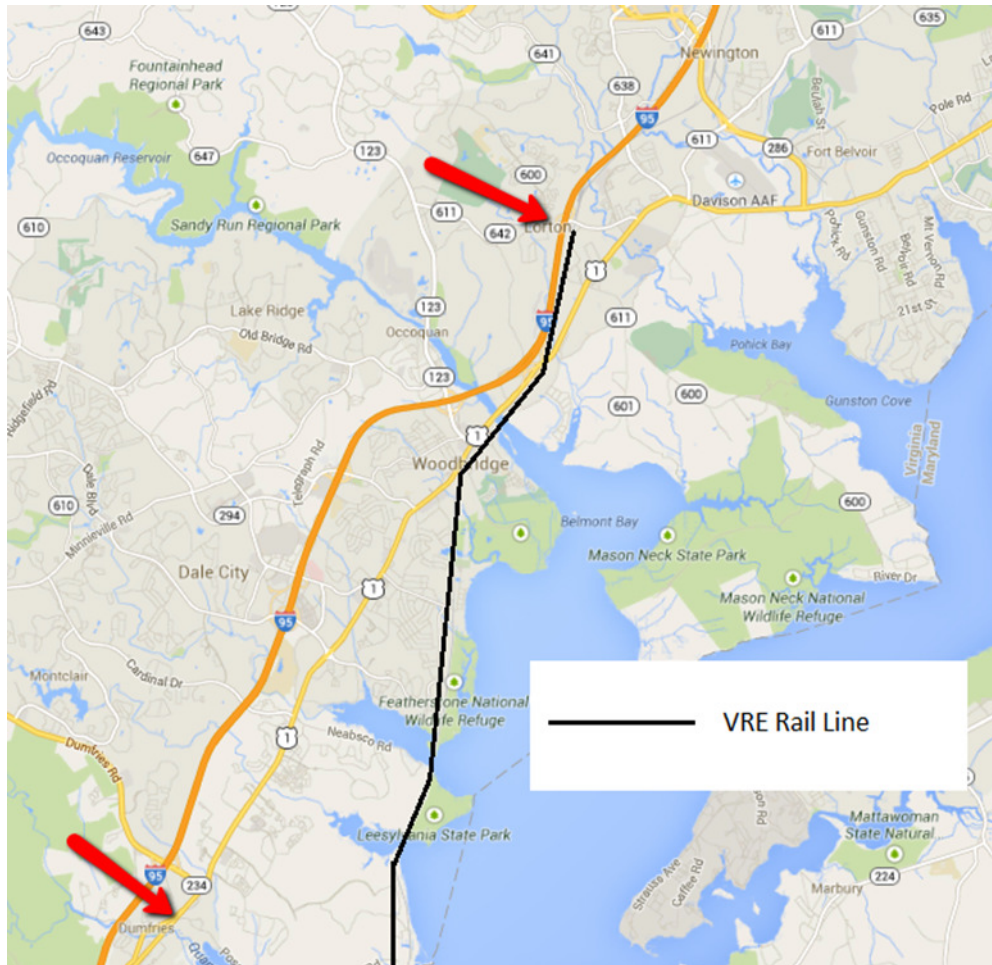

Figure 1. ICM Study Area

Tables 2 and 3 show the parking[26] and transit[27] facilities within the analysis segment.

Table 2. Parking Facilities in the Analysis Segment

Commuter Lot/Park-and-Ride	Number of Spots	Filled by 8:00 AM?	Available Spots
Horner Road	2363	Yes	0
PRTC Transit Center	145	Yes	0
Telegraph Road	200	No	Unknown
Potomac Mills	275	Yes	0
SR234/SR 1	843	Yes	0
Lakeridge	638	Yes	0
Oldbridge/SR 123	580	Yes	0
SR 123/I-95 N	580	Yes	0
VRE (Rippon Station)	676	No	229
VRE (Woodbridge Station)	738	No	221
Total	7038	--	450

Table 3. Transit Routes in the Analysis Segment

Route	Number of Trips (AM Period)	Person Capacity	Capacity Used	Available Capacity
PRTC (Lakeridge-Washington)	10	570	293	277
PRTC (Lakeridge-Pentagon/Crystal City)	6	342	203	139
PRTC (Dale City-Washington)	25	1425	867	558
PRTC (Dale City-Pentagon/Crystal City)	9	513	312	201
PRTC (Dale City-Navy Yard)	6	342	220	122
PRTC (Lakeridge-Capitol Hill)	1	57	25	32
PRTC (South Route 1-Washington)	4	228	155	73
VRE (Fredericksburg Line)	7	5626	4921	705
Total	68	9103	6996	2107

From Table 3, it can be seen that there is extra passenger capacity in the transit system. In general, many factors affect transit ridership. These include transit service quality, transit fares, gas prices, proximity of bus stops to residential areas, availability of parking spots at park-and-ride facilities, etc. Using Table 2 as the basis of argument and without any further considerations, the unused transit capacity could be attributed to the limited availability of parking spots (a deficit of 2065 compared to transit capacity). Additionally, early transit departure times could also limit the full utilization of existing transit capacity. A careful examination at the operating schedule for PRTC buses[26] and VRE trains[27] as presented on their websites indicates that 21 of the 68 transit trips (19 buses, 2 commuter trains) start and end before 6:00 AM. Such a transit operating schedule might not be convenient for many travelers. Regardless of the reason for unused transit capacity, there is a clear potential to institute some transit-oriented ICM strategies that will take advantage of the extra capacity in order to increase corridor person throughput.

Identification of Best Practices and Potential ICM Strategies

In *ICMS Concept of Operations for a Generic Corridor*, Neudorff et al. outlined five categories to aid in the development and selection of ICM strategies.[20] These categories are information sharing/distribution; improving operational efficiency of network junctions and

interfaces to accommodate/promote cross-network route and modal shifts; managing capacity-demand relationship within corridor (real-time/short-term); and managing capacity-demand relationship (long-term).

These guidelines are premised on the coordinated and collaborative nature of ICM deployments, in which individual transportation networks function as a unit for the common goal of improving the overall corridor performance. However, the ICM strategies documented in the guidelines are generic and must be tailored to reflect the specific site conditions of this corridor. In this project, each of the five categories of strategies was explored and specific strategies that conform to the I-95/I-395 ICM initiative were selected. The site-specific strategies (I-95/I-395 corridor) are discussed here.

Information Sharing/Distribution

- A corridor-wide comprehensive information clearinghouse with graphical display of information reporting on corridor infrastructure status, capacity, demand, and incidents is necessary. The information clearinghouse must include park-and-ride availability, transit schedule, and travel times for all major routes/modes. This would require integrating data from VRE, Washington Metropolitan Transit Authority (WMATA), Fairfax Connector, PRTC commuter bus services, local transit services, intercity bus services, VDOT and City traffic authorities.

- Sharing of information among operating agencies must be real-time through voice, data, video, or any protocol adopted for center-to-center communication, in addition to a corridor-based multimodal Advanced Traveler Information System (ATIS) database that provides both pre-trip and en-route traveler information. This would include providing real-time comparative travel time information for general purpose and HOV/HOT lanes, parallel arterial routes, and transit services. Also, information on next-bus and next-train (as well as respective seat availabilities) should be made available on all major routes and modes, as well as key decision points.

- The multimodal traveler information specific to the corridor must be made available through an expanded 511 service, web (one-stop-shop website for all modes and networks), and mobile applications. Alternatively, travelers could assess corridor information through kiosks installed at activity centers such as rest areas, the Mark Center, the Pentagon, and park-and-ride facilities. To support an effective representation of transit conditions in the multimodal traveler information system, transit vehicles must be equipped with Automated Vehicle Location (AVL) and Automated People Counter (APC) devices for accurate reporting.

- A common incident reporting (GIS-based) and decision support system must be developed among the operating agencies in order to optimize incident management within the corridor, which would reduce delays and facilitate the quick return of traffic conditions to normalcy. This would involve the expansion of Public Safety and Transportation Operations Center (PSTOC) coordination functionalities to include Prince William and Stafford Counties, as well as the City of Fredericksburg

Police and Fire/Rescue services and would facilitate the integration of Computer-Aided Dispatch (CAD) programs of constituent Counties. The expansion of the coverage of Safety Service Patrol (SSP) in the corridor would also improve incident management. It is important to note that the coordination of incident management helps to identify shorter routes and signal timing plans to facilitate quicker response. The decision support system would utilize information from the data warehouse and current corridor operating conditions from field devices to generate responses that are suitable for ensuring fluid traffic conditions. With these improvements, the operating agencies could then investigate all possible traffic condition scenarios and develop appropriate responses that to be used in real-time.

- Access to corridor information (e.g., ATIS database) by Information Service Providers (ISP) and other value-added entities must be readily available.

- A parking management and guidance system must also be provided at parking entry points. More detailed signs at parking facilities would help direct drivers to available parking spaces in real-time, using an automated parking space detection system.

Improving Operational Efficiency of Network Junctions and Interfaces

The following strategies are necessary for network junction and interface efficiencies.

- Signal pre-emption or "best route" for emergency vehicles to allow quicker response to emergency situations in the corridor. This would require the coordination of Northern Virginia Smart Traffic Center (NVSTC), Northern Virginia Smart Traffic Signal System (NVSTSS), and the public safety office.

- Multimodal integrated electronic payment would help simplify the mode of payment for travelers and also allow for innovative pricing incentives to encourage multimodal use, such as credits for riding transit. This might involve the integration of payment methods for the proposed HOT lanes on I-95, transit services (VRE, WMATA, PRTC, etc.), and the park-and-ride/parking facilities that charge fees.

- Signal priority (infrared or wireless) for transit vehicles operating behind schedule on arterials that serve as transit routes would reduce the number of delayed transit vehicles and make transit an attractive option to travelers.

- Transit hub connection protection through the display of transit connection information for drivers. Drivers usually lack information about which buses have or have not arrived at connection points, which causes them to make decisions that could leave them stranded at these connecting points. Drivers will be more confident if there are reliable transit connections of which they can be thoroughly informed, so they do not risk being stranded. This kind of reliability would have the potential to permanently influence a shift of significant proportions in the transportation mode within the corridor.[20]

- Coordinated operation between arterial traffic signals and ramp meters in close proximity to avoid queues that extend onto the arterial. This can be achieved through the use of adaptive ramp meters equipped with queue detectors to optimize metering rates on the ramp. Depending on the prevailing conditions, the optimized metering rates would benefit either the freeway or the arterial. Similarly, during incidents that require the rerouting of vehicles onto the arterials, detectors on the off-ramp must be synchronized with the nearby arterial signals to avoid the backing of queues onto the freeway. This can be applied at the corridor hot spots (Routes 1 and 610, Fairfax County Parkway, Duke Street, etc.) that experience excessive queuing. Network junctions should be adequately equipped with closed-circuit television (CCTV) cameras to enable visual verification of queue lengths.

Accommodate/Promote Cross-Network Route and Modal Shifts

Cross-network and modal shifts are critical to the success of ICM. The following strategies can be used to accommodate/promote these shifts.

- Modifying arterial (U.S. 1) signal timing to accommodate traffic that might shift from the freeway (I-95/I-395).

- Modifying ramp metering rates to accommodate traffic, including buses, from arterials.

- Modifying transit priority parameters to accommodate more timely bus service on arterials. Also, during incidents, buses should be re-routed to avoid significant delays.

- Network shifts within the corridor could be promoted by encouraging corridor users through an en-route traveler information service (e.g. DMS, 511, highway advisory radio) based on prevailing conditions within the network to

  — Shift between roadways.

  — Shift from roadways to high-capacity transit services with adequate parking availability.

  — Shift between transit facilities.

Managing Capacity-Demand Relationship within Corridor-"Real-time"/Short-Term

Capacity-Oriented Strategies

- Dynamic lane-use control through reversible lanes (already in use on I-95) and hard shoulder-running (proposed between MM 139.1 and MM 145.3). Hard shoulder running allows vehicles to use freeway shoulders as travel lanes during congested periods and, sometimes, special events. Transit vehicles may also use the shoulder.

Hard shoulder-running requires the use of incident detection systems to ensure its safe use. Dynamic lane control can also be used during construction activities/incidents to direct drivers away from closed lanes.

- Variable speed limits (VSL) can be applied on freeways based on time of day/congestion status, weather conditions, work zones, etc., to minimize speed variance. This ensures the steady flow of traffic and prevents incidents. VSL is often used alongside queue warning signs to warn vehicles upstream about downstream congestion and resulting queues. These can be applied at the five hot spots identified on I-95/I-395 that experience high numbers of crashes and congested conditions during peak hours.

- To facilitate faster transit travel times, some sections of arterials could be dedicated as "transit-only."

- Transit capacity can be increased by adjusting headways and the number of vehicles along a route when the need arises. During special events, transit capacity can be increased by adding temporary services, e.g., express bus service.

- When necessary, extra parking capacity can be added at nearby mall or small church lots, whiles providing shuttle services between these lots and the transit stations.

- The HOV/HOT lanes (I-95 and I-395) can be opened for use by any vehicle during incidents as a means of increasing throughput. The HOT lanes are managed by a private (for-profit) entity; hence, the modalities for financial compensation by VDOT must be sorted out before this strategy can be implemented.

- Scheduled maintenance within the corridor can be coordinated to minimize its impact on the overall corridor capacity.

- As a means of ensuring transit travel time reliability and promoting car/vanpooling, transit vehicles and HOVs could be given priority at ramp meters.

Demand-Oriented Strategies

- Modification of transit/parking fares to encourage ridership during peak periods, special events, and major incidents. Modifying transit fares during peak-periods and adding incentives such as the accrual of credits that could be used for free ridership/parking during off-peak periods has the potential to entice travelers.

Managing Capacity-Demand Relationship (Long-Term)

Capacity-Oriented Strategies

- Addition of HOT/HOV lanes in light of increasing demand in corridor. In anticipation of The Mark Center, an HOV ramp has been proposed to improve traffic operations at the intersection of Seminary Road and I-395.

- Expansion of the capacity of parallel arterials where necessary.

Demand-Oriented Strategies

- Instituting ride-sharing programs.

- Education on flexible work hours and mode shifts.

The above-mentioned ICM strategies are not exhaustive; however, they entail the most current and critical strategies necessary for any successful ICM implementation. As the pioneer sites become fully operational, new and innovative strategies will emerge.

Development of ICM Evaluation Methodology

Given the complexity of ICM and the required interrelationship of systems, the evaluation of strategies requires a detailed methodology that can adequately quantify the effects of each component of the system.

The research team developed a five-step evaluation methodology that provides adequate support to evaluate and quantify the benefits of ICM strategies. The methodology includes the modeling of base conditions, the application of ICM strategies to base conditions, sensitivity analysis of ICM strategies, a test of statistical significance of the effects of strategies, and recommending a combination of strategies. The chart in Figure 2 describes the methodology.

ICM operates within a multidimensional framework with several candidate strategies and varying levels of application. It is therefore difficult to determine a good combination of applicable strategies based solely on expert judgment or random selection. There must be an unambiguous causal relationship between traffic improvement indicators and a set of ICM strategies to justify their selection; such inferences can only be drawn from an experimental design. Experimental designs provide an efficient procedure for planning experiments so that data obtained can be analyzed to give valid and objective conclusions. The evaluation methodology described implicitly entails the experimental design process.

For the purposes of clarity and conciseness, the ICM evaluation methodology will be explained through an illustrative example. In the example, the concept of ICM will be introduced in a hypothetical corridor, and each step of the evaluation methodology will be

applied. A better understanding of the example will facilitate easy application of the evaluation methodology to any corridor of interest.

Evaluation Methodology Example

Consider a corridor that is made up of a 10-mile freeway and an adjacent arterial across the entire length of the freeway. The freeway has six single-lane on-ramps that are not metered, but the signals on the arterial have optimization capabilities.

The corridor experiences excessive congestion during peak periods, partially due to a significant percentage of SOVs, and a small number of operating buses (two buses every hour).
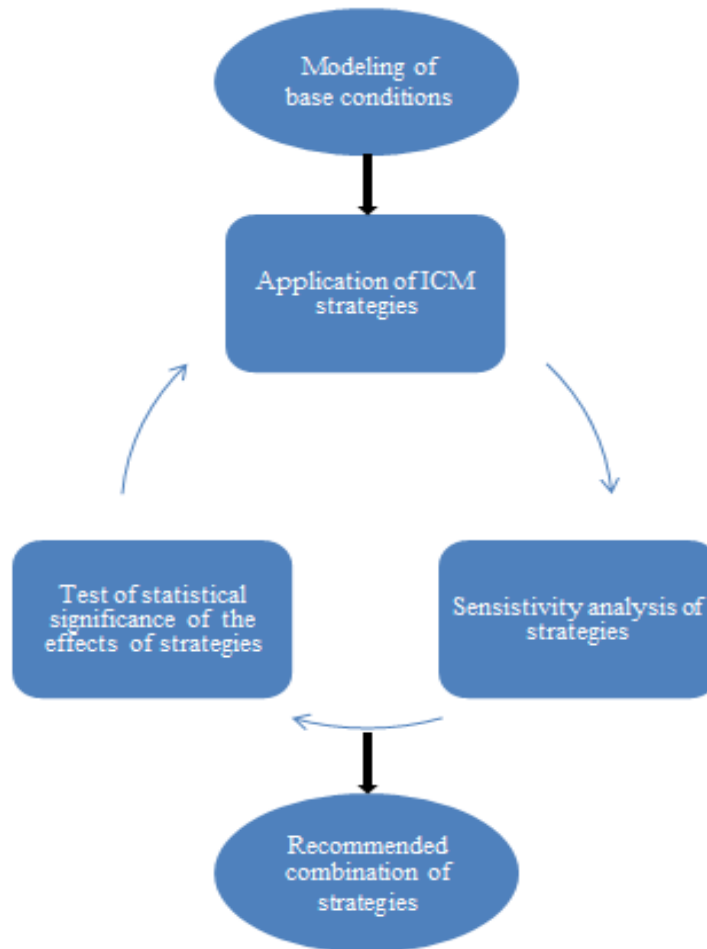

Figure 2. ICM Evaluation Methodology

Stakeholders in the corridor have agreed to implement a set of ICM strategies and these are: ramp metering, VSL, provision of parking facilities, increasing transit capacity by adding more buses, and subsidizing transit and parking fees. How will the evaluation methodology described in Figure 2 apply to this ICM initiative?

Modeling of Base Conditions

Prior to evaluating any ICM strategy, the base conditions must be established. The base case should include all modes and facility types in the corridor. In this example, these include transit, freeways, and arterials. The use of the micro-simulation software VISSIM enables the execution of this task. Performance metrics, which are indicative of corridor operating conditions, are determined from this step. These include average vehicle flow, average travel times, average delays, average emissions of CO_2, NOx, etc.

Application of ICM Strategies

After determining the prevailing operating conditions of the corridor as captured by the performance metrics, the ICM strategies agreed on by the corridor's stakeholders are implemented (modeled). Each strategy in this example is modeled by the characteristic described here:

1. Ramp metering (X_1) – this strategy regulates the flow of vehicles onto the freeway in order to improve freeway traffic flow and safety during merging conditions. The metering rate, which is between 240 and 900 vehicles/hour for a single-lane ramp meter[12] is the main attribute being modeled.

2. Variable speed limit (X_2) – the VSL strategy seeks to improve dense traffic flow by varying speed limits across the length of the freeway to avoid traffic flow breakdown. The percentage of driver compliance with the posted speed limits will be varied to determine its impact. Therefore, driver compliance is the attribute being modeled.

3. Increasing transit capacity (X_3) – the corridor stakeholders want to increase transit capacity by increasing the number of buses from two to six buses every hour. This will decrease the headways from 30 minutes to 10 minutes per bus stop. The capacity of the transit system is the variable being modeled.

4. Provision of parking facilities (X_4). The main attribute of interest is the opportunity provided to drivers who decide to park and use the bus, and that opportunity is quantified in terms of parking capacity.

5. Subsidized transit and parking fees (X_5). The cost of parking and bus fares may deter potential transit users. Corridor stakeholders have decided to subsidize these costs to make transit use attractive. The attribute being modeled is how travelers respond to these financial incentives, in terms of mode shift.

It can be inferred from strategies 3, 4, and 5 (transit and parking capacity increase, financial incentives through subsidy) that traveler behavior is expected to be influenced in order to benefit the transit mode in real-time. However, the magnitude of traveler response is unknown. Therefore, assumptions of percentage shift (range of traveler responses) in mode from SOVs to buses will be made in order to continue with the modeling process. From this, it will be

possible to estimate the limit of effectiveness of influencing traveler behavior toward mode shifts.

Sensitivity Analysis of Strategies

It is worth noting that the individual effects of the five strategies on corridor performance are of less significance within the context of ICM. The underlying principle of interest is how all five strategies combine to improve the operating performance of the corridor. Additionally, there are some strategies whose effects diminish once they are combined with other strategies; such strategies are not worth investing in and must be identified. Therefore, it is necessary to identify among the five strategies those that are critical to the improvement of corridor operating performance. Also, the extent to which unknown traveler behavior (response to subsidized transit and parking fees, extra transit capacity) can improve corridor performance is an important piece of needed information. Estimating the combined effect of the five strategies, identifying those strategies that are critical to improving corridor performance and testing for the limits of effectiveness of unknown traveler behavior can be achieved through sensitivity analysis. The next logical question is how to conduct the sensitivity analysis?

As described earlier, ICM is composed of several strategies; therefore, accurate quantification of its impact requires intensive computation and large amounts of data. For example, in order to estimate the impact of the five ICM strategies (assuming each strategy has a range of 6 values), 6^5 (7,776) different combinations (trials) of these strategies will have to be tested. Additionally, each of these combinations will have to be run at least 5 times in VISSIM to reduce the effect of stochastic variability.[4] An experimental design technique (referred to as the Latin Hypercube Sampling [LHS]), which minimizes the amount of data and computational intensity, but enables accurate estimation of the sensitivity of corridor performance to ICM strategies can be used. This sampling technique helps to achieve the same level of accuracy in sensitivity analysis with fewer number of strategy combinations (trials).

The LHS was developed by McKay and Conover in 1979 as an alternative to simple random sampling in Monte Carlo Studies (MCS).[5] In MCS, values of parameters are selected at random from their assumed probability distributions, and dynamic simulations of the system are repeated for all sampled input parameters. The accuracy of such Monte Carlo simulations depends on the number of model runs, making it less suitable for application to complex systems with many parameters.

In the LHS approach, the range of each of the five variables (strategies) $X_1, X_2, X_3, X_4,$ and X_5 is divided into N (e.g., 6) intervals in such a way that the probability of the variable falling in any of the intervals is *1/6*. Then, one value is selected at random from each interval. The *6* values obtained for the first variable X_1 are paired randomly with the *6* values of the second variable X_2. These pairs are furthermore randomly combined with the sampled values of the third variable, and so on, which finally results in *6* combinations of five variables. This set of five tuples is the Latin hypercube sample that is used for successive execution of model runs. It is convenient to think of this sample as forming a (*6 X 5*) matrix of input where the ith row contains specific values of each of the *5* input variables to be used in the ith run of the micro-

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simulation model.[6] Thus, with LHS, a smaller number of trials achieve the same accuracy as a larger number of Monte Carlo trials.

As shown in Figure 3, each of the cells represents a combination of strategies that could be run in a micro-simulation model. The LHS technique helps select a smaller number of combinations (cells with polygons) that will result in the same accuracy level as the maximum possible number of combinations. The LHS technique can be coded in MATLAB and statistical packages such as R and SAS.
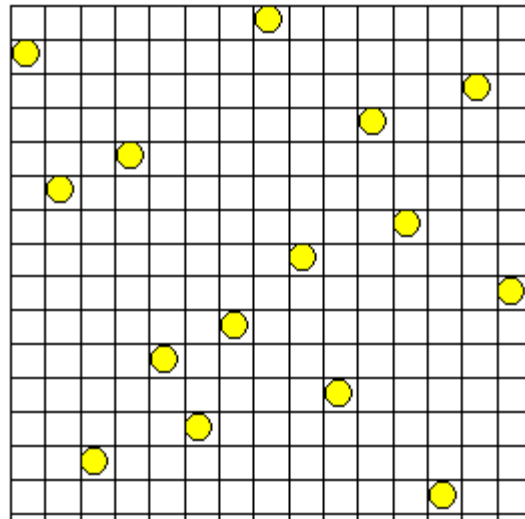

Figure 3. Latin Hypercube Sampling Diagram

Once the required feasible number of strategy combinations has been determined using LHS, they are used as inputs to run the micro-simulation model (VISSIM). The outputs and inputs of the micro-simulation runs are used to develop regression and correlation equations (sensitivity analysis techniques) based on which:

- The combined effect of the five ICM strategies on corridor performance is estimated.

- The limits of effectiveness of unknown traveler behavior are determined.

- The most critical ICM strategies among the proposed five are identified.

Three sensitivity techniques are used (standardized regression coefficient, linear correlation coefficient, and semi-partial correlation coefficient) to identify the most critical of the five ICM strategies.

Standardized Regression Coefficient (SRC)

Multiple linear regression models are often used to determine the relationship between model parameters and model output. The coefficients of regression (b_i) of model parameters, which is interpreted as the amount of change in model output based on a unit change in a model

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parameter (while all other parameters are held constant) are in different units; preventing any meaningful comparison between the significance of model parameters.[7] To make these coefficients comparable, they must be standardized. Standardization of regression coefficients (b_s) can be achieved by multiplying ordinary regression coefficients (b_i) by the ratio between the standard deviation of the respective model parameters (s_p) and the standard deviation of model output (s_o).

Assuming an ordinary linear regression equation is developed from the micro-simulation outputs and inputs as shown in equation 1:

$$A = b_0 + \sum b_i(X_i) \tag{1}$$

where

A = the micro-simulation output
b_o = the regression constant
b_i = the parameter (ICM strategies) coefficients for I = {1, 2, 3, 4, 5}.

Then, the SRC will be

$$b_s = b_i\,(s_p/s_o) \tag{2}$$

The mathematical form of a standardized regression is as shown in Equation 3.

$$A = b_1(X_1) + b_2(X_2) + b_3(X_3) + b_4(X_4) + b_5(X_5) \tag{3}$$

The standardized coefficients are interpreted as the standard deviation change in the dependent variable (corridor performance indicators) when an independent variable (ICM strategy) is changed by one standard deviation, holding all other variables constant. Instead of comparing changes by one unit, the comparison is between changes in standard deviation.[7]

Once the coefficients become comparable, a ranking (in terms of absolute coefficient values) of all the coefficients of the five ICM strategies is made. The accuracy level of the SRC as a relative sensitivity measure depends on how well the regression fits the parameter data, the level of correlation among parameters, and how realistic estimated parameter variance is.

A quality of fit close to 1 and a weak or zero correlation among model parameters make SRC a valid measure of sensitivity. In order to ensure that model parameters are not correlated (multi-colinearity), the Variance Inflation Factor (VIF) of the standardized regression typically should be less than or equal to four or at most less than 10.[8]

Linear Correlation Coefficient (LCC)

The LCC is the most simple and widely used measure that reflects the linear relationship between model output (A) and model parameters (X_i). It can be expressed as the ratio between

the covariance of model output and parameters ($cov\ (A,\ X_i)$), and the product of the variances of model output ($var\ (A)$) and parameters ($var\ (X_i)$). This can be written mathematically as

$$LCC = cov\ (A,\ X_i)/(var\ [A] * var\ [X_i]) \qquad (4)$$

The LCC is computed for each of the five ICM strategies, based on which a ranking (in terms of absolute LCC values) of the importance of these strategies to corridor performance improvement is developed.

The LCC is used as a sensitivity measure since it expresses the relative change of a quantity with relation to its standard deviation (taking into account the effects of correlation among parameters). If the relationship between X_i and A is almost linear and if the correlation between the parameters X_i is weak, then the LCC is a measure to quantify sensitivity and will be approximately equal to the SRC. LCC value ranges between 1 and -1, with the sign indicating positive or inverse correlation.

Semi-partial Correlation Coefficient (SPC)

SPC is similar to LCC, but corrects model parameters for the effects of correlation among each other. If the correlation between the corrected parameters is weak, the SPC is approximately equal to the LCC and the SRC. In case of a strong correlation between the corrected parameters, this measure can give a misleading impression of parameter sensitivity. Similarly, ranking the importance of the five ICM strategies based on SPC absolute values is developed. The SPC can be expressed mathematically as

$$SPC = SRC/\sqrt{VIF} \qquad (5)$$

At the completion of any parameter sensitivity analysis, a ranking of the input parameters sorted by the amount of influence each has on the model output is generated. The model output of interest in this research as far as ICM strategy sensitivity analysis is concerned is corridor person throughput; this is because it is not mode-specific and measures the ultimate objective of a corridor – to transport people. The different sensitivity analysis measures (SRC, LCC, and SPC) might produce varying rankings; however, the actual position in the ranking (based on the different measures) is not as important as is the specification of which strategies consistently appear near the top of the list regardless of which measure was used.[9] An example of the results of model parameter (parameters for the different strategies) rankings using the different sensitivity measures is as shown in Table 4. The rankings and coefficients are hypothetical and meant for illustration purposes only.

Table 4. Hypothetical Sensitivity Rankings

ICM Strategy	SRC	Ranking	LCC	Ranking	SPC	Ranking
Ramp Metering (X_1)	155	1	0.88	1	0.74	3
VSL (X_2)	148	2	0.65	3	0.91	1
Transit Capacity (X_3)	110	3	0.35	5	0.44	5
Parking Capacity (X_4)	50	4	0.75	2	0.62	4
Subsidies (X_5)	30	5	0.55	4	0.81	2

It can be inferred from Table 4 that ramp metering (X_1) and VSL (X_2) consistently appeared near the top of the rankings regardless of which sensitivity measure was used. If the coefficients of these two strategies are statistically significant (as will be shown in the next section), then, it implies that they are the most critical among the five ICM strategies intended to be introduced in the hypothetical corridor.

Test of Statistical Significance of the Effects of Strategies

In order to ascertain that the coefficients of the ICM strategies as shown in Table 4 are not due to chance, they must be tested for statistical significance. Two types of t-statistic are used to test for statistical significance at a 5% significance level.

Model coefficients obtained from LCC and SPC are tested for statistical significance using a t-statistic defined mathematically as

$$t = r \sqrt{(N-2)/(1-r^2)} \qquad (6)$$

where

   r = the correlation coefficient
   N = the sample size
   N-2 = the degrees of freedom.

For model coefficients generated based on SRC, the t-statistic is computed by the formula

$$t = Regression\ coefficient\ (b_i)/Standard\ error\ of\ b_i \qquad (7)$$

Recommended Combination of Strategies

After identifying the most critical of the five ICM strategies and testing for statistical significance, any of the strategies that were not statistically significant can be dropped so that the model can be re-run. New sets of outputs are obtained based on which sensitivity analysis and the test of statistical significance are conducted again. This procedure will be repeated until the best set of ICM strategies that will improve the corridor operating performance is identified.

Development and Validation of Simulation Network

A comprehensive network of all the road facilities within the analysis segment was coded in VISSIM 5.4. In developing the network, the Google Earth application was used to collect geometric characteristics of the road facilities.

The facilities coded include I-95 N GP and HOV lanes, the primary arterial U.S. 1N, VRE rail line, the intersecting arterials (running east-west and west-east) that include Dumfries road (SR 234), Lorton road (SR 642), Dale Blvd (SR 784), Prince William Pkwy (SR 294), Gordon Blvd (SR 123), and the bus transit routes. Traffic flow data were obtained from the most

recent VDOT Average Annual Daily Traffic (AADT) estimates to develop vehicle origins and destinations. Travel time data provided by INRIX was obtained from the vehicle probe suit of Regional Integrated Transportation Information System (RITIS). The travel time and traffic flow data were used to calibrate and validate the model against actual driving conditions. The selected ICM strategies were then incorporated into the simulation model.

A total of 50 VISSIM simulation runs were conducted to aid in the calibration process, and the results are as shown in Table 5. The simulation was run for a 90-minute period of the morning peak but data collection was scheduled to begin after the warm-up period of 30 minutes. For acceptable calibration results, travel times and speeds must be within 15% of the corresponding field values. The GEH, a modified chi-squared test, compared the simulated vehicle flow per hour with traffic data obtained from VDOT's AADT estimate. The GEH statistic must be less than 5 in order to be considered acceptable.[10]

Table 5. Model Validation Results

Segment	Average Travel Time (minutes)			Average Speed (mph)			Flow (Vehicles/Hour)		
	Base	Model	% Change	Base	Model	% Change	Base	Model	GEH Value
I-95 N (SR234-SR123)	16.3	17	4.3	38	37	2.6	5416	5542	1.7
I-95 N (SR123-SR642)	10.6	10.1	4.7	26.5	25.3	4.5	5652	5668	0.2
I-95 N HOV(SR234-SR123)	8	7.6	5	60.3	58	3.8	2047	1901	3.3
I-95 N HOV(SR123-SR642)	4	4	0	55.8	54	3.2	3965	3759	3.3
U.S. 1N(SR234-SR123)	19.8	20.6	4	32.8	33.2	1.2	1931	2060	2.9
U.S. 1N(SR123-SR642)	9.7	10.1	4.1	28	26.8	4.3	2566	2488	1.6

Evaluation of Proposed ICM Strategies

Eight ICM strategies were selected for evaluation in the simulation environment based on their relative ease of implementation, proven effectiveness in reducing congestion, and ability to interact and complement other congestion mitigation techniques. For those strategies that sought to influence traveler behavior in real-time/short-term, assumptions about traveler responses were made because of lack of such information in the published literature. The eight strategies are VSL, ramp metering, increasing transit and parking capacity, high occupancy vehicle/toll lanes, financial incentives, ramp meter bypass/high occupancy access treatments and transit signal priority.

Variable Speed Limits (VSL)

VSLs have been used as a congestion mitigation measure for some time now, making it easier to have access to its implementation algorithms/codes. The research team modified a publicly available VSL code, as described here.[11]

All VSL signs were set to display 55 mph during the first cycle in the simulation's warm-up phase. Each detector then gathered data and recorded the instantaneous speed data for every vehicle that crossed over the detector, as well as volume (which are tallied up into a cumulative volume [cum_vol] value). As the VISSIM software was developed in Germany, it is necessary to convert the speeds from km/hr to mph. This instantaneous speed data is then converted into space mean speed (*speed = (1/vf)*, where vf = the instantaneous speed of a vehicle recorded over a detector), which was added up during the course of the cycle to obtain a cumulative speed value (cum_speed).

Using the cumulative data from the end of each cycle (a cycle being the time period between speed limit updates – 5 minutes in this case) space mean speed, flow, and density values were calculated for the data from each detector using the following equations:

$$space\_mean\_speed = \frac{cum\_vol}{cum\_speed} \qquad (8)$$

where

space_mean_speed = the total space mean speed at a detector over the course of one 5-minute cycle

cum_vol = volumes accumulated over the course of one 5-minute cycle

cum_speed = accumulated speed values over the course of one 5-minute cycle

$$Flow = 12*cum\_vol \qquad (9)$$

where

flow = The equivalent hourly flow based on a cycle's volume (in this case, 12 is used in the equation due to a 5-minute cycle time)

cum_vol = volumes accumulated over the course of one 5-minute cycle;

$$density = \frac{flow}{space\_mean\_speed} \qquad (10)$$

where density = the calculated density used to determine posted speed limits.

The next step is to determine the worst (highest) density at each VSL sign location (which is where detectors are located). As there is a detector in each mainline lane at each sign location, the worst density represents only one lane, but is used to represent the entire location.

Once the worst density has been determined for each location, the desired speed can be determined based on downstream density (for example, location 3's desired speed is based on the density at location 4, the next downstream location. This is to allow vehicles to prepare for upcoming conditions). Desired speeds to which each VSL sign is set are derived from pre-

determined density ranges that are appropriate for optimal speeds. The Greenshield and Greenberg equations were used to determine an average optimal density that corresponded to five ranges of speed as shown in Table 6.

Table 6. Variable Speed Limits and Density Ranges

Density (pc/mi/lane)	Speed Range (mph)	Speed Limit (mph)
0 to 34.2	Greater than 52.5	55
34.2 to 45	Between 47.5 and 52.5	50
45 to 56.4	Between 42.5 and 47.5	45
56.4 to 68.5	Between 37.5 and 42.5	40
Greater than 68.5	Below 37.5	35

Figure 4 is an example of the downstream and upstream VSL system layout for a typical bottleneck location. The reason for placing the detectors immediately upstream of the bottleneck was to identify as close to the time as possible when the bottleneck was activated so that mitigation techniques might be implemented. This was done to allow sufficient time and distance for vehicles to reduce their speed in case of any downstream congestion.
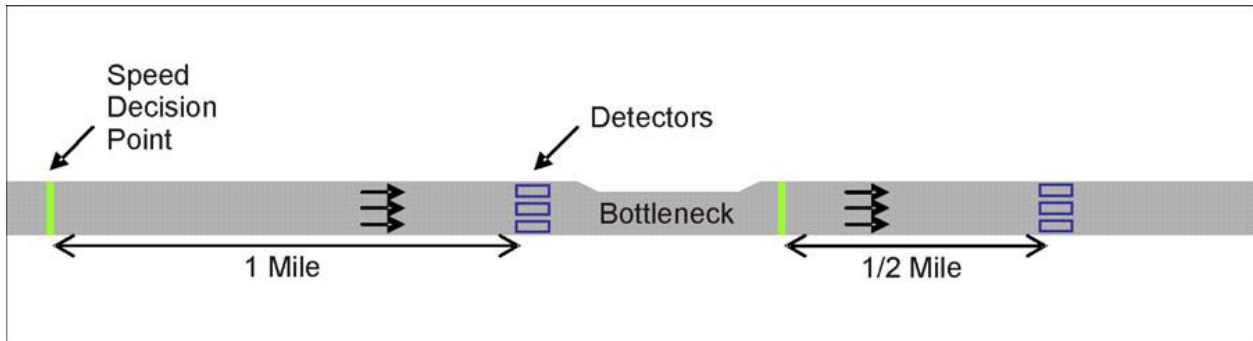

Figure 4. A Typical Layout of VSL System. Source: Mazzenga, N.J., and Demetsky, M.J. *Investigation of Solutions to Recurring Congestion on Freeways***. VTRC 09-R10. Virginia Transportation Research Council, Charlottesville, 2009.**

Driver compliance rates are critical in determining the impact of VSL systems on flow. VISSIM offers the capability to define the percentage of the driver population who will not adhere to speed limits. This driver population belongs to a vehicle type labeled Non-Compliant (NC) in the model. The compliance rates modeled range from 45% to 90% to evaluate the range of expected performance.

Ramp Metering (RM)

The concept of ramp metering was selected to regulate the flow of vehicles from side streets onto the freeway. The metering rate can range from 240 to 900 veh/hr for a single-lane on-ramp.[12] In order to hold the metering rate constant for each scenario, a fixed ramp metering operation was used. The range of metering rates tested was between 500 and 900 veh/hr. To make the ramp metering operation more realistic, meters were turned off for the first 30 minutes

of the simulation because the freeway was operating at/near free flow conditions. Similarly during the simulation of incident conditions, ramp meters were only turned on after the incident had occurred so that congestion on the freeway was not exacerbated. Ramp meters were provided at all 10 on-ramps within the analysis segment.

Transit and Parking Capacity (TPC)

Park-and-ride facilities and associated transit services along with park-and-pool facilities formalize and make readily available the option of mixed-mode travel. The combination they facilitate allows the use of a low-occupancy mode, most often driving alone, where travel densities are low and high-occupancy modes are inconvenient. It allows transfer to a high occupancy mode—rail transit, bus, vanpool, or carpool—where travel densities become higher and more supportive of high-occupancy mode efficiencies.[13] Since transit and parking facilities are complimentary in mixed-mode travel, the ability of available capacities to attract new transit riders was the attribute of interest. Turnbull et al. cited two studies that suggested that an added park-and-ride space attracts 0.22 new transit riders.[13] This traveler response does not represent decisions taken by travelers in real-time. Rather, they are indicative of long-term traveler behavior in response to the increase in parking capacity. However, this served as a guide in choosing the traveler response rate to test, taking into account the proposed addition of 3000 new parking spots within the corridor. The research team assumed an attraction between 7.5% and 23% of SOVs to transit.

A new "vehicle type" group labeled TPC in VISSIM was created to model the impact of transit and parking capacities. For the purposes of real-time/short-term application, TPC vehicles behave as SOVs during the first 30 minutes (warm up period) of the simulation, and begin to exit toward parking facilities and transit stops when congestion begins to build (after warm up period).

High Occupancy Vehicle (HOV) Lanes

HOV facilities provide preferential treatment for transit, vanpools, carpools, and other designated vehicles by providing lanes and roadways reserved for their use.[14]

HOV lanes usually carry two to five times as many persons as GP lanes, and have the potential to double the capacity of roadway to move people.[14] The analysis segment contains two reversible HOV lanes that operate in the analysis direction (north) during the morning peak with an occupancy requirement of three or more. The HOV lanes carry about 25% of the vehicle traffic (compared with GP lanes) and still have extra capacity to attract new users (over 1,000 veh/hr between SR 234 and SR 123; over 500 veh/hr between SR 123 and SR 642). The ability of this extra capacity to attract new users is the attribute of interest. Therefore, a new "vehicle type" group called HOV-E was created in VISSIM to model the attraction of new HOV users from the existing SOVs. The attraction of new HOV users is possible through real-time information dissemination. The assumed range of new users modeled was from 0% to 15%. Similar to TPC vehicles, HOV-E vehicles become operational after the first 30 minutes of the simulation.

High Occupancy Toll (HOT) Lanes

The use of market forces to allocate limited highway capacity among users by their need to travel and willingness to pay, usually referred to as congestion pricing in the literature is a known congestion mitigation measure. Drivers who are not willing to pay may choose not to travel or select an alternative time, route, or mode, and those who pay receive the value of being able to drive, when they choose to, with reduced congestion. The concept of HOT lanes seek to achieve better utilization of special lanes such as HOV lanes by making them accessible to low occupant vehicles (LOVs) who are willing to pay. The research team is not interested in which toll amounts result in better utilization of HOT lanes, but rather in the impact of the HOT lane concept in increasing carpools and ridesharing.

One reason for this impact is because it is believed that drivers get a tangible sense of the cost savings offered by carpooling when tolling is introduced rather than paying alone to enjoy the better services of the HOT lanes.[15] Therefore, the ability of HOT lanes to reduce the percentage composition of LOVs and SOVs through carpool and ridesharing formations was modeled. A reduction range of 0% to 15% was assumed. To model this, a new "vehicle type" group called HOT was created in VISSIM.

This strategy was considered because of plans by VDOT to introduce HOT lanes in the corridor in future. HOT vehicles also become operational after 30 minutes (after the warm up period) of simulation.

Financial Incentives

Transit and parking pricing play an important role in transit ridership. The most common objective of transit pricing and fare changes is to increase revenues in response to actual or forecasted increases in operating costs. Such changes usually involve fare increases for most transit users. An associated objective is to minimize the ridership loss usually involved in fare increases.[16] Similarly, the primary objective for setting a price on parking for parking facility owners/operators is to cover cost and earn a reasonable return on investment.[17]

The research team believes that these costs may stifle transit ridership increases. For example, if a traveler decides to park at a parking facility in order to use transit, he/she must pay for parking and transit costs, as well as a reduced level of comfort compared to driving alone. Providing financial incentives to travelers to cover parking and transit costs may help to increase transit ridership and reduce congestion in the corridor. Therefore, the power of financial incentives to reduce the percentage of SOVs was the attribute modeled. In VISSIM, a "vehicle type" group labeled Financial Incentives (FI) was created to aid in the modeling. The assumed range of reduction in SOVs modeled was between from 0% and 7.5%. FI vehicles also became operational only after 30 minutes of the simulation.

It is important at this stage to clearly outline the similarities and differences between TPC, HOV-E, HOT, and FI as modeled in this study. Both TPC and FI are strategies meant to induce mode shifts (from SOV to transit). However, they are two different strategies. According to the literature, some travelers shift to transit because of available spots at park-and-ride lots or

seats in transit vehicles.[13] Similarly, there is another group of travelers who shift to transit because of reduction in transit[16] and parking[17] fees. It is possible there are some travelers who are induced by both strategies but the extent of intersection is unknown. Independently, each of the two strategies has been discussed in the literature, but their combined effect is also unknown; this knowledge, in conjunction with other implemented ICM strategies, is what has been sought after in this study. Additionally, HOV-E and HOT are both intended to facilitate mode shifts from SOVs to HOVs. The HOT strategy in this study catalyzes the formation of carpools/vanpools as a result of travelers getting a tangible reason for carpooling due to the tolls being charged.[15] On the other hand, some travelers form carpools/vanpools because of congestion on the GP lanes, the travel time reliability afforded by HOV lanes, etc., and not because of tolls.[14] Just as in the case of TPC and FI, there are some travelers who might be susceptible to both HOT and HOV-E. Within the framework of ICM, the desired objective is to determine the combined effect of these strategies, which have traditionally been implemented as stand-alone strategies.

Ramp Meter Bypass and HOV Access Treatments

This strategy gives HOVs priority at metered freeway entrance ramps by providing either a separate lane located adjacent to the metered GP lane or a separate HOV entrance ramp. Either way, they allow HOVs to move around the traffic queue at the meter or otherwise directly enter the freeway. These techniques may be used in combination with a freeway HOV lane or as a stand-alone measure. Direct access ramps from adjacent roadways, park-and-ride lots, and transit stations are also employed in some areas to provide buses, and sometimes vanpools and carpools, with extra travel time savings and trip time reliability.[14] This strategy was modeled by providing separate lanes adjacent to the metered lanes, and restricting the use of the separate lane to only HOVs and buses. The evaluation of this strategy was tied to the ability of HOV lanes to attract new HOV users because it seeks to reduce the percentage of SOVs in the analysis segment.

Transit Signal Priority (TSP)

TSP is an operational strategy that facilitates the movement of transit vehicles (usually those in-service), either buses or streetcars, through traffic signal-controlled intersections. Objectives of TSP include improved schedule adherence and improved transit travel time efficiency while minimizing impacts to normal traffic operations.[18] The main TSP control strategies modeled were green extension and early green (active priority). A constant extension period of 15 seconds was established to facilitate the operation of TSP in VISSIM.

Only one of the transit routes (South Route 1) is on the primary arterial (U.S. 1). This route starts from Fox Lair/Route 1, travels south, and connects to the HOV lanes through SR 234. The effect of TSP on the corridor will be implicitly captured by the number of bus trips recorded during the analysis period. Additionally, bus travel times will also be used to evaluate the effect of TSP.

RESULTS AND DISCUSSION

Literature Review

Since ICM in the United States is yet to be fully operational, the existing literature mostly revolves around foundational research and preparatory activities at the eight pioneer sites. In spite of the limited published literature, the success of any ICM program hinges on three important pillars:

1. Intelligent Transportation Systems: Technology is an essential ingredient in ICM. Recent advancements in ITS technologies provide the opportunity to integrate network operations so as to manage total corridor capacity.[19] ITS technologies such as real-time traveler information, parking management systems, transit signal priority, and electronic tolling systems enhance holistic optimization of transportation systems. This presupposes that investment in ITS technology must precede the implementation of ICM. The ability of ICM to be proactive rather than being reactive is made possible through ITS, which facilitates the capture and rapid processing of traffic information in order to make informed decisions.

2. Stakeholders Partnership: ICM employs a collective approach to optimize the transportation system in a corridor. To accomplish the goals of ICM, all partner agency representatives must put aside their bias as they strive to operate the corridor in a true multimodal, integrated, efficient, and safe fashion where the focus is on the transportation customer.[2] A stakeholder is a person or group with a direct interest in the integration of the corridor and the associated networks and network linkages.[20] These include municipalities, counties, Metropolitan Planning Organizations (MPO), transit authorities, Traffic Management Centers (TMC),etc. It is important to identify all stakeholders as early as possible so as to incorporate their needs and views in the concept development phase. The number and types of corridor stakeholders depend on the transportation networks included in the corridor and the proposed ICM concepts.[20]

3. Information Sharing: As part of the partnership between stakeholders, there is the need to share real-time traffic and incident information within the corridor for the purpose of enhanced decision making. Comparative real-time corridor data on freeways, HOV lanes, arterials, and transit facilities need to be shared among the various operating agencies in order to determine the appropriate strategies to be implemented. Information can be shared through voice, data, video and other media depending on the protocols adopted.[20]

Most ICM strategies are basically intended to influence driving behavior and traveler decision-making so as to maximize the use of existing facilities as shown in Figure 5.
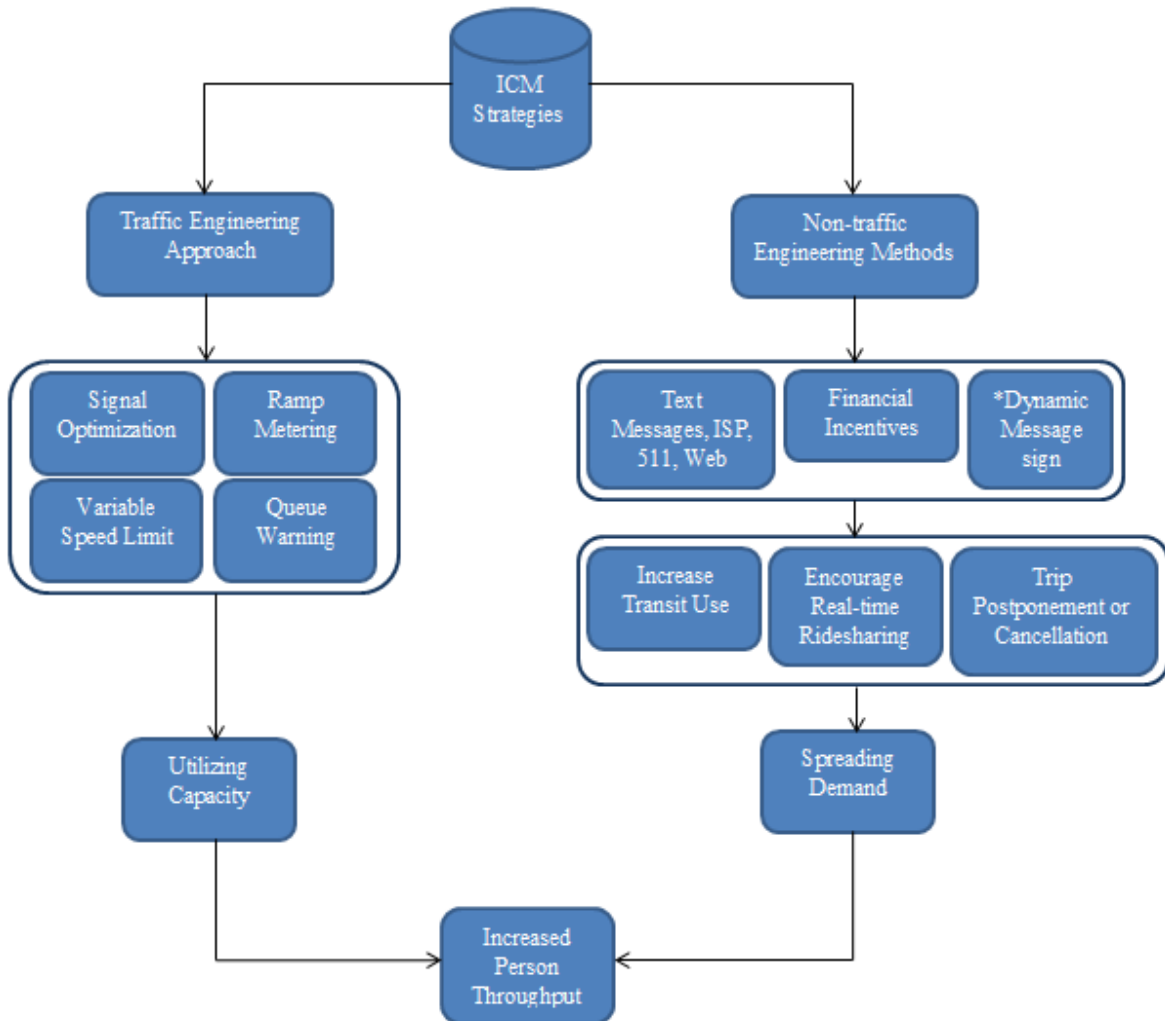
Figure 5. ICM Strategies Flow Chart. *Can also be used as a traffic engineering strategy.

A generic 2006 ICM implementation guide by Neudorff et al. outlined the steps involved in implementing ICM.[21] The procedure is based on the principles of systems engineering, a formal process by which quality is continuously promoted. The systems engineering process is often portrayed as a "V" so as to relate the different stages in the system life cycle to one another. The V-shaped model helps to show the relationship between the work done on each side of the V; for example, the testing of activities on the right side of the V is based on the results (e.g., concept of operations, system requirements, etc.) from the corresponding steps on the left side of the V.

The individual components of the V-shaped systems engineering process include:

- Concept Exploration: Identifying the need for corridor management based on an existing regional ITS architecture and establishing corridor stakeholder group. Consequently, potential corridors and initial boundaries are identified.

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- Systems Engineering Management Plan: Involving the development of a management plan that will be used to implement ICM.

- System Conception: This is an important stage in the systems engineering process since it explicitly defines the ICM concept. It involves inventorying existing systems, identifying existing corridor conditions, the establishment of corridor vision and goals, identifying potential ICM approaches and strategies, etc. Systems conception leads to the development of the concept of operations for ICM.

- System Requirements: This stage of the process looks into defining system level requirements (standards) that will be applicable to the already developed concept of operations. It includes high level ICM requirements, detailed ICM requirements, institutional requirements, and performance analysis. This stage results in a system requirements document.

- ICM High-Level Design: Decomposition of requirements into alternative architectures and identifying system interfaces. This results in the development of an ICM architecture that is consistent with the regional ITS architecture.

- ICM Detailed Design: Decomposition of system and subsystems into hardware, software, database, and other individual components. Subsequently, technologies and design features of each component are laid out.

- Implementation and Deployment: This stage transforms ICM designs into an operating system by verifying and integrating units and subsystems through hardware fabrication, software engineering, and coding. ICM is then deployed and verified for acceptance based on already defined requirements and standards.

- Operations and Maintenance/Evaluation: Managing effectively, the day-to-day operations of the ICM in accordance with operations and maintenance plan. The performance of the system is evaluated continuously, and changes/replacements are made when necessary.

Adequate literature is available from the pioneer sites on the development of the concept of operations, system requirements, analysis, modeling, and simulation methodology for ICM. The remaining stages of the systems engineering process for ICM are still in development.

Concept of Operations (Con Ops)

According to a 2006 generic concept of operations by Neudorff et al., the concept of operations is a formal document that provides a user-oriented view of ICM, its approaches and strategies, and the associated operations.[20] The concept of operations answers the following questions:

- What: the known elements and the high-level capabilities of the system.

- Where: the geographical and physical extents of the system.

- When: the time-sequence of activities that will be performed.

- How: resources needed to design, build, operate, and maintain the system.

- Who: the stakeholders involved with the system and their respective responsibilities.

- Why: justification for the system, identifying what the corridor currently lacks, and what the system will provide.

The Con Ops does not delve into the technological requirements of the ICM system, but addresses the operational scenarios and objectives, information needs, and overall functionality. It must also address the institutional environment in which ICM must be deployed, operated, and maintained. Some of the benefits of Con Ops include:

- Providing a means for engaging ICM stakeholders in order to solicit their views on existing problems and possible solutions.

- Providing a means of describing stakeholders' operational needs for ICM without getting into details.

- Identifying institutional, technical, and operational environment in which ICM will function.

- Formulating definitions and descriptions for ICM and its associated operations.

The development of Con Ops is divided into the following tasks.

Identification of ICM Corridor Boundaries and Travel Characteristics

The boundaries of the proposed corridor must be clearly defined. Corridor boundary definition include its length, constituent individual transportation networks (such as freeways, arterials, railway lines, frontage roads, bus transit systems, toll roads, park-and-ride lots, etc.), any natural features such as rivers within a specified proximity, the geographical orientation (north-south or east-west), the adjoining cities and suburbs, and any other feature or infrastructure whose proximity will affect the corridor's operation.

The travel characteristics of individual transportation networks within the corridor and the areas they serve need to be identified as well. These include capacities of freeways and arterials, the kind of service they provide (commuter, local or regional traffic), economic activities that might influence travel patterns, etc.

Identification of Corridor Stakeholders and Users

By default, the operating agencies of all the individual transportation networks that constitute the corridor are stakeholders.

These include State DOTs, City department of public works/transportation, railway agencies, transit agencies, etc. Another category of stakeholders provide support service and law enforcement. These stakeholders include City and State police, and Fire departments (ambulance and hazardous materials services). Administrative and federal agencies such as MPOs, the Department of Homeland Security (DHS), the Federal Emergency Management Agency (FEMA), Virginia Department of Emergency Management (VDEM), the Virginia Department of Environmental Quality (VDEQ), the Federal Transit Agency (FTA), and the Federal Highway Administration (FHWA) are also part of the corridor stakeholders.

Additionally, institutions and businesses whose activities will be impacted by the corridor's operations will have to be involved in the development of the Con Ops. Examples of such institutions and businesses are courier fleets (U.S. Postal Service, Federal Express, etc.), information service providers, and visitors bureau (representing tourists that use the corridor).

Identification of Needs and the Potential for ICM

The inefficiencies and bottlenecks affecting transportation operations within the corridor have to be outlined, and the potential for ICM to provide the necessary remedies must be demonstrated. Typical issues that undermine efficient transportation systems include congestion during peak periods, bus schedules that are not adhered to, underutilization of existing capacity, lack of coordination and information-sharing among various operating agencies, sparse and disintegrated real-time traveler information, etc. Hence, there is the need for real-time information-sharing (data, video) between all agencies, more of a "corridor-wide" and multi-modal view of ITS operations, improved operational coordination of networks in the corridor, increased transit usage, coordinated and efficient responses to incidents among all stakeholders, and improved dissemination of real-time traveler information across all networks from a single source. The needs listed are not exhaustive and must reflect the existing conditions of the corridor. ICM has the potential to address all these needs, since it focuses on the operational, institutional, and technical coordination of multiple transportation networks and cross-network connections within a corridor.

ICM Vision, Goals, and Objectives

A vision statement outlining the goals and objectives of ICM and the benefits corridor users stand to gain after its implementation must be developed by stakeholders. Using the vision statement as a starting point and taking into consideration the current operating conditions of the corridor, stakeholders will develop specific goals and objectives of the ICM project. The ICM goals and objectives generally revolve around the following:

- Corridor perspective: Corridor goals and objectives take precedence over that of individual transportation facilities.

- Corridor mobility and reliability: Improving travel time predictability and reducing travel times by enabling multi-modal travel and the utilization of spare capacity.

- Corridor traveler information: Providing accurate, reliable, and timely travel time information regarding the entire corridor to enhance traveler decision-making.

- Corridor event and incident management: Providing a corridor-wide and integrated approach to event and incident management, so as to minimize traffic disruptions and the impacts of such incidents.

ICM Operational Approaches and Strategies

After setting the goals and objectives of ICM, stakeholders must identify means of achieving those targets by enumerating specific strategies that can be used as shown in Table 7.

Table 7. ICM Approaches and Strategies

Approach	Idea	Strategy(ies)
Information sharing/Distribution	1. Sharing of real-time information among stakeholders 2. Formation of a corridor-based advanced traveler information system that can be accessed by travelers and value-added entities	1. Pre-trip websites, 511 2. En-route Dynamic Message Signs (DMS), transit public announcement systems
Optimizing operations at network junctions and interfaces	1. Improving cross-network operations 2. Encouraging multi-modal travel 3. Improving communications and protocols among agencies	1. Transit signal priority 2.Transit hub connection protection (e.g., holding buses at rail terminals) 3. Coordinated operation between ramp meters and nearby arterial signals
Accommodate cross-network route and modal shifts	1. Responding to network and modal shifts after putting out information	1. Retiming of arterial signals 2. Modifying ramp metering rates 3. Modifying HOV policies
Real-time demand-capacity management (short-term)	1. Response to events and major incidents	1. Increasing transit capacity through shorter headways and number of vehicles 2. Modifying parking fees 3. Rerouting commercial traffic
Demand-capacity management (long term)	1. Addressing procedural & physical constraints that may limit integrated operations	1. Increasing parking capacity at transit hubs 2. Establishing guidelines for working hours during emergencies/events 3. Low-cost infrastructure improvements

ICM Concept Operational Description

This explains how ICM will function operationally after its implementation. To ensure effective ICM operation, a central corridor decision-making body referred to as the Corridor Operating Panel (COP) must be established. This body will be composed of delegates from each of the stakeholders of the corridor. Second, a control center that will manage the daily operation of ICM must be put in place. This could be a physically centralized (a dedicated building facility) or virtual control center.

Any of the participating corridor agencies with available space in their building facilities can house the control center, or else a new facility should be acquired. However, as a result of high costs associated with the acquisition of new building facilities or lack of available space, a virtual ICM control center would be a cost-effective alternative.

Regardless of the type of ICM control center, there must be a well-defined communication platform based on which real-time data exchange among participating agencies can be carried out. In the event that a participating agency provides space to house the ICM control center, that agency can be the lead agency for the daily operation of ICM. If possible the Northern Virginia Traffic Operations Center (NVTOC) could accommodate the control center and consequently become the lead agency. Functions of the control center would include:

- Investigate and prepare response plans for various scenarios that are likely to occur in the corridor.

- Identify performance measures based on which the effectiveness of ICM strategies can be evaluated.

- Develop and deploy a decision support system for rapid response to changing corridor traffic conditions.

- Monitor corridor travel conditions, implement response plans, and inform participating corridor agencies on prevailing traffic conditions and the impacts of implemented response plans.

The ICM control center would be run by a chief corridor operating officer to be appointed by the COP and supported by either existing staff within respective participating agencies or dedicated staff. Finally, an effective communication channel between corridor traffic managers and travelers as well as among participating ICM agencies is very important to successful ICM operation. Travelers must be kept informed in real-time about prevailing traffic conditions through 511, DMS, websites, radio stations, mobile applications, etc. A real-time communication protocol and standards for information-sharing among agencies and critical support staff must also be adopted.

Required Assets and ICM Implementation Issues

This concerns the identification of ITS asset gaps and potential problems that may affect ICM implementation. The potential problems are grouped into three categories:

1. Technological issues: e.g., Adoption and implementation of ITS standards for the center-to-center (C2C) connections, integration of these standards, bandwidth requirements for C2C communications, etc.

2. Operational issues: Procedure for the shared use of resources/ shared control of ITS assets, policies for implementing demand/capacity management strategies, potential safety concerns for ICM strategies, etc.

3. Institutional issues: Establishment of a more formal institutional structure to bridge the differences between the various operating agencies, establishment of protocols among operating agencies for real-time data-sharing, decision-making and implementation, recruitment of dedicated staff for ICM operations, etc.

ICM Concept Institutional Framework

This relates to the institutional framework based on which ICM will be implemented, operated, managed, and maintained. This framework establishes the leadership of the corridor decision making body (i.e., COP), project initiation and selection, corridor operating policies and procedures, budget development, and overall administration of ICM within a corridor.

An important aspect of the institutional framework is the roles and responsibilities of participating agencies in the daily operation of ICM. This must be clearly defined in order to maximize the potential benefits of ICM. While all participating agencies in a corridor will be collaborating on the implementation of all of the proposed ICM strategies, a lead agency will be assigned for the implementation of a particular strategy. The lead agency will be responsible for the daily operation of the strategy it is in charge of and will coordinate with other agencies that are involved in the operation of such strategy. When issues occur, the lead agency will be responsible for reporting the issues to the ICM control center and will assist the center to resolve the issues.

System Requirements

This is the next step in developing an ICM after producing the Con Ops document. The system requirements describe what the system is to do (functional requirements), how well it must perform (performance requirements), and under what condition (functional or non-functional).[22] Once the system is described in the Con Ops, and these requirements specifications are deployed and integrated among agencies, the new ICM will become fully operational.[22] The following are the key aspects of the system requirement stage in the development of ICM.

Functional Requirements

Functional requirements refer to how the ICM is supposed to function once it becomes operational, especially how it functions to improve the operating conditions of the corridor. They include the following:

- Identification of ICM Subsystems & ICM Requirements. ICM is a system of systems functioning together as a unit. It is therefore important to identify the core subsystems that are critical to its operation. According to the high-level system requirements developed for the U.S.-75 ICM project in Dallas, Texas,[22] the core subsystems for the project were an ICM database subsystem, an evaluation model subsystem, a decision support subsystem, and a web subsystem. The ICM database subsystem will store data within the ICM system; the types of data to be stored include data coming from a data warehouse (historic data), current network data provided by the ICM agencies in the corridor, and output data from the decision support subsystem including response plans and predictive conditions of the network. The evaluation model will be used to evaluate the overall performance of the corridor. The decision support subsystem will be used as a tool for the coordination of responses to events, to evaluate current network conditions, and predict network conditions in order to proactively manage the corridor. Finally, the web subsystem will be a tool to enable the viewing, reporting, and sending of ICM data. The web subsystem will provide an "ICM web interface" for approved users to interact with the ICM data and provide a data feed of current network conditions to corridor ATIS.

- System Requirements for Individual Systems. The individual networks that comprise the corridor are operated as systems by their respective agencies. For them to function as a unit under the ICM there will be the need for some enhancements to their infrastructure and technology in order to deliver the desired benefits. This involves analyzing the current operations and conditions of the individual network assets and proposing the needed improvements required to upgrade them to the standard of an ICM component. The I-394 ICM project in Minneapolis, Minnesota, termed this as "existing systems and field devices" and "planned systems and field devices" in its high-level system requirement document.[23] Additionally, the daily roles of each individual network in the ICM must be specified.

- User Characteristics and Needs. The characteristics of the users of the ICM are critical to the design and development of a system that supports their needs. The main users of the ICM include agency operators, administrators, third parties (additional service providers), and the travelling public. The needs of these users are embodied in the vision, goals, and objectives developed by stakeholders during the Con Ops stage. Hence, the ICM must function in a way to address these needs as thoroughly as possible.

- Major System Constraints. This is meant to bring the challenges faced by the corridor into the development of the functional system requirements. It exposes prevailing operational, technical, and institutional obstacles that might hinder the

smooth implementation and operation of an ICM. Once these difficulties are known, it is expected that stakeholders will devise strategies to fix them, and those strategies will be part of the system requirements.

- Operational Scenarios. Hypothetical operational scenarios of the corridor and how ICM will respond to these scenarios are required in the systems requirement stage. This involves identifying problematic locations within the corridor and their respective traffic conditions, as well as defining how the ICM is supposed to function. This stage is based on the experience of the stakeholders with regard to operating conditions within the corridor.

- Hardware Requirements. Hardware components of the individual networks as well as the ICM must function at certain standards. These requirements are intended to ensure that there are no frequent breakdowns in the operations of the ICM. An example of a hardware requirement could be the accommodation capacity of the message transmission hardware of the ICM traffic operations.

- Interface Requirements. ICM involves the exchange of data among subsystems and other systems by following protocols and standards established for communication. Usually, the interface of exchange follows national ITS standards; however, when necessary, additional requirements can be placed on the system depending on the uniqueness of the ICM.

- Documentation and Training Requirements. This was found only in the system requirement document for the I-394 ICM project in Minneapolis, Minnesota. It is likely that separate developers might develop different portions of the overall ICM, and, during operations, each agency will operate their system as part of the overall ICM. Therefore, there must be documentation of how the individual systems operate and how to train staff who will manage the systems.

Performance Requirements

These are target thresholds set by stakeholders to ensure that the ICM is achieving the desired results. These thresholds are embodiments of the vision, goals, and objectives for the corridor. They are usually long-term targets that provide authorities the opportunity to know whether the performance of ICM is moving in the expected direction or not. For example, stakeholders of the U.S. 75 ICM project in Dallas, Texas, have targeted increasing corridor throughput (persons/trips per hour) by 2%.[22] It must be noted that the targets must be realistic so as to avoid over-expectations.

Analysis, Modeling, and Simulation (AMS)

The purpose of this step is to design a simulation model that can replicate existing operating conditions and quantify the benefits of proposed ICM strategies. This will help in selecting the best combination of strategies to generate the most benefits. A 2008 report by

Alexiadis entitled *Integrated Corridor Management Analysis, Modeling and Simulation (AMS) Methodology* laid out some general principles to be followed.[24]

The methodology centers on the following core values: integrating existing modeling and analysis tools, recognizing limitations in the available tools, development of AMS framework that is vendor-neutral, and development of consistent analytical approaches and performance measures. Essential details of the AMS methodology are summarized here.

Performance Measures and Analysis Approach

The AMS methodology includes the capability to convert all impact/performance measures to non-mode specific measures such as person trips. These mode-independent performance measures will be produced by an interface tool that can translate AMS model components outputs into non-mode specific performance measure output.

Since ICM is multimodal, the operational impacts need to be measured beyond the traditional network-based measures. This will help to evaluate and compare operations among the alternative paths and properly portray the corridor-wide performance. The performance measures must provide an understanding of existing traffic conditions and demonstrate the ability of ICM strategies to improve the corridor's operating conditions. When necessary, performance measures should be reported by mode (transit, single-occupancy vehicle, etc.), facility type (freeway, arterial, etc.), jurisdiction (e.g., County), and peak-periods or by hour of day. The proposed performance measures should focus on the following:

- Mobility: how well the corridor moves people and freight, e.g., delay, travel time
- Reliability: predictability of travel time, e.g., buffer index
- Safety: safety characteristics of the corridor, e.g., crash rate
- Environment: emissions and fuel consumption, e.g., CO_2 emissions.

As part of the analysis approach, adequate data for modeling recurring and non-recurring congestion is needed to establish baseline conditions. Geometric data such as number of lanes on the freeways and parallel arterials, lane and shoulder widths, configurations of key intersections on parallel arterials, and other vital information about the physical structure of the roadway are also required.

Modeling and Limitations

The modeling and simulation step is a critical component of the ICM, since it is the only available means to justify the investments in ICM prior to implementation. It has been observed that each available simulation tool type has different advantages and limitations, and is better than other tool types in some analysis capabilities.

There is no single tool type that can successfully address the analysis capabilities required by ICM. An integrated approach can support corridor management planning, design, and operations by combining the capabilities of existing tools. The existing tools are made up of three different types:

1. Macroscopic models: Models traffic from a global perspective and covers large areas compared to mesoscopic and microscopic models. Effective in estimating mode-shift, e.g., TransCAD.

2. Mesoscopic models: Models individual vehicles but their movement is based on average link speed. They are able to model larger areas compared to microscopic models and are effective in evaluating traveler information systems (pre-trip and en-route), e.g., Dynasmart-P.

3. Microscopic models: Model and simulate individual vehicles based on theories of car-following and lane-changing. Microscopic models capture detailed driver-driver and driver-road interactions and cover less area compared to macroscopic and mesoscopic models. They are effective in evaluating operational control strategies (like ramp metering), e.g., VISSIM.

All these models vary in resolution (detail of analysis) and the geographical scope of application. Less detailed tool types (macroscopic models) are tractable for large networks, while more detailed tool types (microscopic and mesoscopic models) are restricted to smaller networks. Depending on corridor size and the types of analyses required, all tool types are potentially valuable for ICM AMS. Consequently, a proposed AMS framework that integrates all three types is recommended. Combining the strengths of all the three different models will help to better quantify the benefits of ICM.

The proposed AMS methodology includes macroscopic trip table manipulation for the determination of overall trip patterns, mesoscopic analysis of the impact of driver behavior in reaction to ICM strategies (both within and between modes), and microscopic analysis of the impact of traffic control strategies at roadway junctions (such as arterial intersections or freeway interchanges).

The proposed methodology also includes the development of a simple pivot-point mode shift model and a transit travel time estimation module, the development of interfaces between different tools, and the development of a performance measurement/benefit-cost module. In the AMS framework, macroscopic, mesoscopic, and microscopic traffic analysis tools will interface with each other, passing trip tables and travel times back and forth until convergence is achieved between consecutive iterations that produce travel times and number of trips that differ less from one iteration to the next.

Once convergence is achieved, performance measures will be calculated and benefits (such as travel time savings) will be evaluated and compared to deployment costs to produce benefit-cost ratios associated with each scenario/ alternative. With the help of benefit-cost information, alternatives can be ranked and a roadmap can be produced outlining the implementation timeline for ICM strategies. In the ICM analysis, it is important to differentiate between short-term and long-term mode shifts in order to determine if ICM has the potential to impact the choices of travelers in the long-term.

Simulation Results and Analysis

The analysis of simulation results focused on highlighting the impacts of ICM in the analysis segment. Using the LHS technique, 50 scenarios of ICM strategy combinations were tested, with each scenario having different combinations of the ICM parameters.

Several performance measures including individual facility average travel times, average speeds, average vehicular flow, average vehicle delay, corridor person flow, fuel economy and emissions were collected. It is important to note that the analysis was not focused on the performance of individual strategies but on how they perform as a system; therefore, no special attention was paid to any individual strategy during the analysis, unless something unexpected happens having to do with a strategy. In selecting the most critical ICM strategies, corridor person flow per hour was the main performance measure used. This performance measure was chosen because it is not mode-specific and satisfies the performance measure requirement prescribed in the AMS framework.[24]

It is also important to note that the simulation model did not incorporate any information dissemination strategy. In carrying out the analysis, it was assumed that all the necessary means by which real-time traveler information is disseminated were employed. Additionally, those strategies meant to influence traveler behavior (TPC, HOV-E, FI, and HOT) were not intended for only SOVs on the I-95 N GP lanes. Rather, they were meant to influence all SOVs in the corridor. For example, some of the SOVs that would have eventually ended up on the GP lanes exited to a parking facility while traveling on U.S. 1N.

ICM can be beneficial during both incident-induced and recurring congestion periods. Therefore, the ICM strategies were tested under both non-incident and incident conditions. The analyses of simulation results under both conditions are discussed next.

Impact of ICM in Non-Incident Conditions

Limited access facilities such as freeways are designed to operate at higher performance standards (in terms of speed, travel time, flow, etc.) than, for instance, arterials. In the absence of inter-agency coordination among corridor operating agencies, freeway operators (usually the State DOTs) will want to shift freeway traffic to any parallel arterial in order to improve its operating performance. This strategy was tested before incorporating ICM strategies into the simulation model, and the results are as shown in Table 8.

Table 8. Impact of Diversion on I-95 N and U.S. 1N

	I-95 N			U.S. 1N		
% Diverging	Average Travel Time (min)	Average Speed (mph)	Flow (veh/hr)	Average Travel Time (min)	Average Speed (mph)	Flow (veh/hr)
0	27.1	31	5668	30.7	30	2488
5	25	36	5594	32	31	2390
10	24	39	5748	33.5	30	2380
15	22.3	40	5673	35	32	2350
20	22.5	40	5721	37	29	2156

It can be seen from Table 8 that it will take 15% of vehicles diverting from I-95 N to U.S. 1N in order to reduce average travel time on the freeway by about 4.8 minutes and increase corresponding average speed by 9 mph. This will adversely affect traffic conditions on U.S. 1N, resulting in corresponding increase in average travel time of 4.3 minutes. In terms of vehicular flow, neither the freeway nor arterial experience any significant changes.

The ICM strategies tested under non-incident conditions showed significant improvements in most of the performance measures for the individual road facilities as well as the entire corridor.

Average Travel Times

I-95 N experienced a reduction in average travel times for all the 50 tested scenarios. The 8-mile segment between SR 234 and SR 123 experienced a travel time reduction of about 7 minutes, whereas the travel time for the 3-mile segment between SR 123 and SR 642 was reduced by 6 minutes, resulting in a combined travel time reduction of 13 minutes. For the primary arterial, U.S. 1N, average travel times between SR 234 and SR 123 were reduced by almost 6 minutes in scenarios where the percentage of vehicles parking in order to use transit (TPC and FI vehicle types) is high. This reduction in travel time is reasonable because there are less vehicles on the roadway due to those exiting U.S. 1N in order to park and use transit, enabling the remaining cars to travel at or near design speeds. The second segment of U.S. 1N (between SR 123 and SR 642) recorded an average travel time reduction of 3 minutes.

The reversible HOV lanes were not significantly impacted by the ICM strategies in any of the 50 scenarios. The average travel times were not significantly different from the base conditions. This was expected because none of the ICM strategies was directly intended to improve HOV travel times. It is likely that as the percentage of HOV-E and HOT vehicles increases, average travel times on HOV lanes might increase. Table 9 and Figure 6 show the travel time savings for the individual road facilities.

Table 9. Travel Time Savings Due to ICM

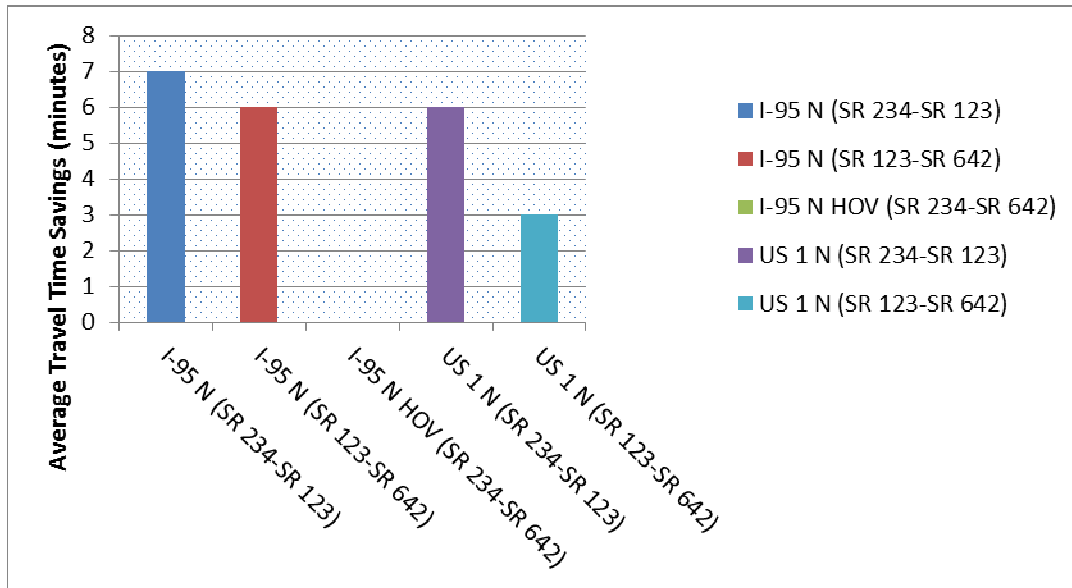| Segment	Average Travel Time Savings (min)	Condition(s)
I-95 N (SR 234-SR 123)	7	All scenarios
I-95 N (SR 123-SR 642)	6	All scenarios
I-95 N HOV (SR 234-SR 642)	0	All scenarios
U.S. 1N (SR 234-SR 123)	6	When TPC and FI % are high
U.S. 1N (SR 123-SR 642)	3	All scenarios

Figure 6. A Plot of Travel Savings Due to ICM

Vehicular Flow and Speed

Vehicular traffic volumes generally decreased along the entire length of the I-95 N GP lanes. This is not unexpected, because most of the ICM strategies modeled are meant to reduce the percentage of SOVs in the traffic stream. Consequently, most of the vehicles exit toward a parking facility in order to use the PRTC buses or VRE commuter trains.

The 3-mile segment of the I-95 N GP lanes only experienced vehicular flow levels close to the base conditions when the percentage of TPC, HOV-E and FI are very low (that is, only a small % of LOV reduction). The HOV lanes occasionally experienced reductions in flow, especially when the percentage of vehicles exiting to parking facilities (TPC) is high. This might be due to the high level of interactions that occur when drivers decide to exit. This usually begins with a reduction in speed, followed by the search for safe gaps in order to carry out lane changes. Therefore, if there are a lot of vehicles trying to exit, it might impact flow conditions. Visual inspection of the simulation revealed that, when the % of vehicles exiting from the GP lanes to SR 234 is large, it reduces the opportunity for HOVs, HOV-Es, and HOTs to access the HOV on-ramp south of SR 234.

Conversely, the segment along U.S. 1N between SR 234 and SR 123 experienced an average vehicular increase of about 500 veh/hr in almost all of the 50 test scenarios. The remaining segment between SR 123 and SR 642 did not experience any significant changes in vehicular flow. Table 10 shows a summary of the impact of ICM on vehicular flow.

Table 10. Impact of ICM on Vehicular Flow

Segment	Impact on Flow
I-95 N (SR 234-SR 123)	Decreased in all scenarios(17%-25%)
I-95 N (SR 123-SR 642)	Only increased when TPC, HOV-E, FI % are low
I-95 N HOV (SR 234-SR 642)	Increased when TPC % is low
U.S. 1N (SR 234-SR 123)	Increased in all scenarios (18%-29%)
U.S. 1N (SR 123-SR 642)	No significant changes

As a result of the reduction in vehicular flow along the I-95 N GP lanes, average speed increased along its entire length. An average speed increase of 10 mph was recorded for the segment between SR 234 and SR 123 and 23.5 mph for the segment between SR 123 and SR 642.

The I-95 N HOV lanes experienced a slight speed increase of 2.9 mph, which is consistent with the corresponding travel times reported earlier. The primary arterial also recorded significant speed increases of 7.9 mph and 8.6 mph between SR 234 and SR 123, and SR 123 and SR 642, respectively. Table 11 and Figure 7 show the benefits of ICM in terms of speed increases.

Table 11. Speed Improvement Due to ICM

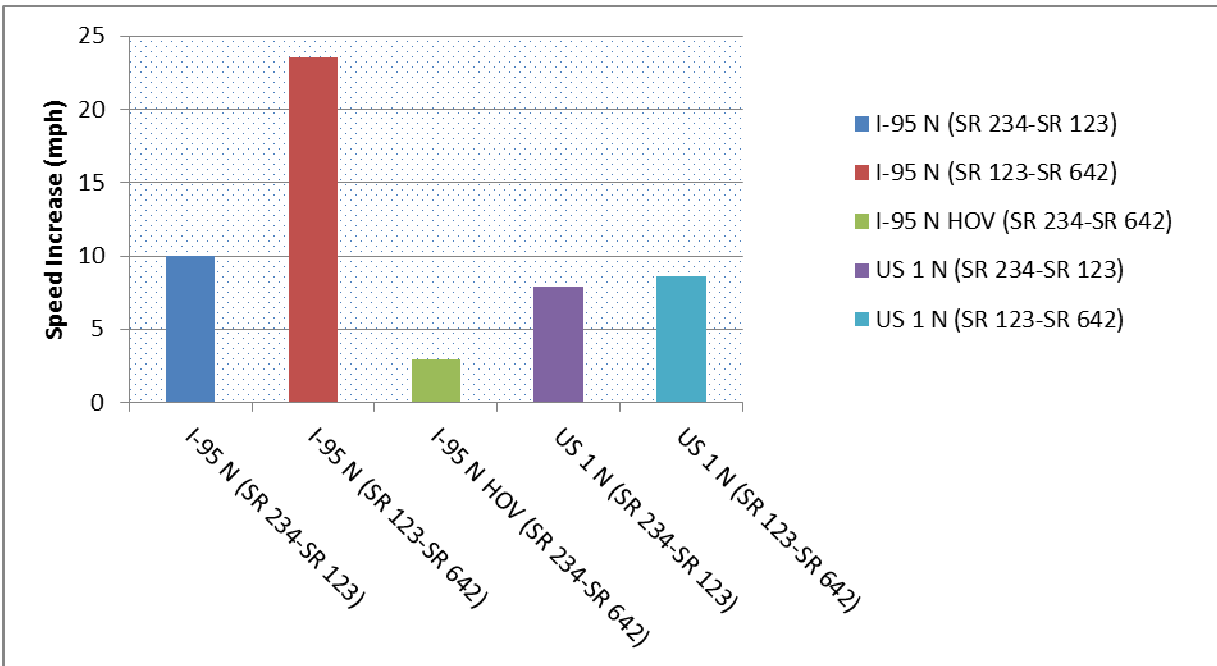| Segment	Speed Increase (mph)
I-95 N (SR 234-SR 123)	10.0
I-95 N (SR 123-SR 642)	23.5
I-95 N HOV (SR 234-SR 642)	2.9
U.S. 1N (SR 234-SR 123)	7.9
U.S. 1N (SR 123-SR 642)	8.6

Figure 7. Improvement in Travel Speeds Due to ICM

Selection of Critical ICM Strategies under Non-Incident Conditions

As described earlier, ICM consists of different congestion mitigation strategies operating together over a large geographical area. It is important to know those strategies that are most critical to the success of the ICM operation. The evaluation methodology developed in this research was used to identify the critical ICM strategies. The main performance measure used in identifying the critical ICM strategies was corridor person flow per hour. The corridor person flow obtained was as follows:

Corridor Person flow (Persons/hr) = GP_{PF} + HOV_{PF} + $US1_{PF}$ + VRE_{PF} (8)

where

GP_{PF} = Total person flow on the GP lanes in 1 hour
HOV_{PF} = Total person flow on the HOV lanes in 1 hour
$US1_{PF}$ = Total person flow on U.S. 1 in 1 hour
VRE_{PF} = Total person flow on the VRE Commuter rail in 1 hour.

VISSIM enables the determination of the number of persons traveling at specific points in a network. Since the direction of travel modeled was toward Washington, D.C. (north), person flow data were collected at the end of the analysis segment, which is the intersection of SR 642 and the individual rail and road facilities. The corridor person flow under base conditions is 22755 per hour compared with 26041 per hour when ICM strategies are implemented, resulting in an increase of 3286 persons per hour (14.4%).

The three sensitivity measures discussed earlier were calculated using results from the 50 test scenarios. From Table 12, it can be seen that HOV-E and HOT have larger coefficients than the remaining ICM strategies based on all the three sensitivity measures (SRC, LCC, and SPC). For the SRC, the R^2 value obtained was 0.985,which implies that the assumption of a linear relationship between corridor person flow and the ICM strategies is justified and that the ICM strategies adequately describe the variability in corridor person flow. Variance inflation factors for the ICM strategies were also less than 4, signifying insignificant correlation among the strategies.

Table 12. ICM Strategies Sensitivity Values

Strategy	SRC	LCC	SPC
RM	0.00185	-0.0555	0.003071
TPC	30721.15	0.3687	0.243221
HOT	117623.5	0.5389	0.293893
HOV-E	142695.9	0.6567	0.394323
FI	128937.7	0.083	0.025769
VSL	17222.5	0.3867	0.206324

There is a need to test the statistical significance of the coefficients of ICM strategies before ranking them. Table 13 shows the t-statistic for the coefficients of ICM strategies at a significance level of 0.05. This implies that for a strategy's coefficient to be statistically significant, the t-statistic must be greater than 1.96.

Table 13. T-Statistic Values for ICM Strategies

Strategy	SRC	LCC	SPC
RM	*3.0	0.4	0.02
TPC	*7.6	*2.7	*1.98
HOT	*29.5	*4.4	*2.13
HOV-E	*34.2	*6.0	*2.97
FI	*8.7	0.6	0.18
VSL	*24.7	*2.9	1.46

*Statistically significant at a 5% significance level.

Finally, the ICM strategies were ranked based on the sensitivity measures. Table 14 shows the ranking from most sensitive (rank equals 1) to least sensitive (rank equals 6) strategies based on the different sensitivity measures.

Table 14. ICM Strategies Sensitivity Rankings

Parameter	SRC	LCC	SPC
RM	6	6	6
TPC	4	4	3
HOT	2	2	2
HOV-E	1	1	1
FI	3	5	5
VSL	5	3	4

From Tables 13 and 14, it was established that HOV-E and HOT were statistically significant and consistently ranked first and second, respectively, based on all three sensitivity measures. It was also evident that RM consistently ranked last in all the three rankings. The exact position of a strategy in the rankings is not as important as how consistently a strategy appears near the top. Based on all the three sensitivity measure rankings, four of the six ICM strategies were statistically significant. These strategies can be considered as the most critical among the six strategies modeled. They are TPC, HOT, HOV-E, and VSL. Note, when implemented in the field, some "shifts" from SOV's to transit or HOV's may be incentivized by more than one of these strategies. In other words, there is likely some "double-counting" in this analysis. However, given the goal of this work to explore feasibility, it can be concluded that each of these strategies does hold significant potential.

The fact that RM was not identified to be critical was not surprising for two reasons. First, from the calibration process, it was discovered that on-ramp demand for all the ramps except for the SR 123 on-ramp were moderate. Additionally, there are extra lanes (usually one or two) from SR 784 to just after SR 294. These extra lanes provide some extra capacity to alleviate the effects of on-ramp traffic disruptions as they merge onto the freeway.

Second, the presence of ICM strategies such as TPC and FI ensures that less vehicles get on to the freeway due to the availability of parking and transit capacity. Therefore, the impact of ramp metering on side streets was negligible since no queues formed.

Another phenomenon that is worth mentioning is the heavy traffic demand from the eastbound on-ramp of SR 123. From visual inspection during the calibration process, the ramp queue usually spills onto the arterial even though there was no metering. By inference, it was expected that the queue length would grow with the introduction of ramp meters. However,

there were no queues when ramp meters were in operation. Again, this might be due to the fact that the ramp meter was not operating in isolation but in conjunction with other ICM strategies.

The use of financial incentives was only statistically significant for the SRC sensitivity measure. This does not necessarily mean that this strategy has no ICM benefits. In this research, financial incentives were used to encourage travelers to park and use transit. Instead, it could have been used to influence travelers to use the HOV lanes. This strategy has been employed in Atlanta, and it proved to be beneficial.[25] Therefore, the final decision to discard a strategy must be taken after all practical uses of the strategy have been exhausted.

Fuel Economy and Emissions

The impact of ICM on fuel usage and vehicular emissions was very significant as shown in Table 15. In all 50 tested scenarios, significant reductions were experienced. Table 15 summarizes the impact of ICM strategies on fuel economy and emissions during non-incident conditions.

Table 15. Impact of ICM on Fuel Economy and Emissions

Condition	Fuel (gallons)	CO (g)	NOx (g)	VOC (g)
Without ICM	12346	863009.4	167910.3	200010.8
With ICM	8111	566988	110315	131405

Limits of Effectiveness of Unknown Traveler Responses to ICM Strategies

As stated earlier, responses to those strategies that were meant to influence traveler behavior (TPC, HOT, HOV-E, FI) were purely based on assumptions since there was no evidence of such responses in the literature. However, it is imperative to know the limits of effectiveness of such responses in terms of how they help improve the corridor's operating performance (increase person flow). It was difficult to establish a clear pattern for the limits of effectiveness taking into account that the modeling experiment was designed to minimize the number of trials.

Impact of ICM during Incident Conditions

Incident-induced congestion accounts for a significant proportion of travel delays, and it is therefore necessary to ascertain how ICM can help lessen its impact. In order to achieve this, an incident was created in the simulation by activating a red light on three of the four GP lanes on I-95 N between the westbound off-ramp onto SR 123 and westbound on-ramp from SR 123. This location was chosen so that all the ICM strategies could be adequately modeled.

The incident was scheduled to occur after the 30 minutes "warm-up" period. The incident lasted for one hour, and data collected during the one hour period were analyzed. Table 16 summarizes the impact of incidents on travel conditions on I-95 GP lanes.

Table 16. Traffic Conditions on I-95 Corridor during Modeled Incident (No Diversions)

Segment	Average Travel Time (min)	Average Speed (mph)	Vehicle Flow (veh/hr)	Corridor Person Flow (persons/hr)
I-95 N (SR 234-SR 123)	32	23.9	2531	--
I-95 N (SR 123-SR 642)	6.2	47.0	3468	18107

From Table 16, corridor person flow per hour during incident conditions was 18107; compared to non-incident conditions, corridor person flow decreases by 4648 persons per hour.

One of the most common approaches in addressing incident-induced congestion is to divert traffic onto adjacent/parallel routes. Usually, this is done without knowledge of traffic conditions on these parallel routes. In the end, corridor flow is significantly reduced. To replicate this condition, the incident was first modeled without incorporating the ICM strategies.

If traffic has to be diverted onto U.S. 1N in order to mitigate congestion on I-95 N GP lanes, what percentage of diversion will result in improved traffic operating conditions? Table 17 shows the impacts of different diversion percentages on both I-95 N and U.S. 1N.

Table 17. Impacts of Diversion on I-95 N and U.S. 1N

	I-95 N			U.S. 1N		
% Diverting	Average Travel Time (min)	Average Speed (mph)	Flow (veh/hr)	Average Travel Time (min)	Average Speed (mph)	Flow (veh/hr)
0	38.2	36	3468	30.7	30	2488
5	36.4	36	2762	30.5	28	2054
10	35.7	34	2869	33.5	27.3	2080
15	33.9	37	2813	35	26	2022
20	32.9	37.5	2876	37	24	2017

From Table 17, 15% of the traffic has to be diverted onto U.S. 1N in order to reduce average travel time by 5 minutes coupled with no significant increase in speed. These diversions can increase average travel times on U.S. 1N up to 7 minutes and reduce average speeds by 6 mph. Regardless of the diversion percentage, there was no significant increase in the vehicular flow on I-95. In contrast, vehicular flow on U.S. 1N reduced by as much as 471 vehicles per hour.

For those vehicles that do divert, their average travel times are as shown in Table 18.

Table 18. Average Travel Times for Diverted Vehicles

Diversion Point	End Point	Average Travel Time (min)
I-95/SR-234	I-95/SR-642	29.9
I-95/SR-769	I-95/SR-642	29.8
I-95/SR-294	I-95/SR-642	23.2
I-95/SR-123	I-95/SR-642	18.7

Even though there were travel time savings for those who exited onto SR 234, only a few vehicles (less than 20) recorded this travel time during the analysis period.

Incorporating ICM strategies into the modeled incident resulted in the findings in Table 19. The next section discusses these results.

Table 19. Impact of ICM during Incident Conditions

Segment	Average Travel Time (min)	Average Speed (mph)	Vehicle Flow (veh/hr)	Corridor Person Flow (persons/hr)
I-95 N (SR 234-SR 123)	15.2	47.2	2823	
I-95 N (SR 123-SR 642)	7.2	50.6	3624	20598 to 29315

Average Travel Time

Average travel time between SR 234 and SR 123 was reduced by 16.8 minutes, with the second segment experiencing an insignificant increase of 1 minute as shown in Table 19. Overall, average travel time on I-95 was reduced by 15.8 minutes when ICM strategies were operational. Figure 8 shows a graphical plot of the travel time savings.
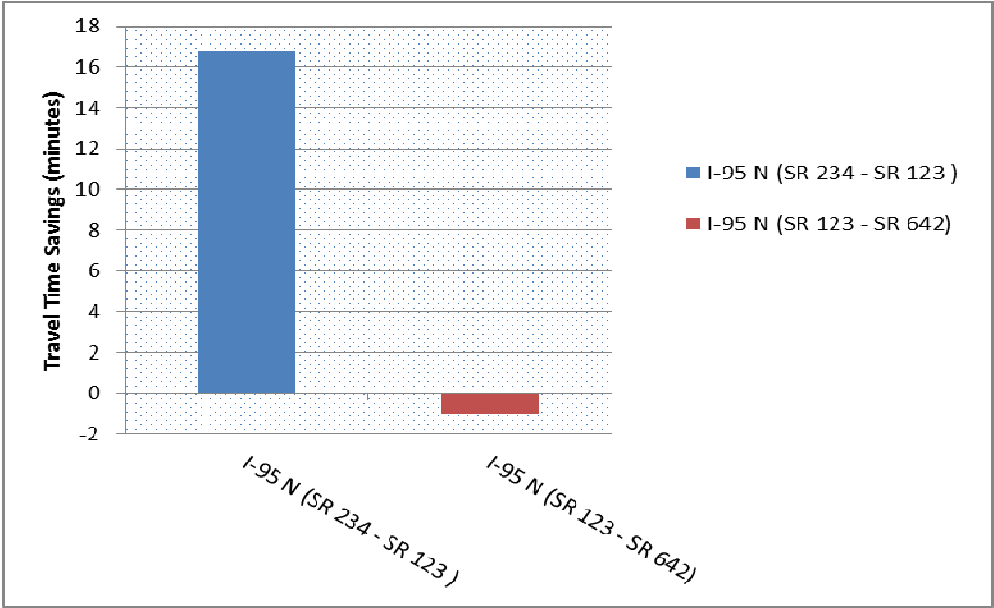

Figure 8. Travel Time Savings Due to ICM Strategies

Vehicular Flow and Speed

There was a significant increase in the vehicular flow of over 300 veh/hr between SR 234 and SR 123 and about 150 veh/hr between SR 123 and SR 642. However, there was a significant increase in average travel speeds by 23.3 mph in the first section and a reduction of 3.6 mph in the second section. Figure 9 shows a graphical plot of the impact of ICM strategies on travel speeds during incident conditions.
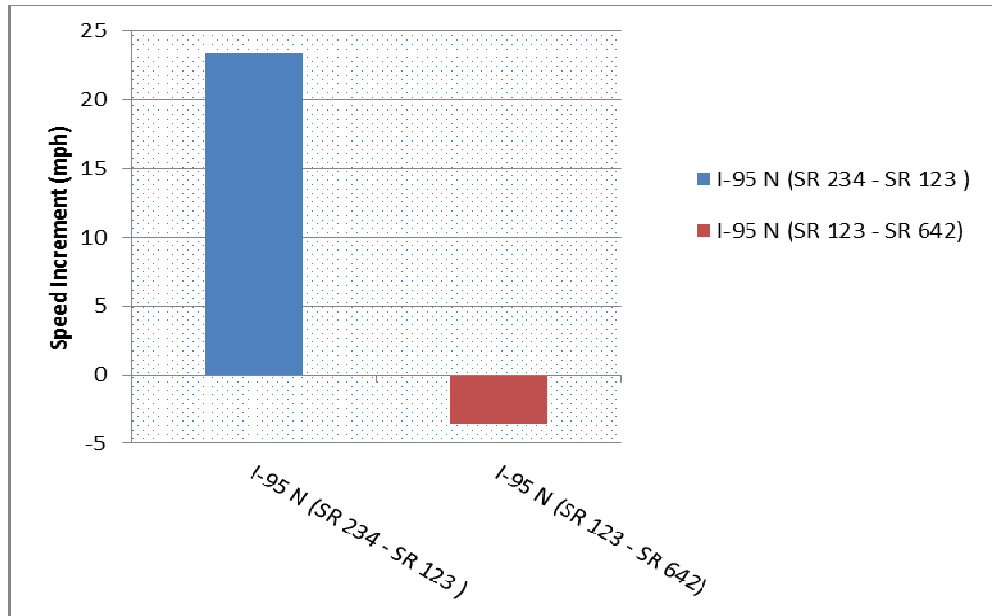
Figure 9. Impact of ICM Strategies on Speed during Incident Conditions

Selection of Critical ICM Strategies during Incident Conditions

The same methodology used in selecting critical ICM strategies during non-incident conditions was used in selecting that of incident conditions shown in Table 20. Similarly, the main performance measure used was corridor person flow per hour. The average corridor person flow experienced when ICM strategies were implemented was 24967 persons per hour. Compared to the case where there were no ICM strategies implemented, corridor person flow increased by 6860 persons per hour (37.8%). For the SRC, it is worth noting that the R^2 value obtained was 0.97; this implies that the assumption of a linear relationship between corridor person flow and the ICM strategies is justified and that the ICM strategies adequately describe the variability in corridor person flow. Also, variance inflation factors computed for each of the variables/strategies was less than 4, implying that there were no significant correlations among the implemented ICM strategies.

Table 20. ICM Strategies Sensitivity Values During Incidents

Strategy	SRC	LCC	SPC
RM	0.00172	-0.1727	0.056993
TPC	26926.81	0.3352	0.234578
HOT	108109.1	0.6038	0.550437
HOV-E	146257.9	0.7716	0.712401
FI	72983.78	0.0201	0.100495
VSL	5147.182	0.0578	0.15004

Table 21 shows the t-statistic of the coefficients of ICM strategies at a significance level of 0.05. This implies that for a strategy's coefficient to be statistically significant, the t-statistic must be greater than 1.96.

Table 21. t-Statistic Values for ICM Strategies During Incidents

Parameter	SRC	LCC	SPC
RM	*2.16	-1.21	0.40
TPC	*5.10	*2.46	*1.98
HOT	*20.85	*5.25	*4.57
HOV-E	*26.98	*8.40	*7.03
FI	*3.81	0.14	0.70
VSL	*5.68	0.40	1.05

*Statistically significant at a 5% significance level.

The ICM strategy rankings are shown in Table 22.

Table 22. ICM Strategy Rankings

Parameter	SRC	LCC	SPC
RM	6	4	6
TPC	4	3	3
HOT	2	2	2
HOV-E	1	1	1
FI	3	6	5
VSL	5	5	4

From Tables 21 and 23, the ramp metering strategy appeared to be less critical among the rest. Similarly, FI and VSL were statistically significant only under the SRC ranking criteria. The three ICM strategies that were statistically significant under all three ranking criteria are HOV-E, HOT, and TPC. Based on the ranking criteria, these three ICM strategies are the most critical.

As stated earlier, the fact that a strategy does not appear critical under one condition does not necessarily make it irrelevant. For example, VSL was identified to be critical during non-incident conditions, but was not included in that of critical ICM strategies under incident conditions. Notwithstanding, VSL is a beneficial strategy in most ICM implementations.

Fuel Economy and Emissions

The impact of ICM on fuel usage and vehicular emissions was very significant as shown in Table 24. In all 50 tested scenarios, significant reductions were experienced.

Table 24. Simulated Impacts of ICM During Incidents on Fuel Economy and Emissions

Condition	Fuel (gallons)	CO (g)	NOx (g)	VOC (g)
Without ICM	13190	922014.1	179390.4	213685.7
With ICM	8828	617079.1	120061.2	143014

Limits of Effectiveness of Unknown Traveler Response to ICM Strategies

As experienced during non-incident conditions, the limits of effectiveness of traveler responses to ICM strategies during incident conditions could not be clearly determined.

Effects of Transit Signal Priority on Bus Travel Times

The impact of the TSP strategy was evaluated by comparing average bus travel times with and without TSP. It is important to note that the impact of TSP within this context is affected by the other ICM strategies modeled. Hence, the effectiveness of TSP as a stand-alone strategy is not the sought after objective, rather it is how TSP performs within an ICM framework. The reductions in average travel time were modest for buses traveling between Dale City and the Washington, D.C., area (2.5 minutes), and between South Route 1 (Dumfries) and Washington, D.C (2.1 minutes). Conversely, the routes between Lakeridge and the Washington, D.C., area experienced an average travel time increase of 3.4 minutes. Buses using this route have stops at three park-and-ride facilities. Roads leading to these park-and-ride facilities experience heavy traffic when the % of vehicles wanting to park and use transit is high. This might slow down buses and increase their travel times. Table 25 shows the impact of TSP on average bus travel times.

Table 25. Impact of TSP on Average Bus Travel Times

Bus Route	Average Travel Time (min) No TSP	Average Travel Time (min) With TSP	Change in Average Travel Time (min)
Dale City-Washington	25.3	22.8	2.5
Dale City-Pentagon/Crystal City	25.3	22.8	2.5
Dale City-Navy Yard	25.3	22.8	2.5
Lakeridge-Washington	19.1	22.5	*3.4
Lakeridge-Pentagon/Crystal City	19.1	22.5	*3.4
Dale City/Lakeridge-Capitol Hill	19.1	22.5	*3.4
South Route 1-Washington	27	24.9	2.1

*Increase in average travel time.

CONCLUSIONS

- *A comprehensive institutional framework within which ICM will be implemented and operated is as critical as the type of strategies implemented.* This framework will define the decision-making structure and establish intra-agency protocols for ICM operation within the corridor, select the lead agency, as well as delegate responsibilities to each agency.

- *The ability to "shift" demand from automobiles to transit will be dependent on the parking capacity at transit access locations.* In the test corridor, it was discovered that transit capacity exceeded parking capacity significantly (a deficit of approximately 2,000 parking spaces). Another consideration was the fact that 21 of the 68 possible transit trips (19 bus trips and 2 train trips) available during the AM period start and end before 6:00 AM. Such early transit trips indicate that demand shifting is most practical during early portions of the peak period.

- *By examining different diversion percentages during non-incident conditions, it was discovered that it will require 15% of vehicles diverting from I-95 N to U.S. 1N in order to reduce average travel time (27.1 minutes) on the freeway by 5 minutes, and increase corresponding average speed (31 mph) by 9 mph.* However, this adversely affected traffic conditions on U.S. 1N, resulting in a corresponding increase in average travel time (30.7 minutes) of 4.3 minutes. This illustrates that the extra capacity on U.S. 1N (principal arterial) is not adequate to accommodate significant traffic shifts from I-95 N.

- *During incident conditions on I-95 N, 15% of the traffic has to be diverted onto U.S. 1N in order to reduce average travel time (38.2 minutes) by 5 minutes coupled with no significant increase in speed.* These diversions can increase average travel times (30.7 minutes) on U.S. 1N up to 7 minutes and reduce average speeds (30 mph) by 6 mph. Regardless of the diversion percentage, there was no significant increase in the vehicular flow on the I-95 N. In contrast, vehicular flow on U.S. 1N was reduced by as much as 471 vehicles per hour. Again this illustrates that freeway/arterial ICM strategies devoid of modal shifts are of limited effectiveness on heavily traveled corridors where demand nears or surpasses capacity.

- *This study demonstrated the need to implement comprehensive ICM as a congestion mitigation measure in Virginia, as opposed to the traditional approach of diverting vehicles to parallel routes.* Overall, there was significant improvement in the performance of the individual transportation facilities (excluding the VRE commuter line, whose performance was not assessed) as well as the entire corridor.

- *The benefits of ICM were more significant under incident conditions than non-incident conditions.* In terms of corridor person flow (the non-mode specific performance measure used in selecting critical ICM strategies), an average increase of 6,860 persons per hour (+38%) was experienced when ICM strategies were implemented during incident conditions. During non-incident conditions, the improvement in average corridor person flow was 3,286 persons per hour (+14%). Under incident conditions, modal shifts between 16% and 21% are required to achieve the 38% increase in corridor person throughput. Similarly under non-incident conditions, modal shifts between 15% and 23% are needed in order to experience the 14% increase in corridor person throughput.

- *HOT lanes, HOV-E, and TPC are the ICM strategies that will bring about the mode shifts under both incident and non-incident conditions.* Additionally, driver compliance rate to VSL must be above 70%. Unused transit and parking capacity of over 2000 seats and 450 spots respectively were identified in the analysis segment. Therefore, it appears there is adequate transit capacity to accommodate the mode shifts but vice versa when it comes to parking. Also the HOV lanes in the corridor currently has excess capacity of about 1,000 veh/hr between SR 234 and SR 123, as well as about 500 veh/hr between SR 123 and SR 642. Hence mode shifts due to HOT/HOV-E can also be accommodated.

- *The ICM strategies identified as critical under non-incident conditions included VSL, increasing the use of HOV lanes/HOV bypass, the impact of HOT lanes in motivating the formation of carpools and ridesharing programs, and the provision of adequate parking and transit capacities.*

- *Under incident conditions, the critical ICM strategies identified were similar to those under non-incident conditions, although VSL was statistically significant for only the SRC sensitivity measure.*

- *Ramp metering was the least critical among the six strategies implemented.* Also the usual formation of queues on on-ramps as a result of metering operations was not experienced at any of the metered on-ramps.

- *In terms of the impacts of TSP within an ICM framework, the reductions in average travel time were modest for buses traveling between Dale City and the Washington, D.C., area (2.5 minutes), and between South Route 1 (Dumfries) and Washington, D.C. (2.1 minutes). Conversely, the routes between Lakeridge and the Washington, D.C., area experienced average travel time increment of 3.4 minutes. Buses using this route have stops at three park-and-ride facilities. Roads leading to these park-and-ride facilities experienced heavy traffic when the percentage of vehicles wanting to park (and use transit) is high. This will potentially delay buses and increase their travel times.*

- *The ICM strategies modeled had a positive impact on the environment.* Under both incident and non-incident conditions, the amount of fuel usage was significantly decreased by 33.1% and 34.3%, respectively, leading to subsequent reductions in the emissions of CO, NOx, and VOC.

RECOMMENDATIONS

1. *VDOT's Operations Division should initiate discussions with other transportation agencies to create pilot ICM implementations that include the following strategies: VSL, increased transit and parking capacity, HOV lanes/HOV bypass, and HOT lanes.* The results of this study indicate that ICM does hold potential to address congestion in major travel corridors of Virginia. The results also indicate that multi-modal ICM (as opposed to highway-only ICM) is necessary to achieve appreciable benefits.

2. *VDOT's Operations Division should take steps to implement VSL functionality into transportation operation centers' operating software platform. Additionally, the VSL system should be capable of providing the actual posted speed limit to the Virginia State Police and other law enforcement agencies in near real-time so that the posted speed limit can be enforced.*

3. *VDOT's Northern Virginia District should investigate incorporating an HOV/bus bypass ramp at SR 123 (Gordon Boulevard) only.* This is because the on-ramp demand from SR 123 is usually high during the morning peak.

4. *VDOT's Operations Division should conduct a study to investigate and identify information dissemination platforms best suited to supporting ICM.* Those ICM strategies intended to influence traveler behavior will require aggressive pre-trip and en-route multimodal

information dissemination (e.g., text messages and mobile phone applications) and platforms to facilitate mode-shifts (e.g., multimodal payment system).

COSTS AND BENEFITS ASSESSMENT

The analysis, modeling, and simulation (AMS) phase of an ICM initiative provides a framework for a benefit-cost (B-C) analysis. This approach was used to estimate B-C ratios for the three ICM pioneer sites (San Diego, Dallas, and Minneapolis). Details of this framework are provided in *Integrated Corridor Management: Analysis, Modeling, and Simulation Results for the Test Corridor Report.*[28] The framework, which uses average cost values that are consistent with the ITS national architecture, was adopted for the B-C assessment of the I-95/I-395 ICM corridor examined in this study.

The costs associated with the basic TMC facilities, highway and transit traveler information, and HOT lanes for the pioneer AMS sites were modified to reflect the specific conditions (such as the number of lane miles) of the I-95/I-395 corridor. The cost of deploying the Transit and Parking Capacity (TPC) strategy completely came from increasing the number of parking spaces, since the existing transit system (especially PRTC buses) has adequate capacity. According to VDOT, the cost of adding 1000 parking spaces to the Staffordboro commuter parking lot is about $9.7 million;[29] since this capacity expansion is synonymous with the TPC strategy tested in this project (maximum of 1000 extra spaces), its cost was adopted for use in the B-C assessment. Similarly, the VSL system deployed as part of the Woodrow Wilson Bridge project (a leased system), which is identical to the VSL strategy in this project has an estimated cost of $1.5 million per year.[30] Therefore, the same cost will be used in this assessment. All costs were adjusted to year 2013 prices using an inflation factor (1.086) obtained from the Bureau of Labor Statistics (BLS)[31] and annualized assuming a 10-year life for all components of the ICM deployment (consistent with AMS B-C framework). Table 26 shows the annualized costs associated with the ICM deployment in this study.

Table 26. ICM Deployment Cost

ICM Components/Strategies	Annual Cost ($)
Basic TMC Facilities	1,165,168
Variable Speed Limit System	1,629,404
Increasing Transit and Parking Capacity	1,635,221
HOT/HOV Lanes	1,542,502
Highway Traveler Information	695,449
Transit Traveler Information	777,660
Total	7,445,404

The benefits of ICM were captured in terms of travel time savings, gallons of fuel saved, and tons of emissions saved. Assuming a 3-hour AM peak-period, the benefits obtained during the 1.5 hours of simulation were multiplied by 2 to produce daily benefits (assumed to be a conservative estimate given likely similar benefits during the PM peak, and other benefits mid-day and evening). The daily benefits were then converted to annual benefits by multiplying by 260 workdays. The analysis assumes that the value of time is $17.03 for non-incident conditions

and $24.12 for incident conditions. These values were derived from the "All purpose" average of $12.50/hour prescribed in the U.S. DOT's *Revised Departmental Guidance of Valuation of Travel Time in Economic Analysis* (Revision 2 – corrected).[32] The value was inflated from year 2009 prices to Year 2013 using an inflation factor of 1.0904 retrieved from the BLS inflation calculator [31] and adjusted by average vehicle occupancies of 1.25 and 1.77 for non-incident and incident conditions, respectively. The annual travel time savings amounted to $21,183,507 and $31,001,458 for non-incident and incident conditions, respectively.

In terms of monetizing the fuel savings, the analysis assumed the cost of fuel to be $4.0 per gallon (consistent with the cost used for the AMS pioneer sites). This translates into annual fuel savings of $8,808,800 for non-incident conditions as well as $9,072,960 for incident conditions. The U.S. Environmental Protection Agency's (EPA) 2005 publication *Emission Facts* stated that each gallon of gasoline consumed may be expected to release 8,788 grams of carbon dioxide (CO_2).[33] Since the gallons of fuel saved is already known, it was possible to estimate the savings in CO_2 emissions. The Interagency Working Group on Social Cost of Carbon prescribes a schedule of monetary values for carbon emissions in any given year; using a discount rate of 3%, a ton CO_2 emissions saved was estimated to be $69.64 (in 2007 $).[34] This value was inflated from year 2007 prices to 2013 prices using an inflation factor of 1.1279 obtained from the BLS inflation calculator.[31] Ultimately, the amount of annual CO_2 savings was estimated to be $1,520,172 and $1,565,760 for non-incident and incident conditions, respectively. Thus, the total annual benefits estimated during non-incident conditions is $31,512,480, compared with $41,640,178 during incident conditions, resulting in B-C ratios of 6:1 during incident conditions and 4:1 for non-incident conditions.

The important factor to consider in this analysis is that, given assumptions and uncertainty, the "true" B-C ratio may range beyond the 4-6:1, however, given this estimate, VDOT can conclude that investment in ICM will result in significant benefits, well beyond the required costs.

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