High Occupancy Vehicle Lane Performance Assessment through Operational, Environmental Impacts and Cost-Benefit Analyses

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Abstract

High Occupancy Vehicle (HOV) lanes are in operation in the U.S. for more than 30 years and used as a tool to alleviate urban freeway congestion. For new HOV projects a need exists to study the feasibility of implementation as well as assess their potential operational and environmental impacts prior to deployment. Equally important is to obtain a clear picture of expected cost and benefits of available options in order to determine the most effective strategy for implementation. This paper reports on a study that was undertaken to determine the need for and impact from the potential deployment of HOV lanes in Birmingham, Alabama. To meet the study objectives, a detailed alternatives analysis and cost-benefit analysis were performed using Traffic Software Integrated System (TSIS) and Integrated Development Assessment System (IDAS) respectively. Three different scenarios and a total of ten options were considered to quantify the operational, environmental, and economic impacts of HOV lanes on traffic operations. The paper provides background information on the models used, data gathered, assumptions made, and outputs obtained. A detailed description of the analysis and results is also presented.

1. INTRODUCTION

Implementation of High Occupancy Vehicle (HOV) lanes along with General Purpose (GP) lanes has already been accepted as an effective method to control urban freeway congestion and to increase the person-carrying capacity of existing road systems. HOV projects are in existence in the U.S. for more than 30 years. The continuous growth of the metropolitan areas coupled with ever increasing demand for freeway capacity, made the conversion of existing GP lanes into HOV lanes a logical freeway operation scheme [4]. In some locations, new lanes have been added to accommodate HOV demand. The best option depends on the severity of congestion, availability of Right-of-Way (ROW), financial resources, and other local considerations.

This paper uses a case study from Birmingham, Alabama to demonstrate considerations that should be made in order to determine whether or not HOV lanes have been an effective traffic management tool at the local level. These relate to evaluation of feasibility, operational impacts, environmental considerations, and costs and benefits from deployment.

Urban areas in Alabama face similar challenges to those experienced nationwide. The 2005 Urban Mobility Study by the Texas Transportation Institute (TTI) listed Birmingham as one of the medium-sized urban areas with higher congestion or faster increases in urban congestion than their counterparts [12]. Based on 2005 data, the average annual hours of delay per traveler in the Birmingham area was 33 hrs, which is more than 50% higher than the figure reported in 1995 (i.e., 21 hrs) and significantly higher than the average reported in the 2005 TTI study for comparable size cities (28 hrs average). As a result, congestion in Birmingham resulted in 12.41 million hours of travel delay and 8.21 million gallons in excess fuel consumption in 2005 alone.

In order to address the continually growing problem of congestion at the Birmingham, AL region, in 2006, the Regional Planning Commission of Greater Birmingham (RPCGB) conducted an initial feasibility analysis (fatal flaws analysis) of highway and/or transit capacity improvements along a 45-mile stretch of the I-65 corridor, which is the main north-south corridor serving metropolitan Birmingham. Transportation options screened for fatal flaws included HOV lanes, express bus lanes, HOT lanes, and bus rapid transit.

The analysis was intended to identify potential opportunities and challenges from the implementation of various highway and transit lane management options [5].

The study recommended further consideration of HOV lanes on the I-65 corridor and indicated that a 12.5 mile-long segment of I-65 extending from Valleydale Rd to I-20/59 had the best potential and greater need for immediate implementation [17]. Based on the initial feasibility study it was required to conduct a more detailed study in order to determine the impacts of the possible implementation of HOV lanes along the subject corridor in terms of travel time savings, changes in average speed, fuel consumption savings, vehicle hours of travel, number of accidents, impacts on emissions etc. Since, transportation infrastructure or service improvement investments involve major funding; proponents are required to study the economic justification prior to such an investment. The Federal Highway Administration (FHWA) also emphasizes the need for an economic justification component in any Highway Feasibility Study. In this paper both of traffic operations and economic justification issues are considered.

2. LITERATURE REVIEW

HOV lanes have been used widely in many parts of the United States since the 1970s [10]. Today there are over 125 HOV lanes projects in 30 cities operating over 2,500 lane-miles of HOV facilities and carrying more than 3 million persons everyday [9]. Examples of states that operate HOV systems include Houston and Dallas, TX; Seattle, WA; Los Angeles, Orange County, and San Francisco Bay, CA; New York City, NY; Northern Virginia, VA; Washington, D.C.; Atlanta, GA; and Boston, MA [13].

Many studies confirm that HOV lane implementation resulted in delay savings and more predictable travel times. For example, the Washington, D.C. region where three interstate HOV lane corridors are in operation reported that HOV operation resulted in travel time savings from 5 to 36 minutes for morning rush hours and 36 minutes for the evening rush [3-5].

Studies also confirm an increase in person-carrying ability of HOV lanes in Dallas and Houston, TX. According to a TTI study, by implementing a barrier-separated contraflow HOV lane on I-30 and buffer-separated concurrent flow HOV lanes on I-35E North and I-635 freeways in the Dallas area, person trips increased by 14% and the HOV lane carried twice the number of people than the adjacent general-purpose lane during the peak hour. Automobile occupancy also increased from 8 to 12% [16]. Furthermore, morning peak hour travel time savings of approximately 2 to 22 minutes were realized in HOV lanes. Periodic surveys of HOV lane users showed that nearly 45% of current carpoolers and 46% of bus riders previously drove alone [2].

In Minneapolis, the design of I-394 that opened in 1993 included three miles of two-lane, reversible, barrier-separated HOV lanes and eight miles of concurrent flow HOV lanes. Based on a 1994 study, the HOV lane's average vehicle occupancy for AM peak-hour was 3.28, more than triple of that of the general purpose lanes averaging just 1.01 persons per vehicle [15].

The Los Angeles County has an impressive system of HOV facilities with 14 HOV corridors covering over 470 HOV lane miles, or approximately 36% of the total 1,320 HOV lane miles in the State of California. These facilities serve an average of 1,350 vehicles or 3,200 people per hour during peak hours or approximately 330,000 vehicle trips and 750,000 person trips per day. Between the years 1992 and 2007, the increase in the total number of carpools on freeways with HOV lanes during the morning 2-hour peak was 79% [1]. Moreover, it is predicted that by the year 2015, the Los Angeles County HOV system will serve more than one million person trips each day [7].

Washington State has implemented approximately 200 lane miles of a planned 300-mile freeway HOV lane and ramp system since 1970. Today, HOV lanes carry nearly 35% of the commuters and 18% of the vehicles during rush hours on freeways. It is reported that the average HOV lane is carrying more than 1½ times as many people as the average general purpose lane during the peak commuting periods and HOV use results in significant time savings [20]. Among the concurrent flow HOV lanes in the U.S., the I-5 facility carries the second largest number of bus riders in the AM peak hours [15].

3. STUDY SCOPE

The study focuses on quantification of impacts from potential implementation of HOV lanes in the Birmingham, AL region as a tool to address local congestion and environmental related concerns. Based on the recommendations of RPCGBs initial feasibility study [17] and on the traffic counts reported by the Alabama Department of Transportation (ALDOT), the study segment selected for analysis is a 12.5 mile-long segment of I-65 extending from the I-459 interchange in the south end to the I-20/59 interchange in the north and is one of the backbones of the Birmingham's transportation system. This section currently consists of three 12-ft general purpose lanes with shoulder in each direction of travel with a posted speed limit of 60 mph.

Table 1. Operational Characteristics of the I-65 Study Corridor-NB Direction [17]

Segments	LOS	v/c Ratio
Valleydale Road to I-459	F	1.55
I-459 to US 31	E	0.99
US 31 to Alford Ave	F	1.47
Alford Ave to Lakeshore Dr	F	1.47
Lakeshore Dr to Oxmoor Rd	F	1.42
Oxmoor Rd to Greensprings Ave	F	1.50
Greensprings Ave to University Blvd	F	1.26
University Blvd to 3rd-4th Ave S	D	0.84
3rd-4th Ave S to 3rd-6th Ave	C	0.67
From 3rd-6th Ave to I-20/59	C	0.64

The daily traffic volumes in 2005 along the study segment ranged from 75,000 to 125,000 with a 10% truck volume. Table 1 summarizes the operational characteristics of the study site based on local studies performed in 2005 and 2006 [17].

The study considered current conditions as the baseline for comparison purposes (Scenario 1) and two major development alternatives. One alternative was to convert one lane in each direction to an HOV lane (Scenario 2) and the other was to add a new lane in each direction designated for HOV usage (Scenario 3). All HOV lanes considered were concurrent flow without buffer separation.

3.1. Study Objective and Approach

The objective of the Birmingham HOV study is twofold:

- Determine the impacts of various HOV strategies on traffic operations especially as they related to mobility and the environment, and
- Quantify the project costs and user benefits from potential implementation and identify strategies with the highest potential return for the investment.

To achieve these objectives, the study performed a detailed alternatives analysis using traffic simulation tools and cost-benefit analysis to predict the traffic operations and economic impacts of HOV implementation along the I-65 corridor, respectively.

The **simulation analysis** was performed using the Traffic Software Integrated System (TSIS). TSIS is a suite of simulation models developed by FHWA that has been used extensively by transportation agencies and practitioners in the U.S. and abroad for over three decades. The CORSIM simulator in TSIS has the ability to simulate fairly complex geometric conditions and realistic driver behaviors and offers the capability to analyze a variety of lane management strategies, including HOV. Like most of the currently available microscopic traffic simulation models, TSIS requires detailed geometric, traffic, and control data as inputs. Geometric data were gathered and incorporated into the model. Vehicle volumes were determined using 2006 Average Annual Daily Traffic (AADT) data. The simulation model was run for the project alternatives under study (Scenarios 1 through 3). Details about the simulation study approach, assumptions, and summary findings are presented next, in Simulation Study Methodology Section.

The **cost-benefit analysis** was performed with the IDAS tool and considered life-cycle costs and benefits of the project alternatives under study in order to identify the most economically efficient investment alternative. The life-cycle costs considered in the analysis included design and engineering costs, right-of-way procurement costs, construction and maintenance costs. Life-cycle benefits included vehicle operating cost savings, travel time savings, safety benefits, and emission reduction benefits. The analysis quantified costs and benefits for all study scenarios and strategies described above. Details on the methodology and summary findings from the cost-benefit analysis are described in Cost-Benefit Analysis Methodology Section.

4. SIMULATION STUDY

4.1. Methodology

Using CORSIM and TSIS tools a simulation model of the study section of I-65 was developed extending from the I-459 interchange in the south to the I-20/59 interchange to the north. The demands used were based on 2006 data that were increased by 15% to account for anticipated increases in traffic volumes. Trucks accounted for 10% of the total volume. Vehicle occupancy of 1.3 persons/vehicle was considered in the general purpose lanes and 2.0 persons/vehicle in HOV lanes. To provide a fair comparison between current and HOV operations, the study assumed that the facility should serve the same number of travelers with or without HOV lanes. Thus the demand used in the HOV scenarios was adjusted accordingly to account for the impact of higher vehicle occupancies. As a result the number of vehicles in the network decreased with the increase of HOV usage, which is indeed the main objective of the HOV implementation. This assumption is referred to as the Equal Person Assumption.

As stated earlier, three scenarios were constructed for the analysis. Scenario 1 described network operations under current conditions (i.e., general purpose lanes only) and provided the baseline for comparisons. Scenario 2 assumed that the innermost general purpose lane was converted to an HOV lane. Scenario 3 assumed that an HOV lane was added to the current design configuration. Scenario 2 considered four options with varying high occupancy lane usage, namely HOV 10%, HOV 15%, HOV 20% and HOV 25%. Similarly Scenario 3 considered five options based on HOV lane usage ranging from 0% (no HOV) to 25%. Every option was run for 2 hrs of simulation time and for 5 replications. Comparisons were based on the Measures of Effectiveness (MOEs) including:

- Total network travel time (veh-hrs);
- Total network delay (veh-hrs);
- Average travel speed (mph);
- Delay time (min/veh-mile);
- Travel time (min/veh-mile);
- Total HC emissions (grams/mile);
- Total CO emissions (grams/mile);
- Total NO emissions (grams/mile); and
- Total fuel consumption (gallons)

Summary results from the simulation study are presented next.

4.2. Operational Performance Results

The results for all scenarios and for various levels of HOV lane usage are summarized in Table 2. Comparison of findings from Scenarios 1 and 2 shows that the conversion of a freeway lane to HOV is not justified on the basis of operational benefits. This is evident from the higher travel times and delays and the lower speeds reported under the

Table 2. Summary of Simulation Results-Operational - MOEs over the Simulation Period

Alternative	Total Travel Time (veh-hrs)	Total Delay Time (veh-hrs)	Avg. Travel Speed (mph)	Delay Time (min/veh-mile)	Total Time (min/veh-mile)
Scenario 1: Base case, no HOV lanes on I – 65					
1: HOV 0%	5,363	1,744	40.38	0.48	1.49
Scenario 2: Conversion of one lane in each traveling direction of I – 65 to HOV lane					
2: HOV 10%	5,450	2,782	29.22	1.05	2.05
3: HOV 15%	5,149	2,433	31.49	0.90	1.91
4: HOV 20%	4,674	1,861	36.01	0.66	1.67
5: HOV 25%	4,800	1,953	35.47	0.69	1.69
Scenario 3: Addition of one lane in each traveling direction of I – 65 and use as HOV lane					
6: no HOV	5,079	1,421	44.08	0.36	1.36
7: HOV 10%	3,553	338	54.19	0.11	1.11
8: HOV 15%	3,491	314	54.52	0.10	1.10
9: HOV 20%	3,456	297	54.74	0.09	1.10
10: HOV 25%	3,459	294	54.80	0.09	1.09

converted lane scenario (Scenario 2) in comparison to the baseline results (Scenario 1). A possible explanation is that the remaining general purpose lanes are unable to handle the non-HOV demand, a fact that leads in increased congestion under the lane conversion scenario, as compared to the baseline.

On the other hand, addition of an extra lane under Scenario 3 (Option 6) improves speeds (by nearly 10%) and reduces delays (by 25%) compared to the baseline (Option 1). Furthermore, the use of the new lane as an HOV lane brings considerable benefits, even when the HOV lane utilization is small. For example, comparison of Options 6 and 7 shows that when the added lane is designated as HOV even a moderate HOV lane usage of 10% leads to significant increase in average travel speeds (> 10 mph) compared to the addition of a general purpose lane. In other words, should a lane be added to the facility, the addition of an HOV would be far more beneficial than an extra general purpose lane and is fully justifiable based on operational considerations, even under the current ride sharing patterns in the region? In summary, and based on the results of the operational analysis, the HOV lane addition strategy (Scenario 3) is the recommended strategy for implementation.

4.3. Environmental Impacts

Table 3 summarizes annual environmental impacts of the various scenarios and options considered in the simulation analysis. The findings support the conclusions derived from the operational analysis.

Table 3. Summary of Simulation Results-Annual Environmental MOEs

Alternative	Total HC Emissions (Tons)	Total CO Emissions (Tons)	Total NO Emissions (Tons)	Total Fuel Use (Mil Gal)
Scenario 1: Base case, no HOV lanes on I – 65				
1: HOV 0%	285.45	2174.20	567.55	13.45
Scenario 2: Conversion of one lane in each traveling direction of I – 65 to HOV lane				
2: HOV 10%	352.66	3061.56	461.77	18.30
3: HOV 15%	298.56	2413.54	446.45	15.63
4: HOV 20%	280.88	2261.05	426.16	14.59
5: HOV 25%	263.19	2109.07	405.88	14.89
Scenario 3: Addition of one lane in each traveling direction of I – 65 and use as HOV lane				
6: no HOV	269.71	1720.85	589.35	13.89
7: HOV 10%	248.24	1579.97	451.91	12.71
8: HOV 15%	237.13	1509.69	509.76	12.15
9: HOV 20%	226.04	1439.08	486.55	11.59
10: HOV 25%	214.95	1368.80	463.35	11.02

More specifically, the lane conversion to HOV operation results in increase of annual emissions and fuel consumption, and thus is not viewed as an environmentally friendly approach. On the other hand, under the study assumptions, the addition of a designated HOV lane is expected to result in HC, CO, and NO emission savings as well as reduction in annual total fuel consumption.

As seen in Table 3, the environmental benefits increase as a higher percentage of travelers shifts to ride sharing options (i.e., as HOV lane utilization increases). Thus Scenario 3 is also the most favorable strategy for adoption as far as environmental impacts are concerned.

5. COST-BENEFIT ANALYSIS (CBA)

5.1. Methodology

The Cost-Benefit analysis (CBA) considered similar scenarios and strategies to the simulation analysis and performed a detailed Cost-Benefit analysis to measure the worthiness of the proposed investment in order to identify the best option. A common methodology was adopted for analyzing the costs and benefits of each option based on (i) Analysis of infrastructure cost for each option and, (ii) Analysis of user benefits for each option. More specifically, the infrastructure cost has two components, namely investment cost, and operation and maintenance cost. Investment cost of the project includes design and engineering costs, land acquisition costs and construction costs. User benefits considered include Vehicle Operating Cost Savings, Travel Time Savings, Safety Benefits (Accident Cost Savings), and Emission Reductions.

In order to conduct the analysis IDAS was used. In the following sections a brief overview of IDAS is provided and the methodology is discussed in greater detail.

5.2. Integrated Development Assessment System (IDAS) Overview

IDAS is an Intelligent Transportation System (ITS) sketch-planning analysis tool that can be used to estimate the impacts, benefits and costs resulting from the deployment of ITS components. IDAS operates as a post-processor to travel demand models and, used by Metropolitan Planning Organizations (MPO), State Departments of Transportation (DOT) for transportation planning purposes. IDAS implements the modal split and traffic assignment steps associated with a traditional planning model.

IDAS is designed to assess impacts and costs for 12 different types of ITS elements. One of these elements is *Generic Deployment*. This element was used to estimate the impacts of HOV lane usage. The set of impacts evaluated by IDAS include changes in user mobility, travel time/speed, travel time reliability, fuel costs, operating costs, accident costs, emissions, and noise. IDAS also provides benefit/cost comparison of various ITS improvements individually or in combination. The tool is comprised of five different analysis modules, namely [6]:

- Input/output Interface Module (IOM);
- Alternatives Generator Module (AGM);
- Benefits Module;
- Cost Module; and
- Alternatives Comparison Module (ACM).

The Benefits Module is further comprised of four submodules: (i) Travel Time/Throughput, (ii) Environment, (iii) Safety, and (iv) Travel Time Reliability. Within each of these sub-modules, both traditional benefits of deployment (e.g., improvement in average travel time) and non-traditional benefits (e.g., reduction in travel time variability) are estimated.

5.3. Input Data for Analysis

The node coordinate data, link data, and trip table data (trips from origin to destination) for the base year were acquired from the TRANPLAN regional planning model for the Birmingham region that is maintained by the RPCGB.

With the input data IDAS constructed the full network, where the facility types along with their attributes, i.e. volume, speed, number of lanes etc. were well defined. Following the simulation study, the Equal Person assumption was considered in the CBA analysis. Equal person assumption more closely approximates the practical situation since this assumption considers the reduction in the number of vehicles due to increase in vehicle occupancy resulted from HOV lane usage. Under this assumption, two different analysis procedures were applied; (i) analysis that considers induced demand and, (ii) analysis that does not consider induced demand. IDAS has an Induced/Foregone Demand module that contains Induced Demand estimation model. The IDAS default values of the Induced Demand model (α = -0.50, β = -0.44 and ε = -0.88) were used in the analysis that considered induced demand [6].

5.3.1. Infrastructure Costs

For Scenario 2 it was assumed that the lane conversion work begins in year 2010 and lasts for one year. The facility would open for regular operation from Year 2011. For Scenario 3, i.e. the lane addition scenario, it was assumed that the project would start in Year 2008 and end in Year 2010. The facility would open for operation in Year 2011.

The construction costs and maintenance costs were estimated on the basis of ALDOT cost estimates and "I–65 Corridor Feasibility Study Report" [11]. The estimated construction costs were $21.42 Million for Lane Conversion (Scenario 2) and $116.55 Million for Lane Addition (Scenario 3). The estimated maintenance costs for the analysis period 2010 – 2030 were $87.50 Million and $85.95 Million for Scenarios 2, and 3 respectively.

5.3.2. Discount Rate

The discount rate, or interest rate, is one of the variables necessary to complete a CBA utilizing the Net Present Value (NPV) method in order to take care of the time value of money. The U.S. Office of Management and Budget (OMB) requires U.S. Federal agencies to use a 7 percent real discount rate to evaluate public investments and regulations [18-19]. FHWA suggests using a discount rate between 3 and 5 percent [14]. ALDOT currently uses a 4 percent discount rate on its life-cycle cost analyses [8]. In this analysis a 4% discount rate was considered.

5.3.3. Benefits of Different Scenario Analysis

The major benefits of highway improvement works arise from (i) vehicle operating cost saving, (ii) value of travel time saving, (iii) accident cost saving and, (iv) emission cost saving. In the output module of IDAS these benefit elements are addressed. However, the IDAS output does not return the Vehicle Operating Cost saving and Value of Time saving directly. In order to convert the physical benefits into dollar value IDAS uses default values which are based on the contemporary rates and prices.

5.4. Cost-Benefit Analysis by IDAS

The results of a Cost-Benefit analysis reveal the alternative that maximizes the net benefits to the public from an allocation of resources and thus identify the economically efficient project. The economic outcome parameters that are obtained from a Cost-Benefit analysis are the following:

- Net Present Value (NPV)
- Benefit Cost Ratio (BCR)
- Internal Rate of Return (IRR)

The Alternative Comparison Module of IDAS returns the Average Annual Benefit, Average Annual Cost and the Benefit Cost ratio. It also returns the Net Benefit, which is the difference between Annual Benefit and Annual Cost and, this value may be considered as an indication of the Net Present Value (NPV). However, the IRR is not possible to calculate through IDAS. The economic analyses were carried out over the time span 2010 – 2030 for each of the options under the study.

5.5. Results of Analysis and Discussion

The results are obtained for both the specific I-65 freeway segment and for the network as a whole. The Scenario and Option specific average results for the major elements of Cost-Benefit Analysis for the study segment of I 65 are presented in Table 4.

5.5.1. Vehicle Operating Cost Savings

As mentioned earlier, IDAS does not return the Vehicle Operating Cost saving directly. But, from the 'Vehicle Miles of Travel (VMT)', 'Fuel Consumption' and, 'Speed' outputs it is possible to get indications regarding the Vehicle Operation Cost Saving.

The Lane Conversion scenario shows a decrease in average VMT and an increase in average speed and fuel consumption when compared to the base case (Table 4). On the other hand, the Lane Addition scenario with 0% HOV results in higher VMT, average speed and Fuel Consumption comparing to the Base Case. The increase in average speed is higher than that in Lane Conversion Scenario; from this perspective the Lane Addition Scenario may be considered as a better option.

5.5.2. Value of Travel Time (VOT) Savings

IDAS does not return the Vehicle Operating Cost saving directly. But, from the 'Vehicle Hours of Travel' (VHT), 'Person Hours of Travel' (PHT) and, 'Hours of Unexpected Delay' outputs it is possible to assess the state of Value of Time Saving for different Options.

Table 4 shows that the Lane Conversion Scenario has lower VHT and PHT values, compared to that of the base case. Regarding one of the most important parameters i.e., 'Hours of Unexpected Delay', the Lane Addition scenario results in the lowest values compared to those of Base Case and Lane Conversion scenario, which makes the Lane Addition option a favorable one.

5.5.3. Accident Cost Savings

The Alternative Comparison Module of IDAS returns the average annual number of accidents. The percentage changes in annual accidents in comparison to the base case for different study Options are summarized in Table 5.

From the information provided in Table 5 it is evident that average annual number of accident reduces most in the Lane Addition Scenario. In consequence, Options 7 through Option 10 of Lane Addition Scenario would result in higher accident cost saving.

Table 4. Scenario and Option Specific Average Results of Cost-Benefit Analysis- I65 Study Corridor

Lane Conversion Scenario			
	Base Case	With Induced Demand	Without Induced Demand
Vehicle Miles of Travel [Mil Mi]	293.33	276.01	273.13
Vehicle Hours of Travel [Mil Hrs]	5.68	4.69	4.63
Average Speed [Mi/Hr]	51.34	54.14	54.12
Person Hours of Travel [Mil Hrs]	8.07	7.43	7.30
Fatality Accidents [Number]	1.94	1.82	1.80
Injury Accidents [Number]	196.57	178.14	175.42
PDO Accidents [Number]	255.83	231.90	228.66
Unexpected Delay [Mil Hrs]	2.09	1.68	1.68
Fuel Consumption [Mil Gals]	9.98	10.92	10.82
Hydrocarbon Emissions [Tons]	290.39	299.54	297.16
Carbon Monoxide Emissions [Tons]	1,564.89	2389.12	2368.27
Nitrogen Oxides Emissions [Tons]	623.83	747.06	742.44

Lane Addition Scenario				
	Base Case	Lane Added 0% HOV	With Induced Demand	Without Induced Demand
Vehicle Miles of Travel [Mil Mi]	293.33	377.86	322.51	316.96
Vehicle Hours of Travel [Mil Hrs]	5.68	5.90	4.98	4.88
Average Speed[Mi/Hr]	51.34	62.89	73.14	73.06
Person Hours of Travel [Mil Hrs]	8.07	8.34	7.67	7.55
Fatality Accidents [Number]	1.94	2.49	2.13	2.09
Injury Accidents [Number]	196.57	210.42	165.23	162.02
PDO Accidents [Number]	255.83	276.07	216.42	211.93
Unexpected Delay [Mil Hrs]	2.09	0.67	0.47	0.39
Fuel Consumption [Mil Gals]	9.98	15.1	13.78	13.6
Hydrocarbon Emissions [Tons]	290.39	402.32	356.99	351.58
Carbon Monoxide Emissions [Tons]	1,564.89	3137.79	3111.17	3080.84
Nitrogen Oxides Emissions [Tons]	623.83	1024.16	939.17	926.36

5.5.4. Emission Cost Savings

The Alternative Comparison Module of IDAS returns the average annual quantity of Hydrocarbon and Reactive organic gases emission, Carbon Monoxide emission and

Table 5. Percent Change in Annual Average Accident Number along I-65 Segment

	% Increase / Decrease (-) in Accident Number				
	0% HOV	10% HOV	15% HOV	20% HOV	25% HOV
Equal Person Assumption	**Lane Conversion: Options 2 – Option 5**				
Induced Demand Considered	-	-12.6	-9.1	-6.4	-9.3
Induced Demand NOT Considered	-	-13.4	-11.2	-7.7	-10.3
Equal Person Assumption	**Lane Addition: Options 6 – Option 10**				
Induced Demand Considered	7.6	-11.0	-15.8	-17.2	-18.1
Induced Demand NOT Considered	4.8	-13.5	-18.1	-18.3	-19.0

Oxides of Nitrogen emission in Tons. From the Emission Output section of the Alternative Comparison Module, increase in emission for all nine Options is observed in comparison to the Base Case Option 1. The percentage of increase in annual total emission for different Options comparing to the Base Case are summarized in Table 6. A close observation of Table 6 reveals that increase in emission is lowest in Lane Conversion scenario. Therefore, Emission Cost savings in Lane Conversion Scenario would be higher than that of Lane Addition scenario.

Table 6. Percent Increase in Annual Average Emission along I-65 Segment

	% Increase / Decrease (-) in Emission				
	0% HOV	**10% HOV**	**15% HOV**	**20% HOV**	**25% HOV**
Equal Person Assumption	**Lane Conversion: Options 2 – Option 5**				
With Induced Demand	-	34	45	42	33
Without Induced Demand	-	32	43	43	35
Equal Person Assumption	**Lane Addition: Options 6 – Option 10**				
With Induced Demand	84	81	88	80	63
Without Induced Demand	83	81	85	77	61

5.5.5. Cost-Benefit Analysis Results

The Cost-Benefit analysis results are summarized in Table 7 and refer to the network as a whole. From Table 7 it may be observed that the investment costs for lane addition scenario (Scenario 3) are almost twice as high as of the lane conversion one (Scenario 2). However, compared to existing operations, much larger benefits are achievable through the implementation of lane addition scenario than those expected from the lane conversion one. Overall, it can be seen that highest average annual benefits may be achieved through the implementation of Lane Addition with 20% or 25% HOV usage of the newly added lane in either travel direction.

The Benefit-Cost (B/C) ratios for different study Options and for the network as a whole are also summarized in Table 7. The B/C rations represent the impact that the studied option has as compared to the base case scenario. Positive values imply an improvement.

The B/C ratios that are summarized in Table 7 indicate that addition of one lane along each direction of the study segment of I-65 results in relatively higher monetary benefits. Table 7 provides further evidence that the highest benefit-cost ratios are achievable through the implementation of lane addition along with 20% to 25% HOV usage. It should be noted that the analysis that considered induced travel demand is expected to yield most appropriate results. On this consideration, Lane Addition Scenario with 20% HOV usage is the most economically efficient Option. In this Option both of the Average Annual Benefit ($50.55 Million) and the Benefit-Cost Ratio (4.38) are highest among other Options with induced demand consideration.

Table 7. Network Wide Average Annual Costs, Benefits [in Mil $] and B/C Ratios for the Analysis Period

Scenario 1: Base Case Scenario, *Other Scenarios are compared to this Scenario*					
Options	Costs	Benefits With Induced Demand	B/C Ratio With Induced Demand	Benefits Without Induced Demand	B/C Ratio Without Induced Demand
Scenario 2: Conversion of one lane in each travelling direction of I – 65 to HOV lane					
2: HOV 10%	5.53	8.17	1.48	11.00	1.99
3: HOV 15%	5.53	8.34	1.51	19.70	3.56
4: HOV 20%	5.53	8.89	1.61	20.09	3.63
5: HOV 25%	5.53	5.38	0.97	20.33	3.68
Scenario 3: Addition of one HOV lane in each travelling direction of I – 65					
6: HOV 0%	11.55	29.23	2.53	39.02	3.38
7: HOV 10%	11.55	30.12	2.61	46.04	3.99
8: HOV 15%	11.55	43.06	3.73	52.48	4.54
9: HOV 20%	11.55	50.55	4.38	55.88	4.84
10:HOV 25%	11.55	50.26	4.35	55.27	4.78

From the analyses results that are summarized in Table 7 it may be observed that all of the Options of the Lane Addition Scenarios yield better economic results comparing to those of the Lane Conversion Scenario. Both of the Annual Average Benefit and Benefit-Cost Ratio are higher in Lane Addition Scenario than those of Lane Conversion Scenario. Therefore, it can be concluded that the lane addition option appears to be the best HOV option from the economic perspective.

6. CONCLUSIONS AND RECOMMENDATIONS

This study analyzed a number of alternative scenarios to determine the operational, environmental, and economic impacts of HOV lanes on traffic operations along the I-65 corridor in Birmingham, AL.

Under the study assumptions, the comparison of the base and HOV scenarios results indicate that the conversion of an existing general purpose lane to an HOV lane is not justifiable based on their impacts on traffic operations. On the other hand, significant gains are realized when adding a new lane and treating it as an HOV lane. For example, assuming a 15% HOV usage a 14.14 mph speed increase is realized compared to the base case, along with a 79% reduction in delay (from 0.48-Option 1 to 0.10-Option 8) and 26% reduction in travel times. Moreover, the results clearly shown that if a lane is added, the designation of this lane as HOV (rather than general purpose lane) is expected to increase the operational benefits from implementation.

It was also observed that the environmental benefits increase as higher percentages of travelers shift to ride sharing options and that the lane addition option is the most favorable strategy for adoption as far as environmental impacts are concerned.

Last but not least, the results of the Cost-Benefit Analysis also imply that the best and most economically efficient alternative to improve the existing traffic congestion situation is to add one HOV lane in each travelling direction of the I-65 corridor segment under study.

Overall the study showcases a methodology that can be used to assess the operational, environmental, and financial impacts of HOV deployment in local settings in order to assist decision makers in determining the best option for implementation.

It is recommended that alternative simulation software tools be considered to address some of the limitations of the TSIS software. Several studies confirm that TSIS tend to overestimate capacity and show that traffic conditions are better than they actually are. Innovative traffic modeling tools such as the Visual Interactive System for Transport Algorithms (VISTA) may be more versatile than traditional models and offer additional capabilities (such as Dynamic Traffic Assignment) which, in turn, may create enhanced modeling opportunities in future work.

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