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PRELIMANRY EVALUATION OF EFFICIENCY OF HOV LANE OPERATION ON I-40 EASTBOUND IN MEMPHIS, TENNESSEE

By

Rohitraj P. Makena

A Thesis

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Abstract

Makena, Rohitraj P. MS. The University of Memphis. December 2011. Preliminary Evaluation of Efficiency of HOV lane Operation on I-40 Eastbound in Memphis, Tennessee. Major Professor: Dr. Stephanie Ivey.

This research is a preliminary evaluation of the effectiveness of the High Occupancy Vehicle (HOV) lane along I-40 eastbound Memphis, TN. This HOV lane is operated from 4 p.m. to 6 p.m. during weekdays. Data for the analysis was collected over a two month period in June and July of 2011 using standard techniques as well as low cost smart phone apps and consumer grade GPS navigational products. The data collected included hourly volume data, average vehicle occupancy, violation rates, travel times and carbon emissions estimates. The analysis consisted of three methods of measuring effectiveness: increasing person throughput, providing travel time benefits and environmental benefits. To check for statistically significant differences between HOV lane and other GP lanes statistical methods including the two sample t-test and Mann Whitney test were used. A concept of a buffer index was also used to check the travel time reliability for each lane. The results showed that the objective of increasing person throughput is not met for this corridor within Memphis, Tennessee, and recommendations to improve the effectiveness of the HOV lane are presented.

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1. Introduction

1.1. Freeway Traffic Congestion

Freeway traffic congestion is a major issue on freeways throughout North America. Traffic congestion results in huge costs every year because of travel time delays, wastage of fuel and environmental externalities such as air pollution, etc. The 2009 Urban Mobility Report states that in 2007, road users traveled 4.2 billion hours more and purchased 2.8 billion gallons of extra fuel, which was an increase of 50% over the previous decade due to traffic congestion (Schrank & Lomax, 2009). Traditionally, adding capacity to existing roads would have been the answer to congestion problems; however, due to the huge costs associated with construction, latent demand, lack of land available for expansion, and the associated environmental concerns, these solutions have been difficult to implement.

In response, the Federal Highway Administration (FHWA) and state Departments of Transportation (DOTs) have proposed and implemented the idea of managed lanes to reduce the problems related to traffic congestion on freeways. According to FHWA, managed lanes can be defined as "*Highway facilities or a set of lanes where operational strategies are proactively implemented and managed in response to changing conditions.*" (FHWA, August, 2008)

Managed lanes strategies fall under three main categories:

1. High Occupancy Vehicle Lanes (HOV): HOV lanes are implemented for the main purpose of encouraging carpooling and increasing travel time reliability and passenger throughput. Vehicles with two or more occupants only can access these lanes.

2. High Occupancy Toll Lanes (HOT): HOT lanes are considered when the HOV lanes are under-utilized or over utilized, to increase lane efficiencies. In this case, single occupant vehicles can access these lanes by paying a toll.

3. Express Toll Lanes: In express toll lanes all vehicles in the managed lane must pay a toll to use it.

Over the past several years, various methodologies were suggested and implemented to evaluate the effectiveness of existing managed lanes. Many studies have focused on evaluating the effectiveness of HOV lanes which are the most common form of managed lanes. Although to date, a standardized procedure to evaluate the effectiveness of managed lane strategies does not exist, key factors taken into consideration in studies include measures of effectiveness (MOEs), level of service (LOS) determination and comparison of managed lanes with the concurrent general purpose lanes. The various common factors taken into consideration during an evaluation of HOV lanes are effectiveness, safety, behavior of the public, compliance rates and enforcement, and environmental issues.

1.2. Managed Lanes in Memphis

HOV lanes in Memphis, TN on I-40 exist from Sycamore View (LM 15.0/16.0 WB) to US 64 (LM 22.0). The HOV lane is the first lane from the left side of the freeway with continuous access and is operational during the periods 7 a.m. to 9 a.m. westbound and 4 p.m. to 6 p.m. eastbound (TDOT, 2011). This is a concurrent type of HOV lane with two HOV lanes in operation and was opened on 5/23/2002. The type of separation is by painted stripes and the facility has intermediate access. The facility consists of 8.7 route miles. It has no toll and motorcycle and taxi eligibility are denied during operating hours. The passenger eligibility for vehicles is 2+ and the violation fine is 50 $ (HOV Facility Inventory, 2011). A study of the HOV lanes on I-40 across Tennessee was conducted by the Tennessee DOT (TDOT) in 2008. The report concluded that the HOV lanes were providing effective level of service but identified the compliance rate as a critical issue. The compliance rate observed during the study ranged from 38 to 53 percent, making I-40 one of top 100 critical projects in terms of violations in the country (TDOT, 2008). To date, no study has been conducted in terms of measuring effectiveness specifically for the section of HOV lanes on I-40 in Memphis, TN. Figure 1 shows the stretch of HOV lane along I-40 in Memphis, TN.

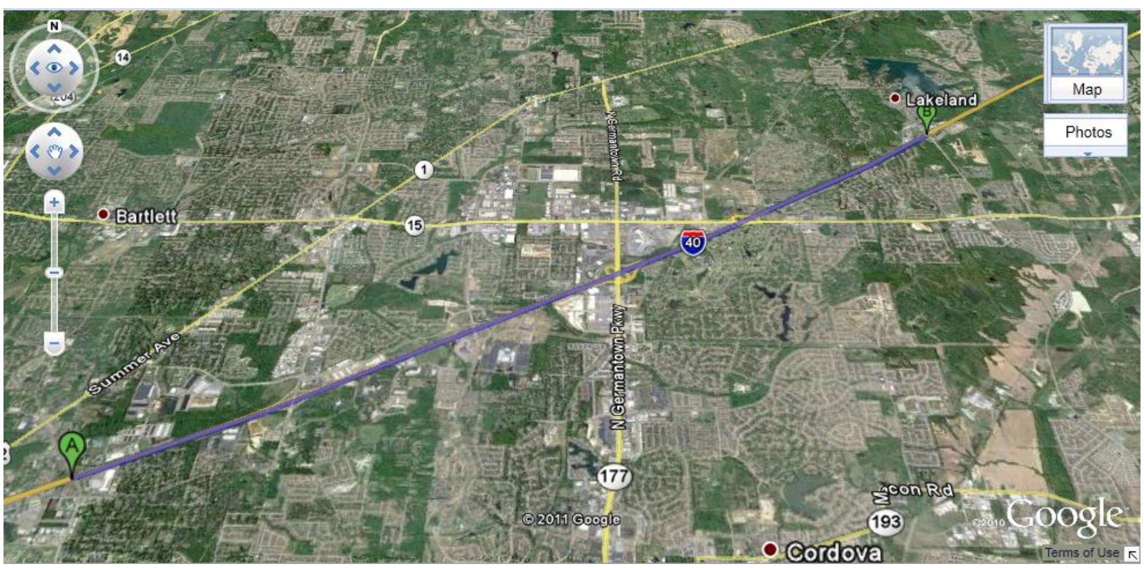

Figure 1. HOV lane on I-40 Memphis, TN. (Image courtesy Google Earth)

1.3. Research Objectives

The primary objective of this research is to conduct a preliminary evaluation of the effectiveness of HOV lanes on I-40 in Memphis, TN and to identify strategies that might be used to improve the effectiveness. Specifically, this research examines the following factors for the selected HOV lanes:

- Person throughput
- Violation Rate
- Travel time savings
- Travel time reliability
- Environmental benefits

The research has been conducted using both existing, ongoing data collection efforts as well as new data collection using new consumer technology, such as smart phone applications, to minimize the resources required for evaluation. A video recording technique is used to collect data to estimate HOV lane utilization to conduct a person throughput analysis and a smart phone application is used to conduct a travel time analysis. These methods are discussed in detail in Section 3 - Methodology

The remainder of this document is organized as follows:

- Section 2 - Literature review on managed lanes.
- Section 3- Data and Methodology used for this study.
- Section 4- Results of the analysis of the effectiveness of HOV lanes in Memphis.
- Section 5- Discussion of results and conclusions.
- Section 6 - Recommendations for improvements.
- Section 7- Limitations of the Study and future research.

It is anticipated that the results of this study will be useful to TDOT in the evaluation of the managed lane system in Memphis by incorporating speed data in addition to other parameters and will help identify whether or not consideration of alternative strategies is necessary.

2. Literature Review

2.1. Managed Lanes

According to the FHWA's "Managed Lanes Primer" over the last 20 years the total number of vehicle miles traveled in the United States has increased to more than 70 percent while the highway capacity has only been expanded by 0.3% (FHWA, August, 2008). The reason for this large variation is due to limited land space and funding. This calls for better management of existing facilities to enhance the capacity of roads for the increasing vehicular volumes. The phenomenon of introducing a set of lanes within a roadway which possess a certain set of operational characteristics assigned to them proactively to improve the operation of the facility is known as managed lanes. Managed lanes can be differentiated from the general purpose lanes by their operational characteristics. Some of the benefits of introducing managed lanes are increasing the capacity of a facility with minimal expansion to reduce congestion, improve safety and environmental aspects. The Managed Lanes Primer classifies the management applications into: pricing (toll lanes etc.), vehicle eligibility (2+ drivers or 3+ drivers only on the lane), and access control (limitation of access) (FHWA, August, 2008). These applications can be combined into different combinations and can be implemented to better manage the operation of the facility. The literature review for this study will be concentrated mainly on HOV lanes and HOT lanes. HOV/HOT lanes are most effective in reducing congestion. This is important, as the Texas Transportation Institute reports that about one third of the total vehicular miles travelled occur during congested conditions (Kockelman, 2009).

The managed lanes strategies of interest in this study are categorized as:

- HOV lanes (vehicle eligibility + access control).
- HOT lanes (Pricing + vehicle eligibility).

2.2. High Occupancy Vehicle Lanes (HOV)

According to the Tennessee Department of Transportation, a successful HOV lane can be defined as "a lane that carries at least the same number of persons in fewer vehicles than the adjacent non-HOV lanes, based on the purpose of an HOV lane to encourage ridesharing and the use of mass transit" (TDOT, 2008).

HOV lanes were first implemented in the late 1960s, but they got a major jumpstart only in the mid-1980s. HOV lanes are a strategy implemented mainly to reduce traffic congestion. Traffic congestion is reduced by restricting the usage of the lane to multi occupant vehicles, which encourages travelers to carpool, thereby reducing the number of vehicles travelling on a facility at a particular time. HOV lanes can move a greater number of people than a general traffic lane, and encourage carpooling and transit use, by providing travel time savings and a more reliable trip time. HOV lanes help to manage congestion and vehicle emissions, and optimize the capacity of highway infrastructure (Kuhn et al., 2005). Over the years many have debated the effectiveness of HOV lanes and the benefits they offer to a facility. This is mainly due to no standardization of the methods used in evaluating the effectiveness of HOV lanes. Various researchers have evaluated HOV lanes in various locations but each one used different methods in evaluating these managed lanes. It seems logical that HOV lanes would provide benefits but the methodologies used to evaluate HOV lanes and the lack of robustness in the data makes it difficult to state this conclusively.

2.3. Types of HOV lanes

The concept of HOV lanes may be applied on both freeways and general arterials. HOV lanes on freeways are the most common and they can be generally classified into three types according to their separation from general purpose lanes:

- Separate HOV lanes.
- Concurrent flow lanes.
- Contra flow lanes.

2.3.1. Separate HOV lanes: Separated HOV lane facilities are an additional segment of the road on a freeway which is separated from the general purpose lanes of the freeway. The separation of these lanes is either by a concrete barrier or a wide painted buffer (Kuhn et al., 2005). Separate HOV lanes are generally one of two types:

- *Two way separated HOV lanes:* In a two-way type separated HOV lane, traffic flow is in both the directions and generally one lane each is allotted. It often has limited access, and may have its own entrance and exit treatments (Carson, 2005).
- *Reversible HOV lanes:* This type of separated HOV lane consists of one or more lanes separated from the general freeway and the direction of the traffic is singular. The direction of the traffic is reversed according to the peak hours. The direction is generally incoming in the mornings and outgoing in the evenings. This is done to improve the efficiency of the HOV facility by allowing the maximum usage during peak hours (Carson, 2005).

2.3.2. Concurrent Flow HOV Lanes: Concurrent flow lanes are an additional lane on a freeway and the direction of the traffic in this lane is in the direction of the general purpose lanes. It is separated from the general purpose lanes by a painted symbol on the surface of the road or a buffer. The symbols are generally painted in diamond shapes and these kinds of lanes are also called diamond lanes and they are the most commonly used. The buffers are marked with painted stripes (Carson, 2005).

2.3.3. Contra Flow Lanes: The concept of contra flow HOV lanes is to convert the direction of an off peak freeway lane into the direction of the peak period freeway lanes. In most cases the inner most lane of the off peak direction is made into a contra flow HOV lane and it is separated from traffic by moveable barriers (Kuhn et al., 2005). A general purpose lane in the off peak hours which is used as an HOV lane in the opposite direction is called a contra flow HOV lane (Carson, 2005).

2.4. Benefits of HOV lanes

The benefits of HOV lanes are outlined below: (NCDOT, 2011)

- Improve travel speeds and reduce trip travel time: An HOV lane is designed to move more people, more quickly than a general purpose (GP) highway lane. While commuters in a general purpose lane (GP) can get stuck in slow-moving peak-hour traffic, an HOV lane user can drive at much faster speeds.
- Travel Time Reliability: Another key benefit of HOV lanes are that they provide more reliable travel times than a general purpose (GP) lane.
- Economic Benefits: Carpooling and ridesharing help in reducing the burden of fuel costs and vehicle maintenance.
- Environmental Benefits: An HOV lane carries a greater number of people in a lesser number of cars with vehicles moving in more constant speeds, which helps reduce the amount of carbon emissions. In a GP lane there is more chance of

acceleration and deceleration which tends to increase the amount of carbon emissions.

- Reduction of the wear and tear of a vehicle: Due to carpooling and ridesharing the number of trips made by a vehicle in a certain period of time is reduced, which helps the vehicle to last longer.

2.5. Inventory of HOV lanes

An inventory of existing and Future HOV Lane facilities as of March 2007 has been compiled on the website of the US Department of Transportation Federal Highway Administration "HOV Clearinghouse" (HOV Facility Inventory, 2011). The operational characteristics of highway and arterial HOV lane facilities in the US and Canada is listed on this website and they are categorized according to:

- State/Province (Name of the State where the HOV is located)
- City/County (Name of the County where the HOV is located)
- Urban Area (Name of the area where the HOV is located)
- Road (Name of the road where the HOV lane is located)
- Segment(From-To) (the start and end point of the HOV lane)
- Type (the type of HOV lane it is)
- Separation (the separation method of the HOV lane from the GP lanes)
- Access (type of access i.e. whether it has continuous access or limited access)
- Date Opened (the date the HOV lane was opened to traffic)
- Status (the current status of the HOV lane i.e. whether it is in operation, planning, construction etc.)

- Number of HOV and GP lanes (the number of HOV lanes and GP lanes on the facility)
- Lane length (the length of the HOV lane)
- Eligibility according to number of passengers (with and without toll)
- Eligibility according to type of vehicle and its fuel consumption characteristics (Hybrid etc.)
- Hours of Operations
- Changes made since they opened
- Peak hour details
- Peak hour travel time savings
- Agencies responsible
- Website source for this data and the contact person information

The categories are extensive and make this database quite a comprehensive one (HOV Facility Inventory, 2011).

There are 345 facilities with HOV lanes in total in the United States. The top five states with the most HOV lane facilities are California with 88, Minnesota with 83, State of Washington with 41, Texas with 35 and Virginia with 21. The twin cities of Minneapolis and Saint Paul have 83 HOV lanes in total, making it the most in a region. It is followed by San Francisco with 47, Seattle and Tacoma with 40, Los Angeles with 23 and Houston with 21. The agencies responsible for the HOV lanes in all the states are the state DOTs. The first HOV lanes in the country were the ones on the I-395 in Virginia connecting Washington D.C and Beltway. Many more facilities have been opened following the success in Virginia. Out of the 345 facilities, 301 are in operation, 10 are in their planning stages, 15 are in the design review, 14 are in construction, and 5 are not active (FHWA, 2008).

According to the FHWA, six common objectives have been listed for installation of HOV lanes: (FHWA, 2008)

1. To maximize the throughput of persons.
2. To reduce congestion.
3. To increase travel time savings.
4. To encourage people to car pool.
5. To reduce air pollution.
6. To increase use of public transit.

In general, the number of HOV lanes being installed throughout the US is increasing, which indicates that this concept has been widely accepted to address the six objectives stated above. However, the implementation of HOV lanes is not suitable in all situations. Before installing such a facility, thorough evaluation must be done on the road network and its requirements. Elements such as effect on general purpose (GP) lanes if the HOV facility is installed, the cost of installation and the environmental aspects must be considered (Kuhn et al., 2005).

2.5.1. HOV lanes in the State of Tennessee: For this project, only the facilities within Tennessee will be discussed in detail. The state of Tennessee has ten HOV lane facilities with four of them being located in Memphis, Shelby County and six in Nashville. Some of these facilities are either under construction or in the design stages. All the existing and planned HOV lane facilities in the state are highway facilities. The list of existing and planned HOV lane facilities in Tennessee are described below: (HOV Facility Inventory, 2011) (Smart Commute Tennessee, 2009)

- US 64 to Sycamore View Rd, I-40, Memphis, Shelby County, Tennessee: This is a concurrent type of HOV lane with two HOV lanes in operation and was opened on 5/23/2002. The type of separation is by painted stripes and the facility has intermediate access. The facility consists of 8.7 route miles. It is operated from 7 a.m. to 9 a.m. in the mornings and 4 p.m. to 6p.m. in the evenings. It has no toll and motorcycle and taxi eligibility are denied during operating hours. The passenger eligibility for vehicles is 2+ and the violation fine is $50.
- Collierville-Arlington Rd to US 64, I-40, Memphis, Shelby County, Tennessee: This is proposed to be a concurrent type of HOV lane with two HOV lanes in operation and it is still in the design stages of the project. The type of separation will be painted stripes and the facility will have intermediate access. It consists of 8 route miles. Motorcycle and taxi eligibility will be denied during operating hours.
- Mississippi State line to Winchester Rd, I-55, Memphis, Shelby County, Tennessee: This project is under construction. This will be a concurrent type of HOV lane with two HOV lanes in operation. The type of separation will be painted stripes and it will have intermediate access. The facility consists of 3.8 route miles. Motorcycle and taxi eligibility will be denied during operating hours.
- Winchester Rd to I-240, I-55, Memphis, Shelby County, Tennessee: This is a concurrent type of HOV lane with two HOV lanes in operation and was opened in July, 2007. The type of separation is by painted stripes and it has intermediate

access. The facility consists of 2.1 route miles. Motorcycle and taxi eligibility are denied during operating hours. The passenger eligibility for vehicles is 2+.

- Briley Parkway to Donelson Pike, I-40, Nashville, Tennessee: This project is under construction. This will be a concurrent type of HOV lane with two HOV lanes in operation. The type of separation will be painted stripes and it will have intermediate access. Its operating hours will be from 7 a.m. to 9 a.m. in the mornings and 4 p.m. to 6 p.m. in the evenings. Motorcycle and taxi eligibility will be denied during operating hours.
- SR-840 to Harding Place, I-24, Nashville, Tennessee: This is a concurrent type of HOV lane with two HOV lanes in operation and was opened in May, 1999. The type of separation is by painted stripes and it has intermediate access. Its operating hours are from 7 a.m. to 9 a.m. in the mornings and 4 p.m. to 6p.m. in the evenings. Motorcycle and taxi eligibility is denied during operating hours. The violation penalty is $50.
- Old Hickory Blvd to Mt. Juliet Rd, I-40, Nashville, Tennessee: This is a concurrent type of HOV lane with two HOV lanes in operation that was opened in 1996. The route mileage for this section is 8 miles and the type of separation is by painted stripes and it has intermediate access. Its operating hours are from 7 a.m. to 9 a.m. in the mornings and 4 p.m. to 6p.m. in the evenings. Motorcycle and taxi eligibility are denied during operating hours. The violation penalty is $50.
- Donelson Pike to Old Hickory Blvd, I-40, Nashville, Tennessee: This is a concurrent type of HOV lane with two HOV lanes in operation that was opened on 5/4/2002. The type of separation is by painted stripes and the facility has

intermediate access. Its operating hours are from 7 a.m. to 9 a.m. in the mornings and 4 p.m. to 6 p.m. in the evenings. Motorcycle and taxi eligibility are denied during operating hours. The violation penalty is $50.

- SR-96 to Amory Drive, I-65, Nashville, Tennessee: This is a concurrent type of HOV lane with two HOV lanes in operation. The route mileage for this section is 15 miles and the type of separation is by painted stripes with intermediate access. Its operating hours are from 7 a.m. to 9 a.m. in the mornings and 4 p.m. to 6 p.m. in the evenings. Motorcycle and taxi eligibility are denied during operating hours. The violation penalty is $50.
- SR-840 to SR-96, I-65, Nashville, Tennessee: This is proposed to be a concurrent type of HOV lane with two HOV lanes in operation and it is still in the design stage of the project. The type of separation will be painted stripes and it will have intermediate access. There are 9.7 route miles on the facility. Motorcycle and taxi eligibility will be denied during operating hours.

The state of Tennessee has introduced a law to allow single occupant hybrid vehicles to travel on HOV lanes. This law states "Vehicles that are considered inherently Low Emission Vehicles and have a gross vehicle weight rating of 26,000 pounds or less are permitted in High Occupancy Vehicle lanes regardless of the number of passengers in the vehicle. Such vehicles must be identified by a decal provided by the Tennessee Department of Revenue (55-8-188(B) (2) (a))." (Smart Commute Tennessee, 2009) All hybrid vehicles using an HOV lane must possess the "HOV Lane Smart Pass" which is issued by the Department of Revenue (Smart Pass Program) which allows hybrid vehicles to move on HOV lanes regardless of the number of passengers (HOV Smart Pass, 2009).

Vehicles eligible for the “HOV Lane Smart Pass” must complete an application (available online at www.tennessee.gov/revenue) and submit it to the Tennessee Department of Revenue (HOV Smart Pass, 2009). The benefit of this program is that it is expected to encourage purchase of Hybrid vehicles, which will in turn improve the economy (decreased fuel consumption) and environment (decreased emissions) (EPA, 2007).

2.6. Critical Issues related to HOV lanes

The installation of HOV lanes comes with various issues. Some of the key critical issues identified in this research are:

- Planning and Design Issues: Before installing an HOV lane on a road network, sufficient amount of study must be conducted to define the goals and objectives of the project. Elements such as user specification and passenger eligibility must be considered as the design elements depend on these (Carson, 2005; Kuhn et al., 2005).
- Issues with Legislation: The local, state and federal agencies involved in the operation of HOV lanes must have the suitable laws and policies dealing with the facility’s operation. These agencies must make sure that the laws and regulations put forth must be flexible for change in the future and a specific structure must be in place (Carson, 2005; Kuhn et al., 2005).
- Acceptance of the Public: It is very important that the idea of HOV lanes in a particular area must be commonly accepted by the general public of that area. There must be various programs in place to educate the public about the

advantages of HOV lanes and gain their involvement by asking them to respect the laws and regulations related to the facility (Carson, 2005; Kuhn et al., 2005).

- Safety Issues: Due to the merging and weaving involved in HOV lanes, appropriate safety measures such as marking and signage, shoulder width, highway patrolling etc. must be properly implemented (Carson, 2005; Kuhn et al., 2005).
- HOV Lane Enforcement Issues: According to research conducted on HOV lane enforcement issues by the Arizona Department of Transportation (Markkula, 2004), it was found that the major issues for enforcement on HOV lanes is that no automated technology exists which can detect violation by counting the number of people who are inside vehicles (due to the frequent heavy tinting of the glass windows of cars). For proper patrolling on highways, extensive space is required on the median which is not always possible due to area restrictions. With the present setup of HOV lanes, located at the innermost lane on the freeway on the left, it is not appropriate for officers to pull over violators to the right. The study suggests a few recommendations which would help counter such issues. Highways could be designed in such a way that it provides sheltered areas which can allow better vigilance. Restrictions can be enforced on the window tinting of vehicles, and posting signs along the side of highways which state the fine for violation could alert the drivers of penalties. Periodical special enforcement followed up with routine regular enforcement would reduce violators. HOT lanes could be considered instead of HOV lanes, which charge non eligible drivers a toll to use the facility. There is a need for new feasible technology to monitor

violation on these facilities. Establishing enforcement areas near on and off ramps and consideration of hotlines for citizens to report violations on the facilities are also suggested to improve compliance rates (Carson, 2005; Kuhn et al., 2005; Markkula, 2004).

2.7. High Occupancy Toll Lanes

To improve the utilization of an HOV lane, it can be converted into a High Occupancy Toll (HOT) lane. HOV lanes converted to HOT are usually concurrent HOV lanes operating with GP lanes (Liu, Zhang, Wu, & Wang, 2009). High Occupancy Toll Lanes can be defined as HOV lanes which allow vehicles which do not comply with the occupancy requirement to use it by paying a toll. Generally, single occupant vehicles are allowed onto an HOV lane by paying a toll. In some cases they are called value-priced lanes and the price of the toll changes regularly according to the congestion levels of the lane (Kuhn et al., 2005).

HOT lanes are usually considered to improve the lane utilization of HOV lanes. The price of the toll is made to fluctuate to manage the lane and avoid unused capacity conditions and congestion. Previous research and experience shows benefits of HOT lanes for drivers who use general purpose lanes. Drivers are willing to pay a toll to reach their destination faster (EPA, 2007).

The concept of using fluctuating pricing to manage congestion and speed is known as “Active Traffic Management” (ATM). This strategy is based on real time traffic conditions and it is modeled in such a way that during high volumes the price of the toll goes up. This is due to the assumption made, i.e., “single occupant vehicles are discouraged from using HOT lanes when the volumes are high on this lane” (Goodall &

Smith, 2009). Although this technique of managing lanes is fast emerging and is politically well supported, little research exists on ATM and the actual driver/lane behavior (Goodall & Smith, 2009). HOT lanes have initially been opened only in 6 states throughout the country and they are California, Texas, Washington, Minnesota, Colorado, and Florida.

2.8. Previous Research

A high occupancy vehicle (HOV) lane is a remedy designed to reduce traffic congestion and address lack of freeway construction space. HOV lanes are implemented for the main purpose of encouraging carpooling and increasing travel time reliability and passenger throughput (Vehicles with two or more occupants only can access these lanes). This section reviews the previous research conducted on the evaluation of HOV lanes over the past 20 years which are most relevant to the current study.

In 1991, Turnbull, Henk, and Christiansen presented a report on “Suggested Procedures for Evaluating the Effectiveness of Freeway HOV Facilities”. As the title suggests, this report presents suggested methods for evaluating HOV lane facilities. This was done by identifying and developing appropriate “objectives, measures of effectiveness, performance thresholds and data collection techniques” (Turnbull et al., 1991) in Houston as the base. The objectives identified in the study were straightforward and effective and included increase in vehicle occupancy, travel time savings, environmental benefits, lane efficiencies, safety and cost effectiveness.

The report also reviewed all the evaluation strategies conducted in various parts of the US during that time and identified the most common goals and objectives to be increasing number of persons per vehicle, increasing operational efficiency of bus services, providing travel time savings and reliability, providing environmental benefits, increasing cost effectiveness of transportation and gaining public support. The main measure of effectiveness (MOE) for the HOV lane to be effective was defined as actual and percentages of average vehicle occupancy (AVO), improved travel time and reduction in fuel consumption. The general threshold value range for travel time savings was identified as 5-7minutes improvement in travel time between HOV and GP lane. There were no specific levels listed for the other MOE's and it was suggested that the ranges would be set according to the individual projects. It was noted that violation rates indicate the level of acceptance of the HOV lane by the public (Turnbull et al., 1991).

An extension to the above framework presented by Turnbull et al., 1991 was done in the year 1999 which was titled "High-Occupancy Vehicle Monitoring and Evaluation Framework". In this report, an evaluation framework for HOV lanes is presented. The objectives in this framework were categorized into primary, supporting and operational groups. The primary objective of this evaluation of HOV lanes was defined as person throughput and its measures of effectiveness (MOE) were listed as per lane efficiency and average vehicle occupancy. The supporting objectives were defined as travel time savings, travel time reliability and public support and their MOE's were listed as difference in travel times (HOV vs. GP lanes), standard deviation of the travel speeds and support for HOV lanes through public surveys, respectively. The operational objectives were defined as compliance and safety and the MOE's were listed as compliance rate and crash rate, respectively.

The framework was applied to evaluate the effectiveness of the HOV facility on the Barnet/Hastings corridor in Houston through a before and after study. The corridor included 6.21 miles of HOV lane and 4.97 miles of GP lanes. The results showed that the AVO improved from 1.32 to 1.35 in the eastbound direction and 1.25 to 1.28 in the westbound direction (note that the average vehicle occupancy figure is inclusive of all lanes, which is the reason for the AVO being less than 2). The travel time difference was 2.8 minutes in the eastbound and 8.1 minutes in the westbound direction. The standard deviation of travel time on the HOV lane was 3.9 in the eastbound direction and 3.0 in the westbound direction, as compared to a standard deviation of 5.1 and 5.2 in the eastbound and westbound directions respectively for the GP lane. The compliance rate for the HOV lane was noted to be 85 and 80% and the speed improvements were 6.84 mph and 3.72 mph in the eastbound and westbound directions, respectively. From these results it was concluded that the HOV lane showed benefits (Bracewell, Sayed, & Shalaby, 1999).

A report conducted by Martin, Perrin, Wu, and Lambert in 2002 evaluated 16 miles of HOV lanes opened on I-15 in Salt Lake Valley. The MOE's used to determine the effectiveness of the HOV lanes were person throughput, travel time savings, travel time reliability and violation rates. Data such as volume counts per lane, travel time and speed; and violations on the segment were collected manually during operation. It was concluded that the HOV lanes considered in the study were successful in their operation and recommendations were made to improve their performance. Findings in the report were that the HOV lanes carried the same amounts of person volumes and 44% of vehicular volumes when compared with GP lanes during peak periods. Travel time savings were evident on HOV lanes throughout the day as the speed of travel was higher on HOV lanes. Violation rates varied during peak periods. They were in the range of 5-13 percent along the study segment of I-15. In general, afternoon peak period violation rates were higher than the morning peak periods. Average vehicle occupancy increased 17 percent from 1.1 to 1.3 (persons/vehicle) (Martin et al., 2002).

In 2005, Carson developed a report titled "Evaluating Managed Lanes" which documented the most common and best objectives, performance measures, data collection requirements and evaluation methodologies suggested over the years in various studies on managed lane facilities. The goals/objectives suggested in this report were categorized as providing mobility (increasing person throughput, reducing average travel times, increasing speeds, decreasing violators), reliability (travel time reliability), safety (reduction in incidents and in incident severity), and environmental effects (decreased fuel consumption and improved air quality) during congestion. The threshold values suggested in this report are developed based upon all of the previous evaluations conducted in the country which were reviewed, so the threshold values listed here are those which are most relevant to the current research. The report suggested a range of 870 to 1,274 vehicles per hour per lane for p.m. peak hour volume, an AVO range of 2.63 to 3.35 vehicles on an HOV lane, a compliance rate of 80-95%, a standard deviation for travel time of 3 to 3.9 on HOV and 5.1 to 5.2 on GP lanes (note the standard deviation difference between HOV and GP suggests better travel time reliability on the HOV lane), and a travel time saving of greater that 5-7minutes or a minimum of 1 minute savings per mile of HOV lane. (Carson, 2005).

Bauer, Cameron , Bumker, and Wikman in 2005 developed a qualitative and quantitative framework for evaluating HOV lanes in Australia. They considered similar measures of effectiveness (MOE's) such as person moving efficiency, travel time savings, travel time reliability, transit efficiency, violations, and environmental effects. The case study included 2 segments of roads, one in Brisbane (separated HOV lane which is approximately 8 kilometers long operating from 7 to 9 a.m. and 4 to 6 p.m.) and the other in Queensland (Concurrent flow lane which is 1.9 kilometers operating during 7 a.m. to 9 a.m.), Australia. The measures of effectiveness included AVO, Travel time difference and travel time reliability by comparing standard deviations.

The results showed that there were varied benefits in travel time savings, reliability and AVO. The segment observed in Brisbane showed variable travel speed on the HOV lane. It showed a standard deviation of 3.4 on the HOV lane and 3.3 on the GP lane respectively, the AVO on the HOV lane was 2.89 and the AVO on the GP lane was 1.92 which implied that the HOV lane increase person throughput and the travel time difference (HOV – GP lane travel time) was -5.39 minutes. The second segment studied showed better results as the travel time saving was 6 minutes and the AVO on the HOV lane was 5.37 and the AVO on the GP lanes was observed to be 1.89. The travel time reliability on this segment was slightly better (The standard deviation of travel speeds on the HOV lane was 2.5 and the standard deviation of travel times on the GP lane was 2.7). Hence it was concluded that the results in both cases showed positive achievements in AVO and travel time savings, but the variable travel speeds on the HOV were a concern to be addressed. The study further concluded that a more comprehensive framework must be developed using this study as a base (Bauer et al., 2005).

In 2007 Kwon and Varaiya presented a study of the 1171 mile High Occupancy Vehicle (HOV) system in California using peak hour traffic data from 700+ loop detector stations over the months of January to June 2005. The findings were as follows: The

HOV lane system was found to be under-utilized; the speeds in the HOV lanes were less than 45 mph for 10% of the weekdays (18% in A.M. peak hours and 32% in P.M. peak hours.) Travel time savings were reliable but did not provide a statistical significance for carpooling encouragement and the HOV lanes reduced congestion slightly when the GP lanes were congested. Overall it was concluded that the HOV lanes were not effectively operating, but the authors suggested that with better management strategies the actual goals of the HOV lanes could be met (Kwon & Varaiya, 2007).

In 2011 a report was submitted by Chien, Mouskos, Boile, Kim, and Golias to the FHWA which conducted a comprehensive study on the travel time variability on various segments on the following highways: "Routes US 1, NJ 3, NJ 4, US 9, NJ 17, US 22, NJ 24, NJ 42, US 46, NJ 70, NJ 73, NJ 29, I-76, I-78, I-80, NJ 208, I-280, and I-287". The travel times on each segment were collected using GPS technology during the time period of October 8, 2007 and April 21, 2008 from 6:15 to 8:15 a.m. on weekdays. To check for travel time variability the measure of effectiveness used was a buffer index. The concept of buffer index was defined as the ratio between 95 percentile of travel times and mean (μ) for the travel times collected on each of the segments. If (95 percentile/μ) was observed to be closer to 100% then it was concluded that the segment had low travel time variability (Chien et al., June 2011). The concept of buffer index is used in this study to check travel time reliability.

2.9. Motivation for Current Research

Previous research has shown that HOV type managed lane strategies do not improve congestion problems in all cases. In 2008, TDOT conducted an I-40/I-81 Corridor Feasibility Study based on data collected in 2005. This study concluded that the

HOV lanes seemed to provide an adequate level of service, however the study also found that for some sections meaningful time savings were not occurring. The study indicated that the lack of speed data made this observation difficult to confirm with certainty. It also reported that the compliance rate in Nashville and Memphis regions were noted to be ranging from 38-52%, placing these projects among the 10 most serious for enforcement breaches from more than 120 projects across the country (TDOT, 2008).

Although this TDOT study concluded that HOV lanes provided an adequate level of service statewide, no specific study has been conducted to evaluate the effectiveness of the HOV lanes on I-40 in Memphis. In addition, as the compliance rate for the Memphis region was mentioned to be problematic in the TDOT study, a site specific study would be able to quantify this issue more accurately. Thus, in this research a preliminary analysis for the evaluation of HOV lanes eastbound on I-40 Memphis, TN was conducted to serve the following purposes: to measure the HOV lane effectiveness and to check if the main objectives of HOV lanes (i.e., increasing person throughput, travel time savings, travel time reliability and compliance rate) are met. It is expected that this research will help TDOT in the evaluation of the managed lane system in Memphis by incorporating speed data in addition to other parameters and will help identify whether or not consideration of alternative strategies or increased enforcement is necessary.

3. Data and Methodology

3.1. Introduction

An evaluation of HOV lanes in Memphis, TN was conducted to serve the following purposes: to measure the HOV lane effectiveness and to determine if the main objectives of HOV lanes (i.e., increasing person throughput, providing travel time savings and travel time reliability, and producing environmental benefits) are met. The analysis for this research consists of three parts:

- Person Throughput Analysis: PM peak traffic volumes were collected at a selected site on I-40 eastbound for each lane by using both manual and video data collection techniques for estimating the percentage lane utilization, person throughput and violation rate on the HOV lane on I-40 in Memphis, TN. These values were compared with the threshold values suggested by Carson in 2005.
- Travel Time Analysis: Travel times and travel speeds on both the HOV and GP lanes for a segment of I-40 were collected using a GPS tracking smartphone application. Results were analyzed for travel time savings and travel time reliability and then compared to threshold values suggested by Carson in 2005.
- Environmental Benefit Analysis: The average carbon footprints for a trip on the HOV lane versus other GP lanes were collected using the Garmin Nuvi GPS, which provides fuel reports to check for significant environmental benefits provided by the HOV lane.

Each of the above analyses, along with the selected study site, are described in detail in the following sections.

3.2. Time period selection (AM vs. PM and Seasonal Variation)

For this study, data was provided by TDOT from the Intelligent Transport Systems (ITS) radar stations for the time period of February - August 2010. The data included hourly volumes, directional hourly volumes and 15-minute volumes for every ITS station. An analysis of the TDOT ITS data showed that:

- The total Average Daily Traffic (ADT) for summer is higher than the ADT for the spring season during weekdays.
- Average daily traffic for the A.M. periods was observed to be lower during the summer when compared to that of the spring season.
- Average daily traffic for P.M. periods was observed to be higher during the summer when compared to that of the spring season.
- For every month observed, the A.M. peak traffic was lower than the P.M. peak traffic.

An analysis of the 2010 data showed that the p.m. peak (4pm-6pm) on eastbound I-40 in Memphis was the most congested time and direction for the corridor selected for the study. The eastbound direction serves as the major route for workers leaving the downtown Memphis area and traveling to residential areas (primarily located east of the CBD). Thus, data for the current study was collected during the months of June and July 2011 during the pm peak period to evaluate the corridor under the most congested conditions. Details of this analysis can be found in Appendix A.

3.3. Description of Study Site

This study was conducted for the section of I-40 in Memphis between exit 12 and exit 16 for the eastbound lanes during the pm peak hours (4 p.m. to 6 p.m.). This segment of I-40 consists of a single HOV lane and three general purpose lanes in both the eastbound and westbound directions.

Figure 2 shows the location of the corridor under study, although for each of the three analyses in the study, the specific location varied within this corridor based upon data collection needs.

3.4. Person Throughput Analysis

3.4.1. Objective: The main objective of the person throughput analysis was to collect volume, average vehicle occupancy and violation rates on the HOV lane during the P.M. peak along the study corridor and compare these with the threshold values suggested by Carson in 2005.

3.4.2. Data Collection: For person throughput analysis, the study area selected is along I-40 Memphis eastbound from 4 p.m. to 6 p.m. near the Appling road exit. This location was selected because an overpass bridge was located at this exit on which a researcher stood to collect traffic volume (using video camera) and violation rate data on HOV lane. Both vehicle volumes and occupancy data are required for person throughput analysis. The vehicle occupancy data was collected manually by researchers standing on the sidewalk of the overpass bridge at the Appling road exit. In addition, a video camera was set up to record the traffic on I-40 Memphis east bound in the same location in order to obtain vehicle volume data. The data was collected on six days between July 13 and July 21, 2011. Data was only collected on Tuesdays, Wednesdays, or Thursdays, and holidays and days with adverse weather were avoided so that data representative of a typical travel day could be obtained. Figure 3 shows the location of the Appling Road exit along the study corridor and the arrow shows the location the

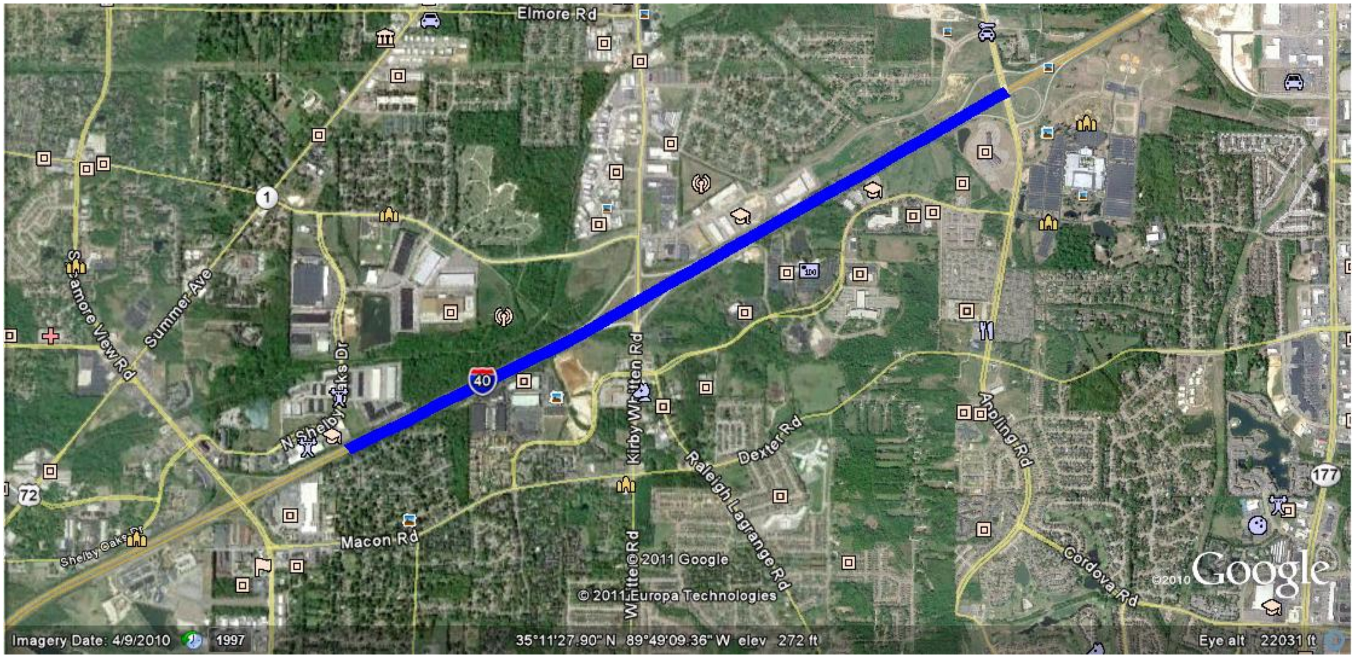

Figure 2. Corridor under study

video camera was set up to collect data.

Figure 3. Location of the Appling Road Exit overpass bridge

3.4.3. Methodology

Average Hourly Volume: The average 15-minute interval volumes were counted by reviewing the video from the camera which was set up on the overpass bridge at exit 15 b. This allowed the peak hour within the 4 p.m. to 6 p.m. time period to be identified and the peak hourly volume to be calculated. The peak hour volumes for each lane on the study segment were estimated by identifying the peak hour from all the 15-minute intervals.

Average Vehicle Occupancy and Violation Rate: The average vehicle occupancy and violation rates were estimated from the data collected manually by the observer standing on the overpass at exit 15 b. The average vehicle occupancy was calculated by assuming that all 2+ passenger vehicles had two passengers only, as it was not possible to determine whether or not additional passengers were present through manual observations. The average vehicle occupancy and violation rate were calculated using the data for vehicles travelling on the HOV lane and the total number of vehicles (TV), the number of single passenger vehicles (SPV) and the number of 2+ passenger vehicles (2PV) on the HOV lane. From these data, the average vehicle occupancy was calculated as shown in equation 1, and the violation rate was calculated as shown in equation 2.

$$\{[2 * (2PV) + (SPV)]\}/\ (TV) \quad (1)$$

$$(SPV)/TV) * 100 \quad (2)$$

The values calculated for the study period were compared with the threshold values suggested by Carson in 2005.

3.5. Travel Time Analysis

3.5.1. Objective: The travel time savings and travel time reliability of HOV lanes are additional measures used to assess effectiveness (FHWA, 2008). The following methodology was followed to check the HOV lane’s effectiveness in these areas.

3.5.2. Data Collection: For travel time analysis, data was collected by making simultaneous trips on I-40 Memphis eastbound in 15-minute intervals from 4 p.m. to 6 p.m. with two cars, one on the HOV lane and the other on a general purpose lane for three days in June 2011 (June 14-16) and for six days in July 2011 (July 13-15 and 19-21). All study days were again Tuesdays, Wednesdays, or Thursdays, avoiding holidays and adverse weather. The starting point for the travel time analysis was exit 12 at Sycamore View Rd and the end point was at exit 15b at Appling Rd, as shown in Figure 4.

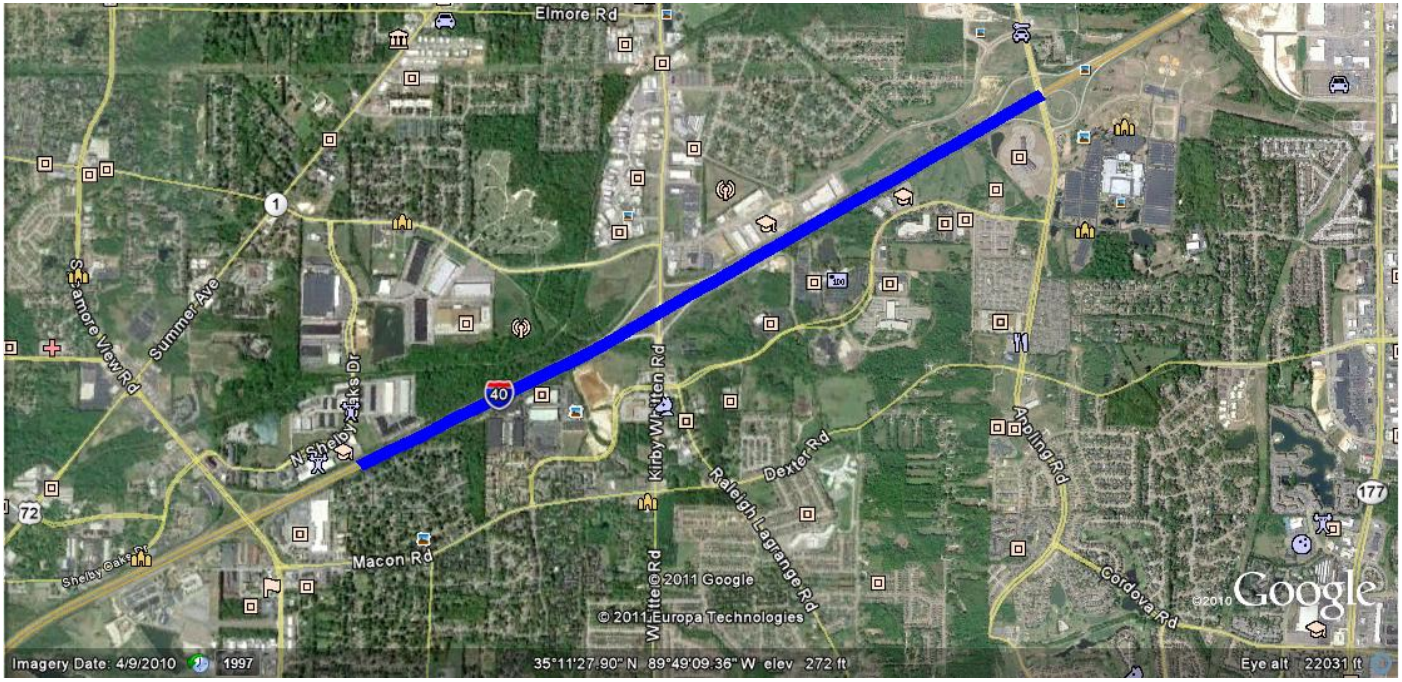

Figure 4. Trip on HOV lane (Courtesy Google Earth)

3.5.3. Methodology: The data collection process was conducted using two cars and two smart phones with the application B.icycle GPS. Each day one car traveled on the HOV lane and the other car traveled on a general purpose lane (the general purpose lanes were chosen alternately starting from the rightmost lane). A Smartphone was used in each of the cars to obtain the trip distance, travel time for the trip and average speed of the trip by using the above mentioned GPS application. The IPhone/Android GPS application which was used to collect data produced a map for each trip made. A description of the B.icycle GPS application is provided below.

B.icycle GPS Application: The B.icycle application which was used for the travel time analysis was chosen because it produced the required data including time taken to complete the trip, the trip distance, maximum speed during the trip and average speed of the trip. It is expected to give reliable information, even though originally designed as a bicycle application, because it only considered the type of vehicle (bicycle) to calculate the number of calories which are burned during the trip and this does not affect the speeds and travel times recorded. The application contains features such as a timer which works like a stopwatch, a map which shows the location of the trip and also a tab which gives the complete details of the trip.

Travel Time Savings: Travel time savings is obtained by evaluating the travel time difference between the general purpose and HOV lanes. The data collected were sorted into different data sets for travel times of the HOV lane, travel times of GP1 lane, travel time of GP 2 lane and travel time of GP 3 lane. An aggregate of all three GP lane's travel time data was compared to the travel time data of the HOV lane. A One Way Analysis of Variance (ANOVA) was used to determine whether there existed a statistical difference between the travel times on each of the GP lanes.

An ANOVA can extend the two-sample t-test for testing the equality of two population means to a more general null hypothesis of comparing the equality of more than two means, versus them not all being equal. In the case of travel times of three different lanes, the response variable is the travel time in seconds and the factor influencing the variable is the lane number.

The first step in conducting Analysis of Variance is checking if the assumptions are satisfied. The assumptions in conducting ANOVA are:

- The values in each of the groups (as a whole) follow the normal curve,
- Independence.
- Homogeneity of Variances.

After this analysis, each lane's travel time data was compared to the travel time data of the HOV lane for each day that data was collected. A normality test for each data set was conducted to check for normality. If both the data sets were shown to be normal, a 2 sample t-test was conducted to check for significant differences between the HOV and GP lanes. If the datasets were not normal, then the non-parametric Mann Whitney test was conducted to check for significant differences.

Travel Time Reliability: The standard deviation of travel times on the HOV and GP lanes were compared to determine travel time reliability (Bauer et al., 2005). If the standard deviation of the travel times on the HOV lane was significantly less when compared to other GP lanes then it was concluded that the HOV lane was effective in terms of providing travel time reliability. Also the concept of a Buffer Index was used to determine the reliability of travel times on each lane. The mean (μ_{HOV}) for the travel times on the HOV lane and the mean (μ_{GP}) for the travel times on the GP lane were considered and the 95 percentile for each of the data sets was calculated. If (95 percentile/$\mu)_{HOV}$ is observed to be greater than (95 percentile/$\mu)_{GP,}$ then it was concluded that the travel times on the HOV lane were more reliable. (Chien et al., June 2011)

3.6. Environmental Benefits Analysis

3.6.1. Objective: The other main objective of an HOV lane is to provide environmental benefits (FHWA, 2008). The following methodology was conducted to evaluate the HOV lane's environmental benefits.

3.6.2. Data Collection: For environmental benefit analysis, data was collected by making simultaneous trips on I-40 Memphis eastbound in 15-minute intervals from 4 p.m. to 6 p.m. with two cars, one on the HOV lane and the other on the general purpose lane for four days in July 2011 as shown in table 1.

Table 1. Dates of Data Collection for Environmental Benefit Analysis

Serial Number	Date
1	Thursday, July 14, 2011
2	Tuesday, July 19, 2011
3	Wednesday, July 20, 2011
4	Thursday, July 21, 2011

3.6.3. Methodology: One measure to evaluate environmental benefits is to estimate the carbon footprints (i.e. the amount of CO_2 release for each trip made on the HOV and GP lane). For this, both the test cars were equipped with a Garmin Nuvi GPS which produced mileage reports for every trip made. Simultaneous trips were made on the HOV lane and a GP lane from exit 12 to exit 15b on I-40 eastbound Memphis, TN (the same corridor used for travel time analysis). The difference between each of the lanes versus the HOV lane was checked using a non-parametric Mann Whitney test. This test was used because the data set collected was small and it did not follow a normal distribution. If there was a significant difference (benefits) between the HOV lane and the GP lanes, the HOV lane was concluded to be effective in terms of the environmental impact.

4. Data Analysis and Results

4.1. Introduction

Periodical monitoring and data analysis of the HOV system are essential for efficient operation of the system. In this chapter, we present an analysis of the data collected during this research. We examine whether the measures of effectiveness (MOE) defined earlier are met. The data analysis and results in this section will be presented in three parts:

- Person throughput analysis
- Travel time analysis
- Environmental benefits

4.2. Person Throughput Analysis

The main objective of the person throughput analysis was to collect volume, average vehicle occupancy and violation rates on the HOV lane during 4 p.m. to 6 p.m. on I-40 in Memphis, TN and compare them with the thresholds values suggested by Carson in 2005. The results obtained are compared with the threshold values suggested and they are presented below.

4.2.1. Peak Hourly Vehicle Volume on HOV lane: Tables 2 and 3 respectively show the average 15-minute volumes and hourly volumes per lane for 4-6pm for all of the days on which data for the Person Throughput Analysis was collected. The peak hour was noted to be from 4:30 p.m. to 5:30 p.m.

Table 2. Average 15-minute volumes

	15-minutes period							
Lane number	4:00-4:15 p.m.	4:15-4:30 p.m.	4:30-4:45 p.m.	4:45-5:00 p.m.	5:00-5:15 p.m.	5:15-5:30 p.m.	5:30-5:45 p.m.	5:45-6:00 p.m.
Lane 1*	223	253	301	318	351	374	285	257
Lane 2	317	354	372	404	432	411	361	336
Lane 3	265	315	351	353	355	427	345	292
Lane 4	309	353	387	401	458	416	363	366

***HOV Lane**

Table 3. Average peak hour volume (veh/hr/lane)

Lane number	**Peak Hour (4:30 - 5:30 p.m.)**	**Peak Hour Factor (PHF)**
Lane 1*	1343	0.90
lane 2	1620	0.94
lane 3	1485	0.87
lane 4	1662	0.91

***HOV Lane**

From Table 6 it is observed that the peak hour volume on the HOV lane was 1343 vphpl. When this number is compared to the threshold value suggested by Carson in 2005 which is 870 to 1274 vphpl for the p.m. peak hour volume on the HOV lane, it exceeds the range. This suggests that the HOV lane is over utilized as the total number of vehicles moving on the HOV lane during the peak hour period was greater than the threshold range and this was due to the violation rate being very high.

4.2.2. Average Vehicle Occupancy and Violation Rate: Table 4 shows the average vehicle occupancy and violation rates recorded for each day the data was collected over a period of two hours from 4 p.m. to 6 p.m.

Table 4. Average Vehicle Occupancy (AVO) and Violation Rate

Serial number	Date	Day	Total Vehicles Observed	Single Person Vehicles	2+ person Vehicles	AVO	Violation Rate (%)
1	7/12/2011	Tuesday	1477	1143	334	1.23	77.39
2	7/13/2011	Wednesday	1506	1195	311	1.21	79.35
3	7/14/2011	Thursday	1632	1261	371	1.23	77.27
4	7/19/2011	Tuesday	2243	1733	510	1.23	77.26
5	7/20/2011	Wednesday	1694	1361	333	1.20	80.34
6	7/21/2011	Thursday	2164	1734	430	1.20	80.13
		Average Daily	1786	1405	382	1.21	78.62

From table 4 it is observed that the daily average vehicle occupancy ranges from 1.20 to 1.23 which is very low when compared to the threshold values suggested by Carson which are 2.63 to 3.35. In fact, it is lower than the actual rule for legitimate use of the HOV lane, which is a minimum of 2 passengers per vehicle. The violation rates ranged between 75-80% which is similar to the suggested threshold compliance rate (80-95%). This percentage of violation is excessive. Figure 5 shows the violation rate recorded for each day collected.

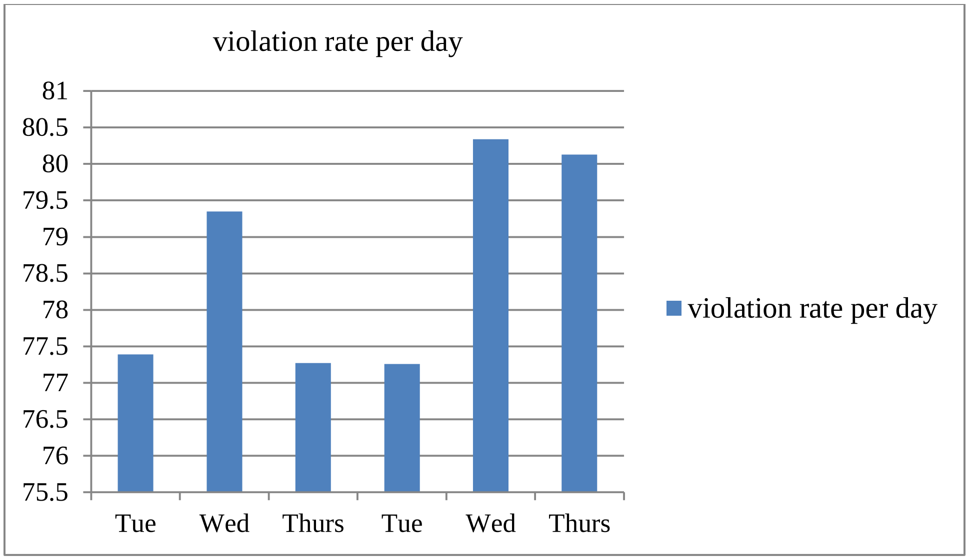

Figure 5. Daily Violation Rates (%)

From the above observations it is concluded that the high violation rates on the HOV lane on I-40 Memphis, TN eastbound contribute to the overutilization of the lane. This high violation rate also indicates that the carpool rule is not being accepted/followed by the general public. From the violation rates recorded it can be inferred that there is insufficient enforcement of the carpool rule.

4.2.4. Summary of Person Throughput Analysis: Table 5 shows the summary of the results obtained and the threshold values used to compare the results.

Table 5. Summary for Person Throughput Analysis

Serial number	Objective	Results obtained	Threshold values
1	Peak hour volume on HOV lane	1343 vphpl	870 to 1274 vphpl
2	Average Vehicle Occupancy	1.20 to 1.23	2.63 to 3.35
3	Violation Rate	75-80%	10-15%

The results give a clear indication that the HOV lane is over utilized. In addition, the average vehicle occupancy was recorded to be 1.20 to 1.23, which is very low when compared to the threshold value of 2.63 to 3.35. In fact it is lower than the carpool rule of 2+ passengers per vehicle and this explains the reason for the huge violation rate which was recorded to be at 75-80%, which is nowhere near the threshold value of 10-15%.

4.3. Travel Time Analysis

The main objective of the Travel time analysis was to collect travel time for various trips made on the HOV lane and other three GP lanes during 4 p.m. to 6 p.m. (for every 15-minute intervals) on I-40 in Memphis, TN. The travel times on HOV lane on a whole were compared with the aggregate of all three GP lane travel times and travel times on HOV lane were compared to travel times collected on each GP lane separately. The results obtained were compared with the threshold values suggested by Carson in 2005 and they are presented below.

4.3.1. HOV Lane vs. Aggregate of All Three GP lanes: In this section the travel time data collected on the HOV and other GP lanes will be compared to one another and the results presented. The travel time savings and travel time reliability of the HOV lane when compared to other GP lanes is observed. Table 6 shows the travel times and speeds on the HOV lane and other GP lanes for each trip made from exit 12 to exit 15 b on I-40 east.

Table 6. Travel time and speed data collected

Serial number	HOV (Travel Time in sec)	GP (Travel Time in sec)	Travel time savings (sec)	HOV Speeds (mph)	GP Speeds (mph)	Speed Improvements
1	125.35	163.93	38.59	71.8	54.9	16.9
2	126.05	161.00	34.95	71.4	55.9	15.5
3	131.77	160.71	28.94	68.3	56	12.3
4	128.94	177.17	48.23	69.8	50.8	19.0
5	130.62	143.77	13.15	68.9	62.6	6.3
6	126.23	152.03	25.80	71.3	59.2	12.1
7	124.83	169.81	44.98	72.1	53	19.1
8	117.96	157.34	39.39	76.3	57.2	19.1
9	126.40	143.54	17.14	71.2	62.7	8.5
10	128.39	151.77	23.38	70.1	59.3	10.8
11	133.33	185.19	51.85	67.5	48.6	18.9
12	151.77	243.24	91.47	59.3	37	22.3
13	136.78	149.25	12.48	65.8	60.3	5.5
14	132.74	134.33	1.58	67.8	67	0.8
15	124.83	138.25	13.42	72.1	65.1	7.0
16	135.75	132.35	-3.39	66.3	68	-1.7
17	130.25	128.94	-1.31	69.1	69.8	-0.7
18	127.84	144.00	16.16	70.4	62.5	7.9
19	129.12	135.34	6.21	69.7	66.5	3.2
20	124.48	134.73	10.25	72.3	66.8	5.5
21	131.39	155.17	23.79	68.5	58	10.5
22	126.94	150.50	23.56	70.9	59.8	11.1
23	128.76	157.34	28.59	69.9	57.2	12.7
24	152.28	155.71	3.43	59.1	57.8	1.3
25	133.73	152.03	18.30	67.3	59.2	8.1
26	129.50	152.03	22.53	69.5	59.2	10.3
27	124.65	149.50	24.85	72.2	60.2	12.0
28	125.87	147.78	21.91	71.5	60.9	10.6
29	125.00	137.20	12.20	72	65.6	6.4
30	133.14	147.30	14.16	67.6	61.1	6.5

Table 6 (Continued). Travel time and Speed data collected

Serial number	HOV (Travel Time in sec)	GP (Travel Time in sec)	Travel time savings (sec)	HOV Speeds (mph)	GP Speeds (mph)	Speed Improvements (mph)
31	122.45	144.23	21.78	73.5	62.4	11.1
32	121.29	158.73	37.44	74.2	56.7	17.5
33	127.66	153.06	25.40	70.5	58.8	11.7
34	127.12	149.50	22.38	70.8	60.2	10.6
35	121.95	135.95	14.00	73.8	66.2	7.6
36	128.21	143.31	15.11	70.2	62.8	7.4
37	123.46	127.66	4.20	72.9	70.5	2.4
38	130.81	129.87	-0.94	68.8	69.3	-0.5
39	132.94	152.03	19.09	67.7	59.2	8.5
40	132.74	136.57	3.83	67.8	65.9	1.9
41	121.46	136.57	15.11	74.1	65.9	8.2
42	125.52	148.27	22.75	71.7	60.7	11.0
43	130.06	144.00	13.94	69.2	62.5	6.7
44	121.29	125.87	4.58	74.2	71.5	2.7
45	132.16	134.53	2.37	68.1	66.9	1.2
46	119.68	148.27	28.59	75.2	60.7	14.5
47	125.17	129.87	4.70	71.9	69.3	2.6
48	125.35	117.65	-7.70	71.8	76.5	-4.7
49	127.48	160.43	32.95	71.7	56.1	15.6
50	127.30	144.69	17.40	74.2	62.2	12.0
51	126.23	148.51	22.29	68.1	60.6	7.5
52	128.21	153.06	24.86	75.2	58.8	16.4
53	131.00	174.08	43.08	71.9	51.7	20.2
54	126.23	147.78	21.56	71.8	60.9	10.9
Average	**128.53**	**149.18**	**27.72**	**70.4**	**61.1**	**9.3**
Standard Deviation	**6.16**	**18.53**		**3.26**	**6.39**	

The data shows an average travel time of 128.53 seconds on the HOV lane and 149.18 seconds on the GP lanes with an average travel time savings of 27.72 seconds. The average speed on the HOV lane was determined to be 70.4 mph and on the GP lanes it was 61.1 mph, which resulted in an average speed improvement of 9.3 mph on the

HOV lane. The travel times on the HOV lane were more reliable than the travel time on the GP lanes as the standard deviation on the HOV lane was 6.16 seconds as opposed to the standard deviation of the GP lanes which is 18.53 seconds.

Summary of Travel Times Collected on Each GP Lane: In this section travel times collected on each GP lane were presented. It is suspected that the reason for the standard deviation of the GP lane travel times being so high could be because of the fact that the travel times were collected on three different lanes. Table 7 shows the travel times in the three GP lanes.

Table 7. Travel times of GP lanes

Serial number	GP1 (Travel Time in sec)	GP2 (Travel Time in sec)	GP3 (Travel Time in sec)
1	134.33	163.93	169.81
2	138.25	161.00	157.34
3	132.35	160.71	143.54
4	128.94	177.17	151.77
5	144.00	143.77	185.19
6	135.34	152.03	243.24
7	134.73	149.50	149.25
8	135.95	147.78	155.17
9	143.31	137.20	150.50
10	127.66	147.30	157.34
11	129.87	144.23	155.71
12	152.03	158.73	152.03
13	136.57	153.06	152.03
14	136.57	149.50	160.43
15		148.27	144.69
16		144.00	148.51
17		125.87	153.06
18		134.53	174.08
19		148.27	147.78
20		129.87	
21		117.65	

Results of One Way ANOVA. To check if there is a statistical difference between each GP lane a one way ANOVA was conducted. Figure 6 shows results obtained from Minitab to evaluate the assumptions of the One Way ANOVA as described in the previous chapter. Based on these results, we show that assumptions are satisfied.

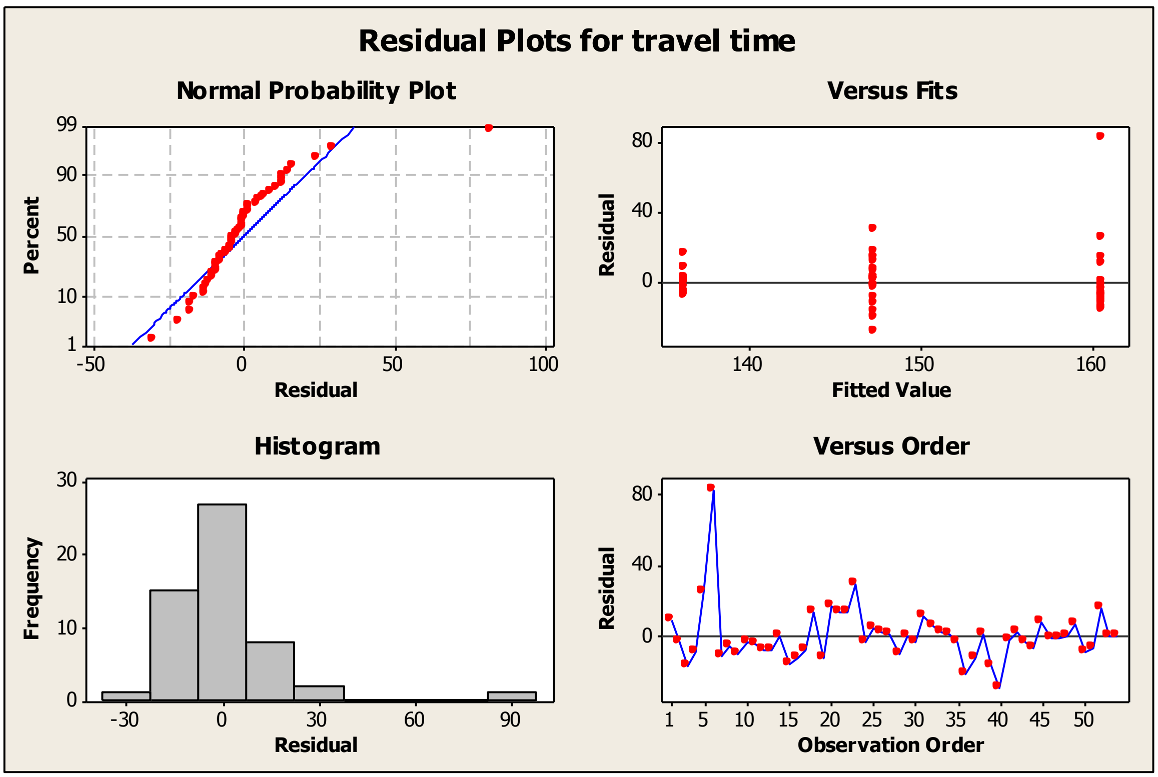

Figure 6. Tests to check if the assumptions are satisfied

The One Way ANOVA results indicate that there is sufficient evidence that not all the means are equal when alpha is set at 0.05 (p = 0.000). This is expected as different lanes have different traffic and the travel times on each lane would differ, particularly for the outermost GP lane (i.e., GP 3), as this lane experiences speed and volume adjustments due to access to exits and merging maneuvers. Figure 7 shows ANOVA results obtained in Minitab.

One-way ANOVA: travel time versus Lane number

```
Source        DF     SS    MS     F      P
Lane number    2   4829  2415  9.21  0.000
Error         51  13369   262
Total         53  18199

S = 16.19   R-Sq = 26.54%   R-Sq(adj) = 23.65%


                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level   N    Mean  StDev  ----+---------+---------+---------+-----
1      14  136.42   6.52  (-------*------)
2      21  147.35  13.55             (-----*-----)
3      19  160.60  22.54                        (-----*-----)
                          ----+---------+---------+---------+-----
                            132       144       156       168

Pooled StDev = 16.19
```

Figure 7. One way ANOVA results

Hence, it is more appropriate to compare the travel time on the HOV lane with the travel time of each GP lane. The comparison of lanes is presented in the following order:

- HOV lane vs. GP lane 1
- HOV lane vs. GP lane 2
- HOV lane vs. GP lane 3

4.3.2. HOV lane vs. GP lane 1: The HOV lane and GP lane 1 are compared below and it is seen that both the lane distributions are normal. Hence a two sample t test is conducted and the results are presented.

Figures 8, 9, and 10 below show the normality test for travel times on HOV lane, GP lane 1 and box plot comparison of travel times for both lanes respectively.

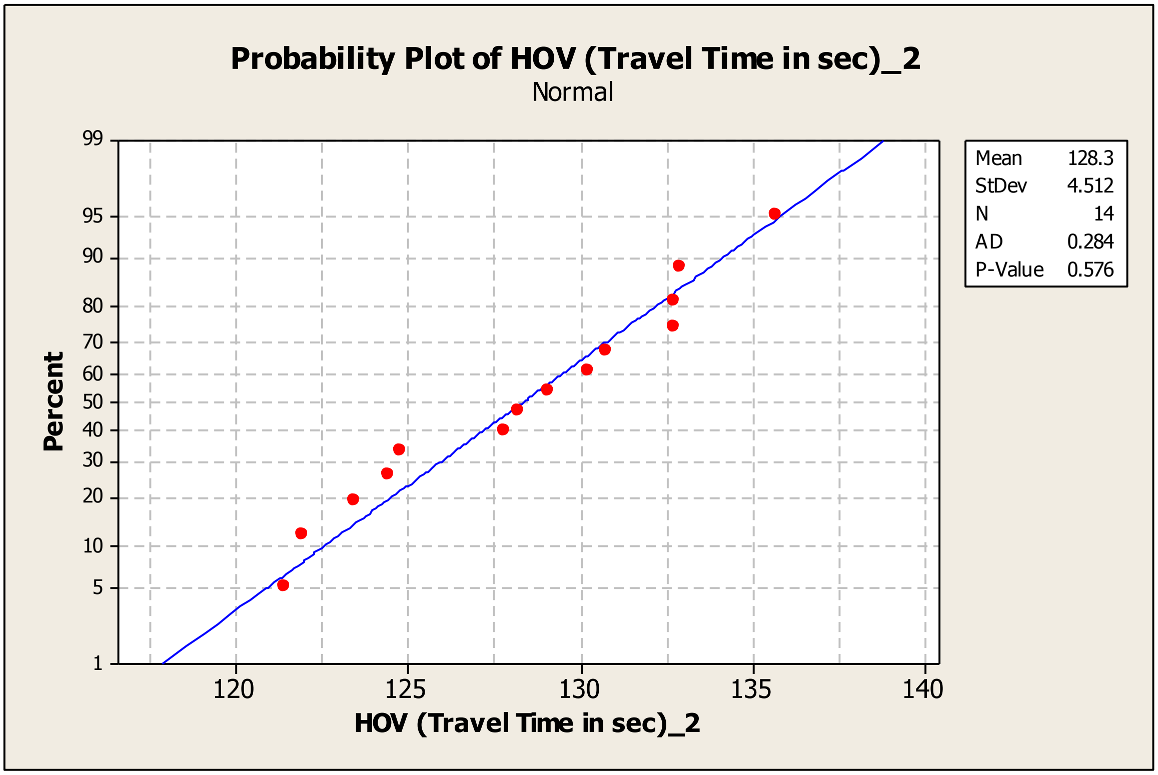

Figure 8. Normality test for travel time on HOV lane

It is observed that the p value for the Anderson-Darling normality test is 0.576 which is greater than α level of 0.05. Hence the distribution of the travel times of HOV lane is normal.

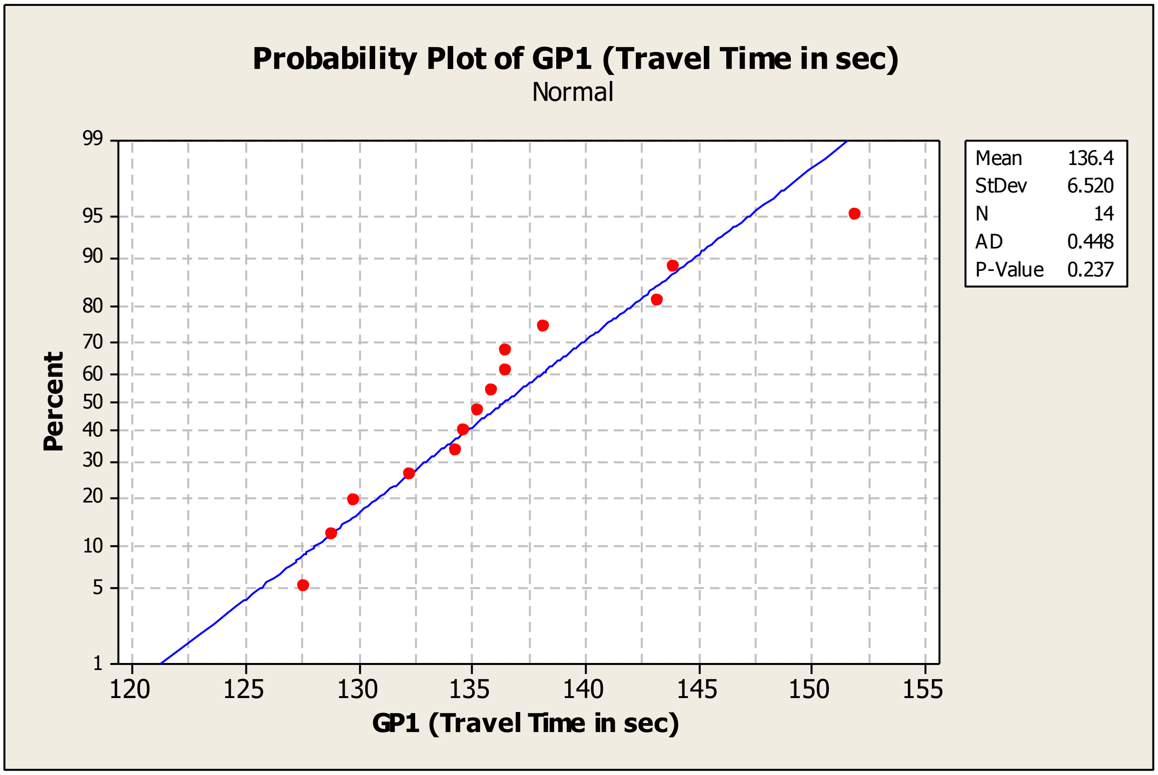

Figure 9. Normality test of GP lane 1

It is observed that the p value for the Anderson-Darling normality test is 0.237 which is greater than α level of 0.05. Hence the distribution of the travel times of GP lane 1 is normal.

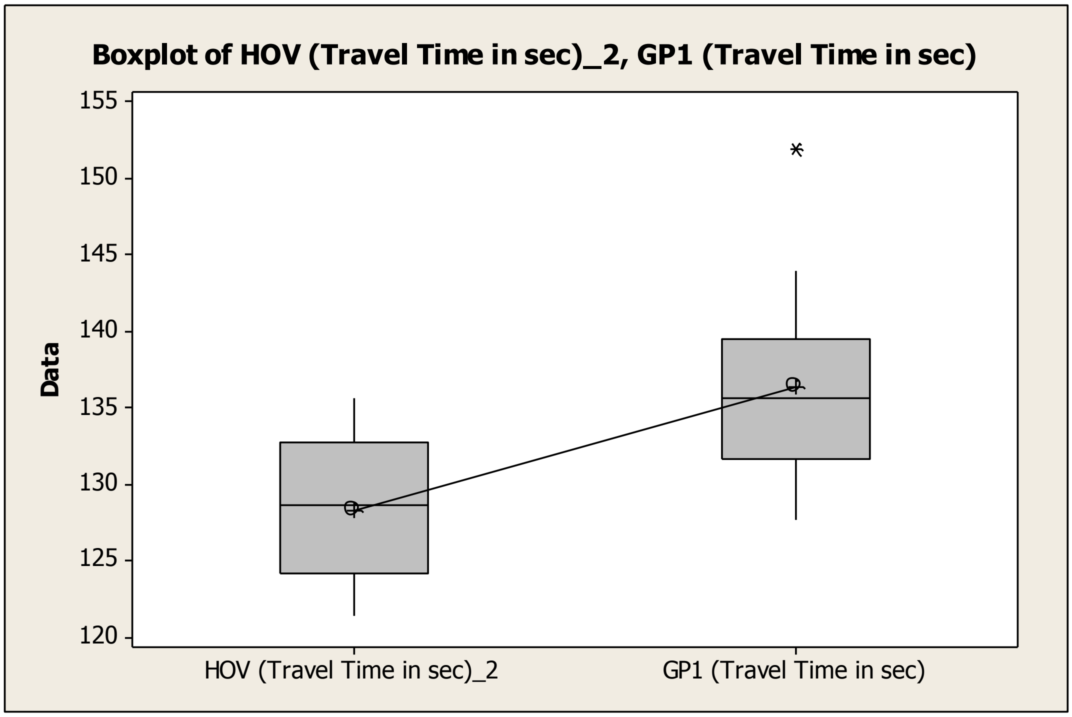

Figure 10. Box Plot Comparison for travel times (HOV vs. GP 1)

A two-sample t-test (unpaired) is conducted on the two data sets: HOV lane travel time and GP lane 1 travel time. The null hypothesis is that both the means are equal, with the alternative hypothesis being that of unequal means. The results obtained for this test are shown below in tables 8 and 9.

Table 8. Two-sample T for HOV (Travel Time in sec) vs GP1 (Travel Time in sec)

H_0: $\mu_{HOV} = \mu_{GP1}$; H_a: $\mu_{HOV} \neq \mu_{GP1}$
Difference = μ (HOV (Travel Time in sec)) - μ (GP1 (Travel Time in sec))
Estimate for difference: -8.09
95% CI for difference: (-12.48, -3.71)
T-Test of difference = 0 (vs not =); T-Value = -3.82; P-Value = 0.001; degree of freedom (DF) = 23

Table 9. Mean and Standard deviation (HOV vs. GP 1)

	Observations (N)	Mean (μ)	Standard deviation (σ)	Standard Error (SE)
HOV lane travel times (secs)	14	128.33	4.51	1.2
GP lane 1 travel times (secs)	14	136.42	6.52	1.7

According to the t-test, the p value is less than 0.05. Hence we reject the null hypothesis. This indicates that there is a statistically significant difference between the mean travel times on the HOV and GP lane 1. It also shows that the standard deviation of the HOV lane is 4.51 when compared to the GP lane 1 which is 6.52. Hence it can be concluded that travel times on HOV lanes are more reliable than GP lane 1. It is observed that the 95% confidence interval for the travel time difference is (-12.48, -3.71) in seconds for a trip length of 2.5 miles. The HOV lane on I-40 Memphis, TN is 9 miles long, so the travel time savings for a trip length of 9 miles would range from 13.36 seconds to 44.9 seconds. From a practical standpoint, a maximum travel time savings of just about a minute for a total trip length of 9 miles may not be significant to drivers. When compared with the threshold value of 5 minutes travel time savings or minimum of 1 minute per HOV mile, the savings obtained here are minuscule. But, the travel times on the HOV lane are found to be very reliable when compared to the GP lane 1 and to check the travel time reliability of both lanes the concept of Buffer Index is used. The buffer index for HOV lane travel times was 0.95 and the buffer index for GP lane 1 travel times was 0.94. Though the values are similar, HOV lane was observed to have a lower standard deviation than that of GP lane 1. Hence, it is concluded that HOV lane provides marginally more travel time reliability than GP lane 1. The table 10 below shows the Buffer Index analysis.

Table 10. Buffer Index Analysis (HOV vs. GP lane 1)

Serial number	HOV (Travel Time in sec)	GP1 (Travel Time in sec)
1	132.74	134.33
2	124.83	138.25
3	135.75	132.35
4	130.25	128.94
5	127.84	144.00
6	129.12	135.34
7	124.48	134.73
8	121.95	135.95
9	128.21	143.31
10	123.46	127.66
11	130.81	129.87
12	132.94	152.03
13	132.74	136.57
14	121.46	136.57
Mean	128.33	136.42
95 percentile	121.78	128.49
Buffer Index	0.95	0.94

4.3.3. HOV lane vs. GP lane 2: The HOV lane and GP lane 2 are compared below and it is seen that both the lane distributions are normal. Hence a 2 sample t test is conducted and the results are presented.

Figures 11, 12, and 13 below show the normality test for travel times on HOV lane, GP lane 2 and box plot comparison of travel times for both lanes respectively.

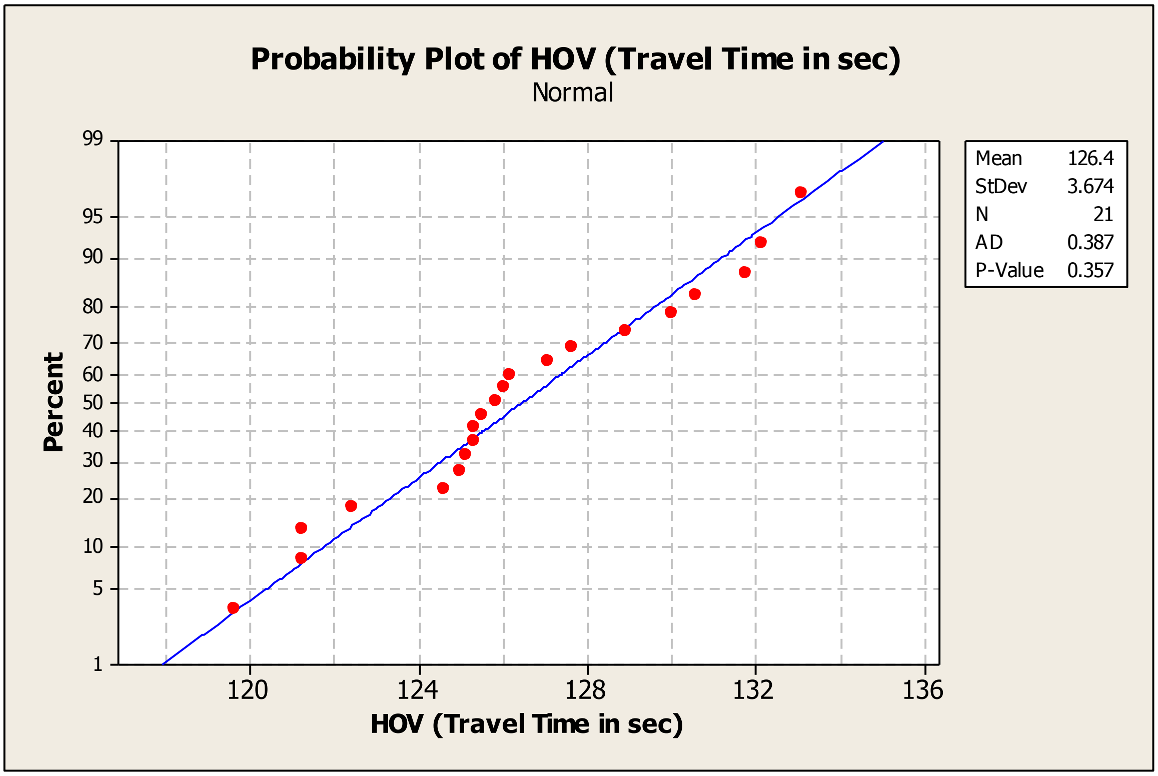

Figure 11. Normality test for HOV lane travel times

It is observed that the p value for the Anderson-Darling normality test is 0.357 which is greater than α level of 0.05. Hence the distribution of the travel times of HOV lane is normal.

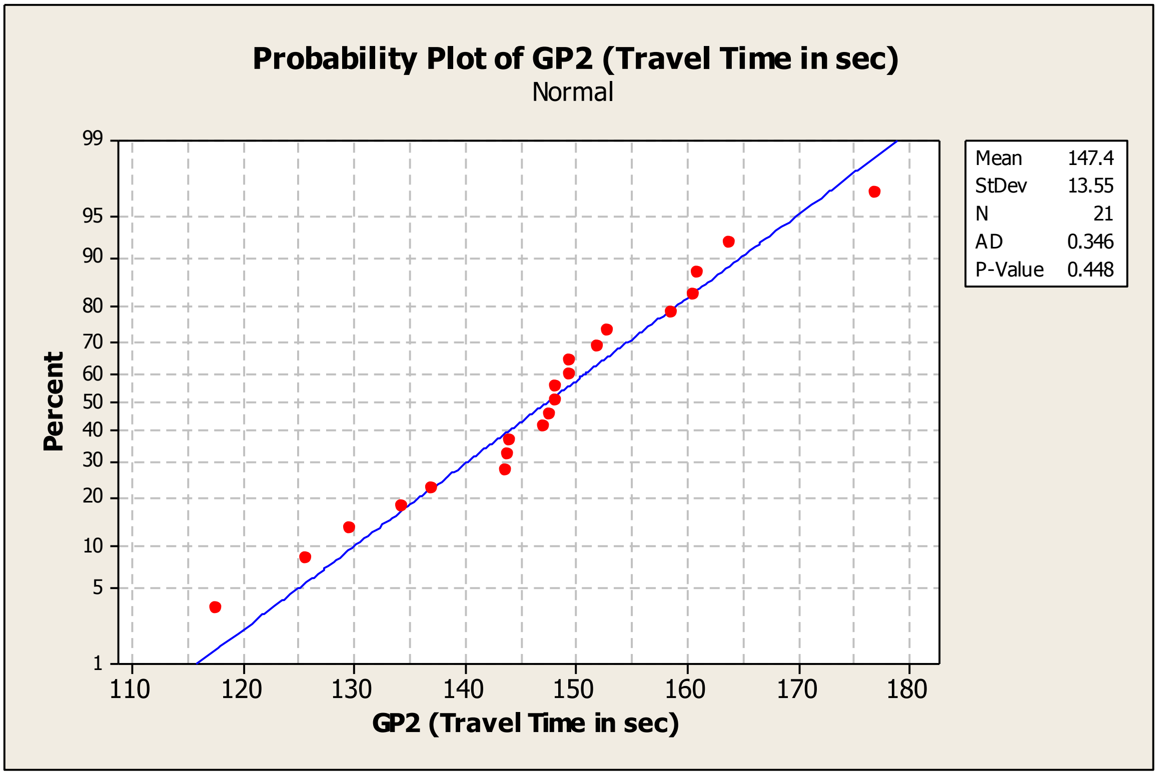

Figure 12. Normality test for GP lane 2 travel times

It is observed that the p value for the Anderson-Darling normality test is 0.448 which is greater than α level of 0.05. Hence the distribution of the travel times of GP lane 2 is normal.

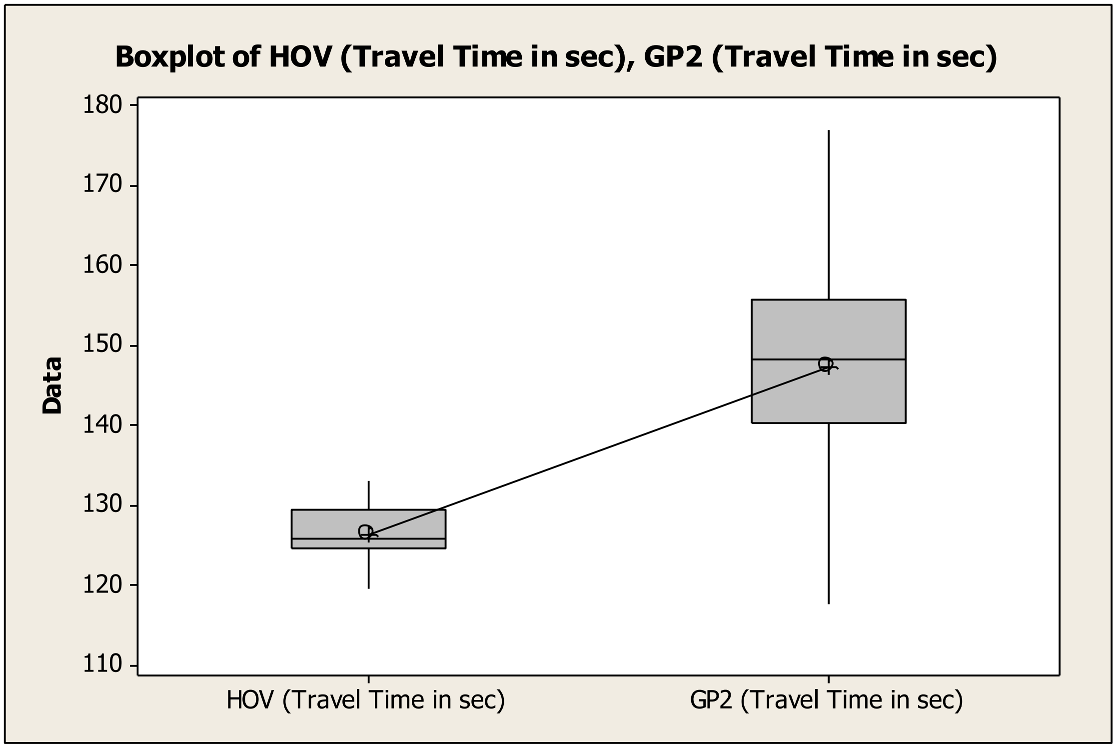

Figure 13. Box Plot Comparison between HOV and GP lane 2 travel times

A two-sample t-test (unpaired) is conducted on the two data sets; HOV lane travel time and GP lane 2 travel times. The null hypothesis is said to be that both the means are equal, with the alternative hypothesis being that of unequal means. The results obtained for this test are shown below in tables 11 and 12.

Table 11. Two-sample T for HOV (Travel Time in sec) vs GP2 (Travel Time in sec)

H_0: $\mu_{HOV} = \mu_{GP2}$; H_a: $\mu_{HOV} \neq \mu_{GP2}$
Difference = μ (HOV (Travel Time in sec)) - μ (GP2 (Travel Time in sec))
Estimate for difference: -20.90
95% CI for difference: (-27.26, -14.55)
T-Test of difference = 0 (vs not =); T-Value = -6.82; P-Value = 0.000; degree of freedom (DF) = 22

Table 12. Mean and Standard deviation (HOV vs. GP 1)

	observations (N)	Mean (μ)	Standard deviation (σ)	Standard Error (SE)
HOV lane travel times (secs)	21	126.45	3.67	0.8
GP lane 2 travel times (secs)	21	147.4	13.6	3

According to the t-test, the p value is less than 0.05. Hence we reject the null hypothesis. This indicates that there is a statistically significant difference between the mean travel times on the HOV and GP lane 2. It also shows that the standard deviation of the HOV lane is 3.67 seconds as compared to GP lane 2, which is 13.6 seconds. Hence it can be concluded that travel times on HOV lanes are more reliable than GP lane 2. It is observed that the 95% confidence interval for the travel time difference is (-27.26, -14.55) in seconds for a trip length of 2.5 miles. The HOV lane on I-40 Memphis, TN is 9 miles long, so the travel time savings for a trip length of 9 miles would range from 52.3 seconds to 98.1 seconds. Practically, a maximum travel time saving of 1.6 minutes for a total trip length of 9 miles is a little more when it is compared to the GP lane 1, but it is not much of a savings as it is still less than the threshold value of 5 minutes travel time savings or a minimum of 1 minute per HOV mile. But, the travel times on the HOV lane are found to be very reliable when compared to the GP lane 2 and to check the travel time reliability of both lanes the concept of Buffer Index is used. The buffer index for HOV lane travel times was 0.96 which is greater than the buffer index for GP lane 2 travel times was 0.85. Hence, it is concluded that HOV lane provides more travel time reliability than GP lane 2. The table 13 below shows the Buffer Index analysis.

Table 13. Buffer Index Analysis (HOV vs GP lane 2)

Serial number	HOV (Travel Time in sec)	GP2 (Travel Time in sec)
1	125.35	163.93
2	126.05	161.00
3	131.77	160.71
4	128.94	177.17
5	130.62	143.77
6	126.23	152.03
7	124.65	149.50
8	125.87	147.78
9	125.00	137.20
10	133.14	147.30
11	122.45	144.23
12	121.29	158.73
13	127.66	153.06
14	127.12	149.50
15	125.52	148.27
16	130.06	144.00
17	121.29	125.87
18	132.16	134.53
19	119.68	148.27
20	125.17	129.87
21	125.35	117.65
Mean	126.45	147.35
95 percentile	121.29	125.87
Buffer Index	0.96	0.85

4.3.4. HOV lane vs. GP lane 3: The HOV lane and GP lane 3 are compared below and it is seen that both the lane distributions are not normal. Hence a nonparametric method, the Mann Whitney test is used, to check if there is statistically significant difference between both lanes and the results are presented.

Figures 14 and 15 below show the normality test and statistical summary for travel times on the HOV lane and GP lane 3, respectively.

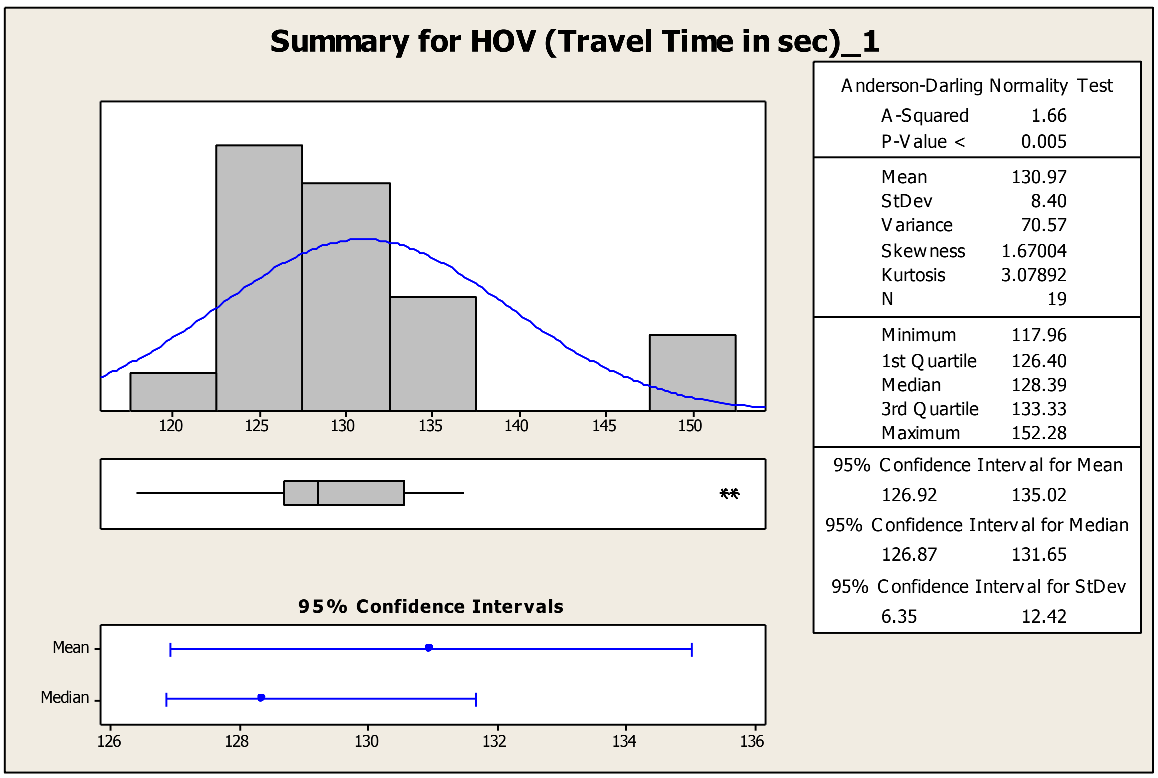

Figure 14. Graphical Summary and Normality Test for HOV lane

It is observed that the p value for the Anderson-Darling normality test is less than α level of 0.05. Hence the distribution of the travel times on the HOV lane is not normal. Though the other two data sets of HOV lane travel times which were presented in the previous sections followed a normal distribution, it was observed that the third dataset had two outlier points, as shown in figure 16. These outlier points were not removed from the dataset as it was due to the heavy traffic at that period the travel times were higher and not because of any technical flaws in data collection or due to any special events (the results did not show much of a difference even when the outlier pints were removed). This is the reason for this dataset not to have a normal distribution.

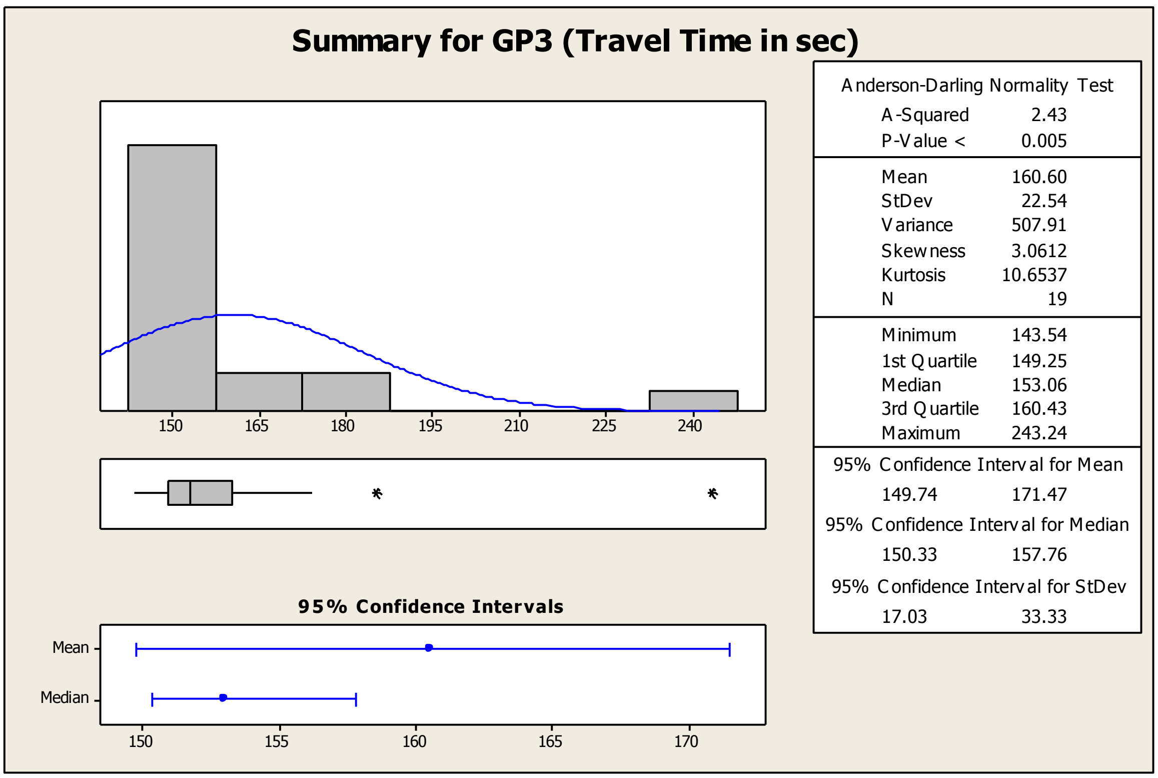

Figure 15. Graphical Summary and Normality Test for GP lane 3

The P value for both the distributions (i.e., HOV travel time and GP3 Travel time) is less than 0.05. Hence we use nonparametric method, the Mann Whitney test, to check if there is statistically significant difference between both lanes and the results are presented below in tables 14 and 15.

Table 14. Mann Whitney Test Results (HOV vs. GP lane 3)

H_0: $\mu_{HOV} = \mu_{GP3}$; H_a: $\mu_{HOV} \neq \mu_{GP3}$
Difference = μ (HOV (Travel Time in sec)) - μ (GP3 (Travel Time in sec))
Point estimate for ETA1-ETA2 is -24.47
95.3 Percent CI for ETA1-ETA2 is (-29.48,-20.57)
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0000

Table 15. Median and Standard deviation (HOV vs. GP lane 3)

	observations (N)	Median	Standard deviation (σ)
HOV lane travel times (secs)	19	128.39	8.4
GP lane 3 travel times (secs)	19	153.06	22.54

The P value is 0.0000; hence we reject the null hypothesis. This indicates that there is a statistically significant difference between the mean travel times on the HOV and GP lane 3. It also shows that the standard deviation of travel times on the HOV lane is 8.40 seconds when compared to the GP lane 3 which is 22.54 seconds. Hence it can be concluded that travel times on the HOV lanes are more reliable than GP lane 3. It is observed that the 95% confidence interval for the travel time difference is (-29.48, -20.57) in seconds for a trip length of 2.5 miles. The HOV lane on I-40 Memphis, TN is 9 miles long, so the travel time savings for a trip length of 9 miles would range from 74 seconds to 106.1 seconds. Practically a maximum travel time saving of 1.8 minutes for a trip length of 9 miles is not much of a savings as it is less than the threshold value of 5 minutes travel time savings or a savings of 1 minute per HOV mile. But, the travel times on the HOV lane are found to be very reliable when compared to the GP lane 3 and to check the travel time reliability of both lanes the concept of Buffer Index is used. The buffer index for HOV lane travel times was 0.95 which is greater than the buffer index for GP lane 3 travel times was 0.90. Hence, it is concluded that HOV lane provides more travel time reliability than GP lane 3. Table 16 shows the Buffer Index analysis.

Table 16. Buffer Index Analysis (HOV vs. GP lane 3 travel times)

Serial number	HOV (Travel Time in sec)	GP3 (Travel Time in sec)
1	124.83	169.81
2	117.96	157.34
3	126.40	143.54
4	128.39	151.77
5	133.33	185.19
6	151.77	243.24
7	136.78	149.25
8	131.39	155.17
9	126.94	150.50
10	128.76	157.34
11	152.28	155.71
12	133.73	152.03
13	129.50	152.03
14	127.48	160.43
15	127.30	144.69
16	126.23	148.51
17	128.21	153.06
18	131.00	174.08
19	126.23	147.78
Mean	130.97	160.6
95 percentile	124.14	144.58
Buffer Index	0.95	0.9

Hence it could be concluded that though the HOV lane provides more reliable travel times when compared to the other GP lanes it does not provide sufficient travel time savings to say that the HOV lane is beneficial.

4.3.5. Summary of Travel time Analysis: The summary of Travel time analysis is explained according to two objectives (travel time savings and travel time reliability). The summary of the results obtained for both the objectives are shown below (in table 17 and 18) where the HOV lane was compared with all the three GP lanes separately.

Table 17. Summary for Travel Time Savings

Serial number	Comparison	Travel time Savings Range	Threshold Travel Time Savings Range
1	HOV vs GP lane 1	13.36 to 44.9 seconds	5-7minutes or 1 minute/mile
2	HOV vs GP lane 2	52.3 to 98.1 seconds	5-7minutes or 1 minute/mile
3	HOV vs GP lane 3	74 to 106.1 seconds	5-7minutes or 1 minute/mile

In the above table (table 17) it shows that the HOV lane did provided travel time savings when compared with the other GP lanes. The HOV lane provided 13.36 to 44.9 seconds range of travel time savings for a trip length of 9 miles when compared to GP lane 1. This range when compared to the threshold value of 5-7minute savings is not significant in a practical point of view as the maximum savings recorded is less than a minute. The HOV lane provided 52.3 to 98.1 seconds range of travel time savings for a trip length of 9 miles when compared to GP lane 2. This range when compared to the threshold value of 5-7minute savings is still not significant enough in a practical point of view as the maximum savings recorded is about 1.6 minutes. The HOV lane provided 74 to 106.1 seconds range of travel time savings for a trip length of 9 miles when compared to GP lane 3. This range when compared to the threshold value of 5-7minute savings is also still not significant enough in a practical point of view as the maximum savings recorded is about 1.8 minutes.

The travel time savings were for a trip length of 9 miles, which is the total length of the HOV segment on I-40 Memphis, TN eastbound. An average trip length for a vehicle travelling on this stretch of road would be less than the total length of 9 miles, as most residential areas and commercial complexes are located near the exits before the end point of the HOV lane. This means that the travel time savings would reduce as the trip length decreases. Hence, it can be concluded that the HOV lane is not providing significant travel time savings.

Table 18. Summary for Travel Time reliability

Serial number	Comparison	Travel time Reliability		Threshold Travel time Reliability	
		Standard Deviations (σ)	Buffer Index (BI)	Standard Deviations (σ)	Buffer Index (BI)
1	HOV vs GP lane 1	HOVσ = 4.51, GP 1σ = 6.52	HOV BI = 0.95 > GP lane 1 BI = 0.94	HOVσ = 3 to 3.9 GP σ = 5.1 to 5.2	BI (HOV) > BI (GP1)
2	HOV vs GP lane 2	HOVσ = 3.67, GP 2σ = 13.6	HOV BI = 0.96 > GP lane 2 BI = 0.85	HOVσ = 3 to 3.9 GP σ = 5.1 to 5.2	BI (HOV) > BI (GP2)
3	HOV vs GP lane 3	HOVσ = 8.40, GP 3σ = 22.54	HOV BI = 0.95 > GP lane 3 BI = 0.90	HOVσ = 3 to 3.9 GP σ = 5.1 to 5.2	BI (HOV) > BI (GP3)

The above table (table 18) shows the travel time reliabilities of both the HOV and other GP lanes which are compared separately. The travel time reliability of HOV lanes was checked in two parts; comparison of the standard deviations of HOV and GP lanes and Buffer Index of HOV and GP lanes. The threshold values were used as a reference and the conclusions were based on the difference between both the standard deviations (HOV vs. GP lanes). It was concluded that if the difference between the standard deviations between the lanes was more than 2 (since the threshold values for standard deviations had a difference of about 2) and the buffer index of HOV lane was higher than the other GP lanes, the HOV lane was providing better travel time reliability.

The standard deviation of HOV lane was 4.51 seconds when compared with the standard deviation of GP lane 1 which was 6.51 seconds. The buffer index of HOV lane was 0.95 and the buffer index of GP lane 1 travel time was 0.94. The difference between the standard deviations was greater than 2 (HOV lane_{σ} < GP lane 1_{σ}) and the buffer Index of HOV lane was greater than GP lane 1. Hence it was concluded that the HOV lane travel time were more reliable than GP lane 1.

The standard deviation of the HOV lane was 3.67 seconds when compared with the standard deviation of GP lane 2, which was 13.6 seconds. The buffer index of the HOV lane was 0.96 and the buffer index of GP lane 2 travel times was 0.85. The difference between the standard deviations was greater than 2 (HOV lane_{σ} < GP lane 2_{σ}) and the buffer Index of HOV lane was greater than GP lane 2. Hence it was concluded that the HOV lane travel times were more reliable than GP lane 2.

The standard deviation of HOV lane was 8.40 seconds when compared with the standard deviation of GP lane 3 which was 22.54 seconds. The buffer index of the HOV lane was 0.95 and the buffer index of GP lane 3 travel times was 0.90. The difference between the standard deviations was greater than 2 (HOV lane_{σ} < GP lane 3_{σ}) and the buffer index of HOV lane was greater than GP lane 3. Hence it was concluded that the HOV lane travel times were more reliable than GP lane 3.

4.4. Environmental Benefits

The carbon footprints (i.e. the amount of CO_2 release for each trip made on the HOV and GP lane) were collected in the month of July simultaneously during the travel time data collection where the origin was exit 12 and destination was exit 15b on I-40 east. For this, both the test cars were equipped with a Garmin Nuvi GPS which produced mileage reports for every trip made. The following was the data obtained and is shown in table 19.

Table 19. Carbon Footprints (HOV vs. GP lanes)

Date	HOV			GP		
	Distance (ml)	CF (lbs)/(ml)	CF HOV Gms/ml	Distance (ml)	CF (lbs)/(ml)	CF GP Gms/ml
7/14/2011	2.2	0.64	290.71	2.5	0.87	394.63
7/14/2011	2.2	0.69	311.33	2.3	0.76	344.73
7/14/2011	2.2	0.72	325.76	2.5	0.73	331.12
7/14/2011	2.3	0.77	347.10	2.5	0.82	371.95
7/14/2011	2.3	0.63	285.96	2.4	0.82	371.95
7/14/2011	2.3	0.67	305.68	2.5	0.82	371.95
7/14/2011	2.3	0.66	297.79	2.5	0.78	353.80
7/19/2011	2.2	0.75	342.26	2.2	0.9	408.23
7/19/2011	1.6	0.68	309.01	2.2	0.84	381.02
7/19/2011	1.8	0.69	312.47	2.2	0.69	312.98
7/19/2011	2.3	0.64	291.88	2.2	0.74	335.66
7/19/2011	2.3	0.72	325.40	2.2	0.66	299.37
7/19/2011	2.3	0.67	303.71	2.2	0.76	344.73
7/20/2011	2.5	0.82	371.95	2.2	0.66	299.37
7/20/2011	2.6	0.73	331.47	2.2	0.66	299.37
7/20/2011	2.5	0.76	344.73	2.2	0.72	326.59
7/20/2011	2.5	0.74	333.84	2.2	0.69	312.98
7/20/2011	2.4	0.77	347.75	2.2	0.69	312.98
7/20/2011	2.4	0.80	360.98	2.2	0.66	299.37
7/20/2011	2.4	0.79	359.09	2.2	0.7	317.51
7/21/2011	2.5	0.84	381.02	2.1	0.70	394.63
7/21/2011	1.7	0.5	226.80	2.1	0.73	394.63
7/21/2011	2.6	0.9	408.23	2.1	0.67	394.63
7/21/2011	2.5	0.83	376.48	2.1	0.69	394.63
7/21/2011	2.4	0.79	358.34	2.1	0.70	394.63
7/21/2011	2.5	0.8	362.87	2.1	0.74	394.63
7/21/2011	2.5	0.85	385.55	2.1	0.69	394.63
Average	2.26	0.71	323.03	2.27	0.75	344.52

According to the data obtained from the mileage reports produced by the GPS, it is observed that a vehicle travelling on an HOV lane emits about 20 grams less CO_2 than the other GP lane per mile. To check if the carbon footprints for HOV lane and other GP lanes show statistically significant difference a non-parametric test (Mann Whitney Test) is conducted. Figures 16 and 17 show statistical summary and normality tests for HOV and GP lane carbon footprints respectively.

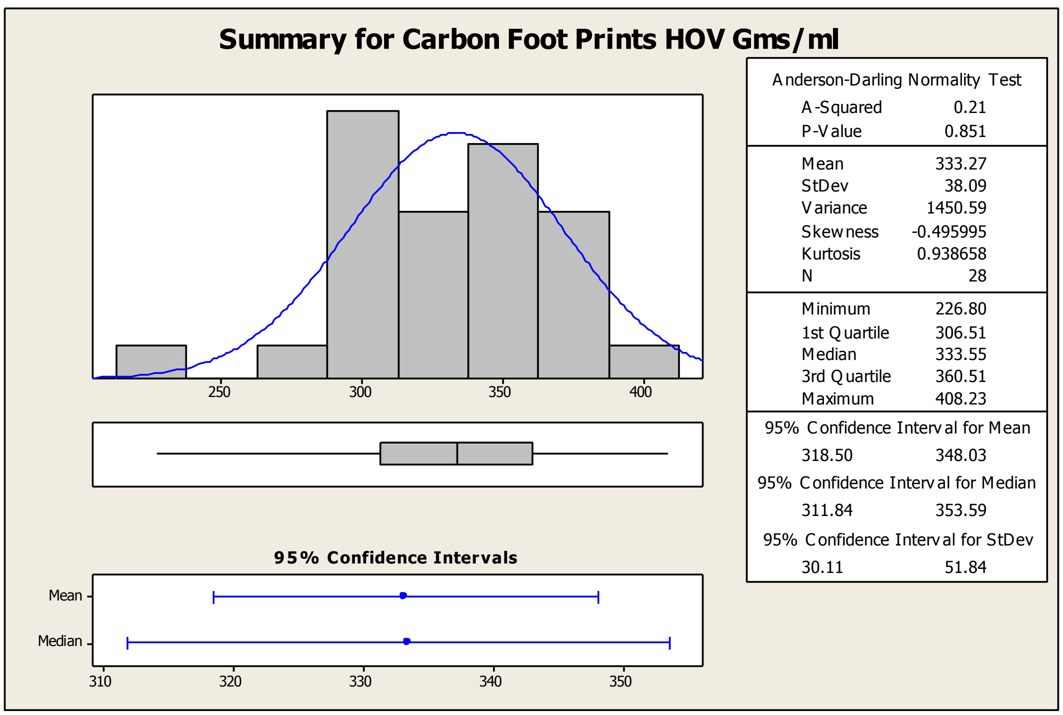

Figure 16. Statistical summary and normality test for HOV lane carbon footprints

The p value is observed to be 0.851 which is greater that α level 0.05. Hence the carbon emissions for HOV lane have a normal distribution.

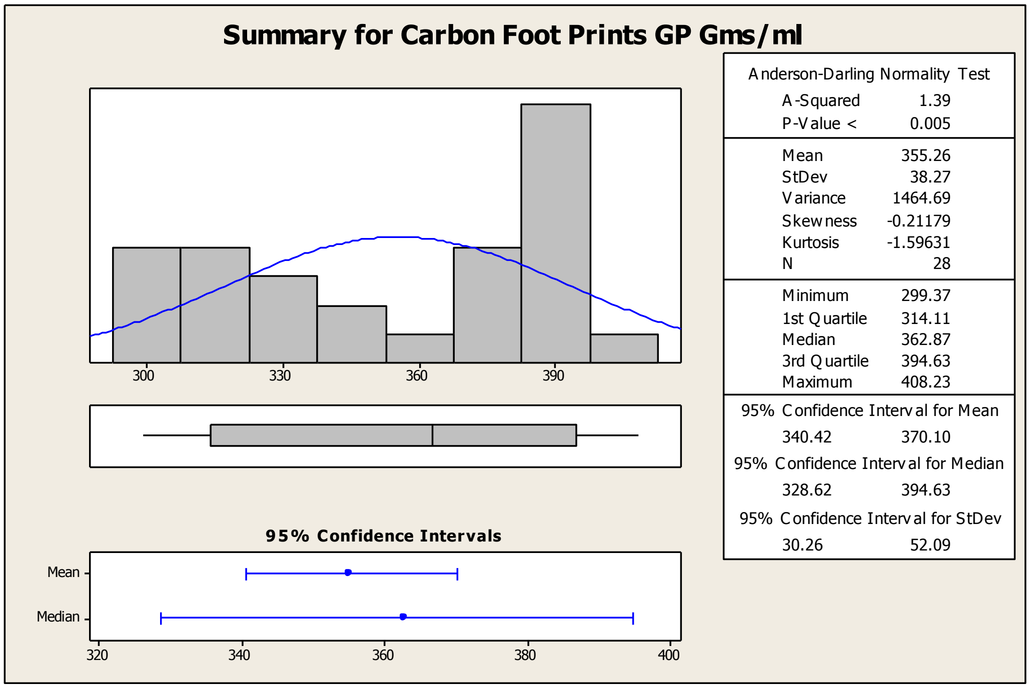

Figure 17. Statistical Summary and Normality test for GP lanes carbon footprints

The normality test conducted for the sample above show that the distribution for carbon footprints on GP lanes (grams/mile) is not normal as the p value is less than 0.05. Hence the nonparametric test Mann Whitney test is conducted to check for statistical difference between the 2 samples. Tables 20 and 21 show the results obtained.

Table 20. Mann Whitney Test Results (HOV vs. GP lanes)

H_0: $\mu_{HOV} = \mu_{GP}$; H_a: $\mu_{HOV} \neq \mu_{GP}$
Difference = μ (HOV (Carbon Footprints Gram/mile)) - μ (GP (Carbon Footprints Gram/mile))
Point estimate for ETA1-ETA2 is -22.27
95.3 Percent CI for ETA1-ETA2 is (-46.18,-0.52)
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0405

Table 21. Carbon footprints median (HOV vs. GP lanes)

	observations (N)	Median
Carbon Foot Prints HOV Gms/ml	28	333.55
Carbon Foot Prints GP Gms/ml	28	362.87

Since the p value is less than α level 0.05, the null hypothesis is rejected. A 95% confidence interval of the difference between HOV carbon footprints and GP lanes carbon footprints was observed to be (-46.18, -0.52) grams/mile.

4.4.1. Summary of Environmental Benefit Analysis: To check if the environmental benefit objective is met on I-40 Memphis, TN eastbound, fuel reports produced by Garmin Nuvi GPS were used for each trip made on the HOV lane and other GP lanes during data collection process. It was concluded that the HOV lane provides environmental benefits if the carbon foot prints on the HOV lane is lower than other GP lanes. It was recorded that for a length of 9 miles of HOV on I-40 Memphis, TN the range for carbon footprint savings on a HOV lane would be 4.64 to 415.38 grams for an average size vehicle.

5. Discussion of Results and Conclusions

5.1. Introduction

In the research conducted for this study we examined the effectiveness of the HOV lane strategy for a section of I-40 eastbound in Memphis between exit 12 and exit 16 during the pm peak hours (4 p.m. to 6 p.m.). The previous section presented the analysis of data and results of the study conducted. This section discusses the ability of the HOV lane strategy to achieve its goals based on the measures of effectiveness listed below:

- Person Throughput Analysis
- Travel Time Analysis
- Environmental Benefits

5.2. Person Throughput Analysis

The primary aim of an HOV lane as a managed lane strategy is to increase the number of persons on a lane by reducing the number of vehicles traveling on them. From the analysis of the data collected during this research it is clear that the current implementation of the HOV lane strategy does not meet the objective of increasing person throughput based on threshold values suggested in the literature. We conclude that the primary factor causing the reduction in effectiveness is due to the excessively high observed violation rates. The violation rates were of the order of 75-80%. In fact, observed vehicle occupancy was 1.20 to 1.23 which is lower than the threshold values suggested in the literature and the actual rule for legitimate use of the HOV lane, which is a minimum of 2 passengers per vehicle. Under current conditions, the HOV lane is over utilized.

5.3. Travel Time Analysis

Another major objective of a HOV lane is to provide travel time benefits to the general public in terms of both travel time savings and improved travel time reliability. The analysis of data collected during this research showed that travel time reliability of the HOV lane was observed to be higher when compared to the other three GP lanes. However only marginal savings in travel time were achieved. These ranged from less than a minute to a maximum of 1.7 minutes for the entire 9 mile stretch of the HOV lane. These savings are well below the threshold of 5-7 minutes of savings suggested by the literature.

5.4. Environmental Benefits

The HOV lane objective of improving the environment is reached by reducing number of cars on the freeway system. It is considered that any kind of environmental benefits given by an HOV lane is good and the real effect on HOV lanes environmental benefits would be seen in the future as the traffic on each lane is expected to increase. Thus, by improving the operations on the HOV lane, the environmental benefits would increase. Hence it is concluded that the HOV lane helps in reducing the carbon emissions which is beneficial to the environment.

5.5. Summary of Conclusions

This study considered three measures of effectiveness for the I-40 Eastbound HOV lane in Memphis: Person Throughput; Travel time benefits, and Environmental benefits. It was observed that there were benefits in regards to the travel time reliability and for the environment but the objectives of increasing person throughput and improving travel times were violated. In addition, the violation rate recorded was very high and the average vehicle occupancy in the HOV lane did not meet either threshold or legal limits.

5.6. Effectiveness of Low Cost Data Collection Techniques

This study used two innovative techniques to collect data without resorting to expensive scientific equipment. The travel time data was collecting using a low cost commercial smart phone app that measured route, speed and travel time data. The environmental analysis was conducted using data collected with consumer grade car GPS navigation systems. The use of these two systems enabled the data collection for this research to be conducted with relatively little set up and preparation and at a significantly lower cost than using survey grade equipment. The data collected was of sufficient accuracy and resolution to make the analysis meaningful.

6. Recommendations

The HOV lane on I-40 Memphis, TN eastbound, which operates weekdays from 4 P.M. to 6 P.M., was observed not to be effective due to critical reasons and they are:

- Very high violation rates.
- Low public acceptance.
- High traffic volumes on the HOV lane vs. very low Average Vehicle Occupancy (less than the minimum of 2 passengers).

These factors also reduced the travel time benefits and environmental benefits and there was observed to be no enforcement at the site. Recommendations to reduce these factors are presented below. While this research seems to indicate that the HOV lane is not effective in its current state, it seems clear that this lack of effectiveness has a primary cause; high violation rates. Hence, it is recommended that strategies to reduce the violation rate to a more acceptable level be investigated. Better enforcement of carpool lane rules should lead to improvements in travel time savings and reliability and benefits to the environment would increase. In addition, this will also improve person throughput. Possible strategies to achieve this might include both public awareness and enforcement components:

6.1. Public Awareness

Additional efforts in educating the general public about the restrictions imposed on the HOV lane and its benefits (such as travel time savings) may be an effective strategy for improving compliance rates.

- Public awareness could be achieved through the media by implementing public outreach programs to encourage the use of HOV lanes.

- The single occupant hybrid vehicle drivers and HOV Lane Smart Pass could also be popularized.
- Public surveys should be conducted to identify areas of misunderstanding, reasons for violations, and areas that should be emphasized to encourage public compliance. The results would be useful in developing good management programs for the HOV facility to improve the operations and increase benefits.
- Vanpooling also needs to be encouraged through a mechanism such as implementing Interest Free Van Purchasing and Van Leasing Programs and City of Memphis website provides more information of the ridership program and it can be found in the reference section (City of Memphis, 2011). Vanpooling especially needs to be emphasized to encourage increased vehicle occupancy on the HOV lane.
- Travel time messages on the TDOT Variable Message Signs along the route about HOV lane travel-time savings (based on either real-time or historical data) could popularize the travel-time benefits of the HOV lanes.

6.2. Enforcement

HOV lanes must be enforced for them to be successful. Enforcement techniques may include automated and manual video surveillance, automatic vehicle identification, infrared technology and patrols, as well as self-enforcement. The penalties should be high enough to discourage violation. Many areas have set up the HERO program where motorists are encouraged to report misuse of the HOV lanes. The HERO program implemented in Washington State began in 1984 and drivers can report HOV violators online or by calling at 1-877-764-HERO. WSDOT then mails educational materials about HOV lane usage to the vehicle that was reported to be violating (WSDOT, 2011).

6.3. Monitoring

As congestion increases the benefits on the HOV lane in Memphis, TN on I-40 are expected to increase. In the future, TDOT can consider other managed lanes options such as pricing or toll to allow single occupants to use the lane by paying a toll. To evaluate the applicability or feasibility of new strategies TDOT will need more comprehensive data about the way the system functions. One possibility is to conduct periodic monitoring programs every two or three years to keep track of the operations on the HOV lane and proactively manage it. It could be performed on a small-scale and include MOEs like vehicle volume, person throughput, travel time, and violation rate. Another innovative strategy made possible by the ubiquity of smart phones and smart phone apps in the present day is to develop a custom smart phone app that measures location, speed and time savings data and reports it to TDOT. TDOT could encourage the general public to download and use the app during their commutes and thus generate a continuous stream of data on the functioning of the system. TDOT could also consider partnering with consumer GPS navigation product companies or smart phone app companies to add these kinds of features to products that already exist and are used by the general public.

7. Limitations of the Study

Since this study is a preliminary analysis of the HOV lane on I-40 Memphis, TN there are a few limitations and they are listed below:

- The HOV lanes on I-40 Memphis, TN are operated directionally during peak periods. It is westbound during the A.M. peak and eastbound during P.M. peak. Due to limited resources such as volunteers and funding the study was conducted only during the P.M. peak which is in the eastbound direction. In general, A.M. peak are considered to be critical as that is the time when the public is in a rush to get to their workplaces. Historic data provided from TDOT, however, showed that the volumes during P.M. peaks were much higher than the A.M. peak periods, which makes the P.M. peak also very critical.
- The fact that the data was collected during the summer (June, July) which are not the typical months to collect data could also be a minor limitation. However, historic data for the year 2010 was considered and the ADT during weekdays do not show much of a seasonal variation though the summer months show slightly higher volumes which justifies the data collection during these months on I-40 Memphis, TN eastbound. Another shortcoming was that the study site selected was small and the data collected comprised of 12 days for travel times, 6 days for traffic volume and violations and 4 days for carbon footprints. The location to observe violations was at exit 15b at Appling road overpass which gives the violations at only that point. The study site for travel time data was also from exit 12 to exit 16 which is about 4 miles and the HOV lane is a total of 9 miles. These limitations were due to limited resources but the site selection was made

considering the proximity of the exits to high usage areas (residential complexes and commercial complexes) to account for the majority of driver usage of the HOV lane.

Future studies could expand the data collection efforts and use traffic simulation software to build simulation models and check the travel time improvements by reducing violation rates to give a clearer picture to TDOT about the operations on the HOV lane for them to consider alternatives to improve the HOV facility.

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9. Appendix A

9.1. Study Time Period Selection (A.M. vs. P.M. and Seasonal Variation) using TDOT ITS Radar Detection Stations

The data for this study was collected in the months of June and July, which are not typical months to collect data, and also the data was collected only during the p.m. peak (4 p.m. to 6 p.m.). To explain the variations in time periods and different seasons the data obtained from TDOT Intelligent Transportation System (ITS) radar detection stations for the year 2010 is described below. The data available from the TDOT system were for the months of February to August. The image below (Figure 18) shows the TDOT ITS radar detection stations which record daily traffic data such as daily hourly volumes and daily directional hourly volumes.

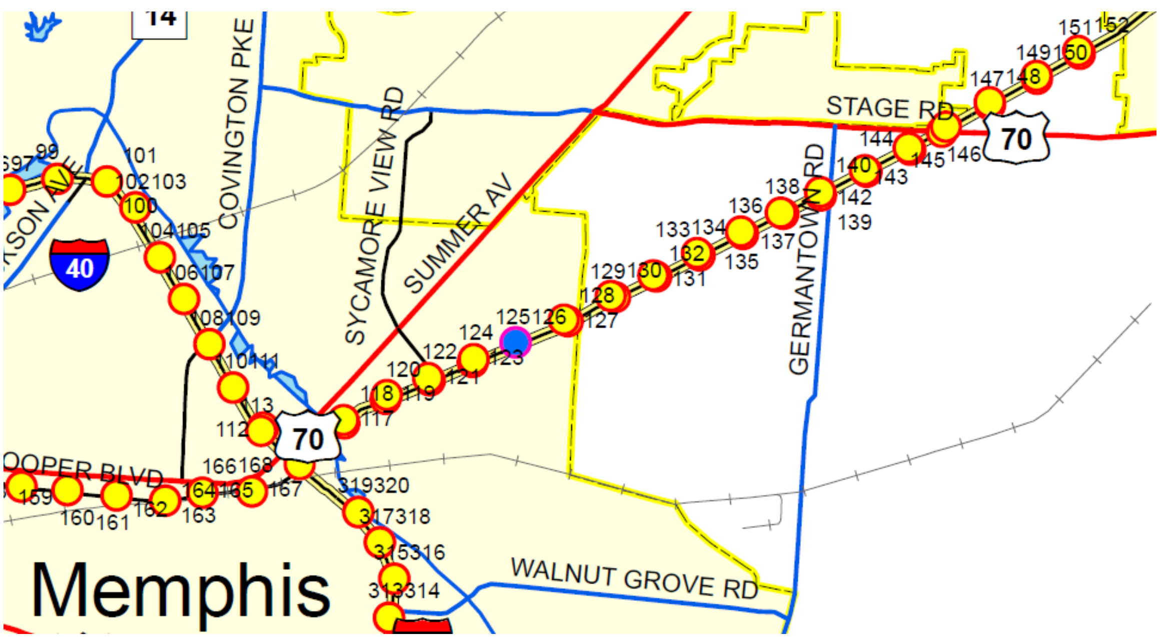

Figure 18. TDOT ITS radar detection stations in Memphis (Courtesy: Tennessee Department of Transportation)

The data from the stations 135 and 136 were considered. Station 135 is located 1,000 feet east of Appling road on I-40 eastbound and station 136 is located 1,000 feet east of Appling road on I-40 westbound. The reason for choosing these particular stations were because they fall along the strip of road used for the study and also the data for these two stations were the most consistent in the dataset (i.e., without any missing data).

The seasonal and peak period variations are shown below.

- Average Daily Traffic (ADT) during weekdays: Table 22 shows the total A.M., and P.M. average daily traffic during weekdays for each month from February 2010 to August 2010. Figures 19 and 20 show the variations for total A.M. and P.M. ADT during weekdays.

Table 22. Average Daily Traffic during Weekdays

Serial number	Month	Average A.M total during weekdays	Average P.M total During weekdays	Average Daily Traffic during Weekdays
1	Feb	40,283	64,065	104,347
2	March	41,050	66,929	107,979
3	April	40,705	71,339	112,044
4	May	37,345	79,266	116,611
5	June	37,701	79,491	117,192
6	July	36,889	80,403	117,291
7	August	36,461	78,634	115,094

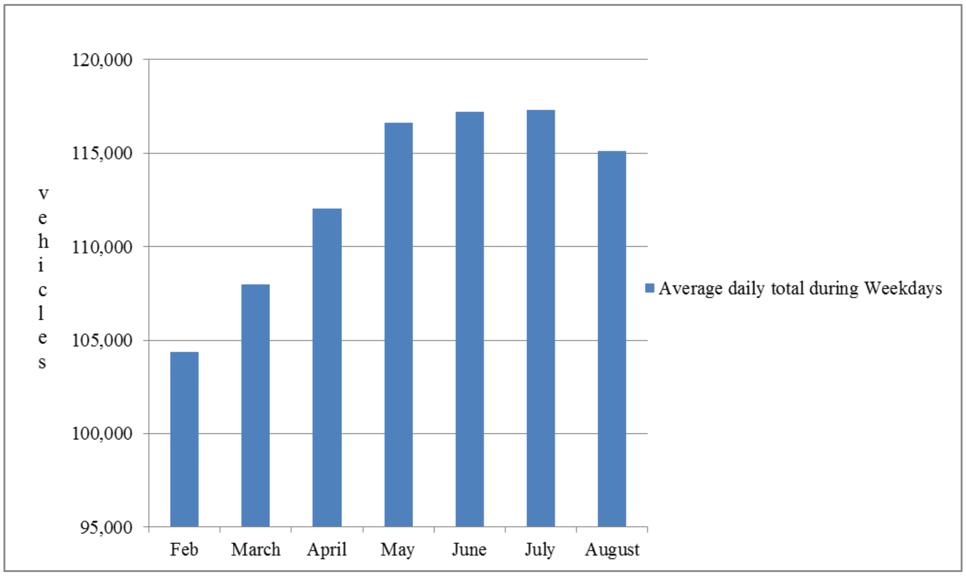

Figure 19. ADT during Weekdays monthly variation

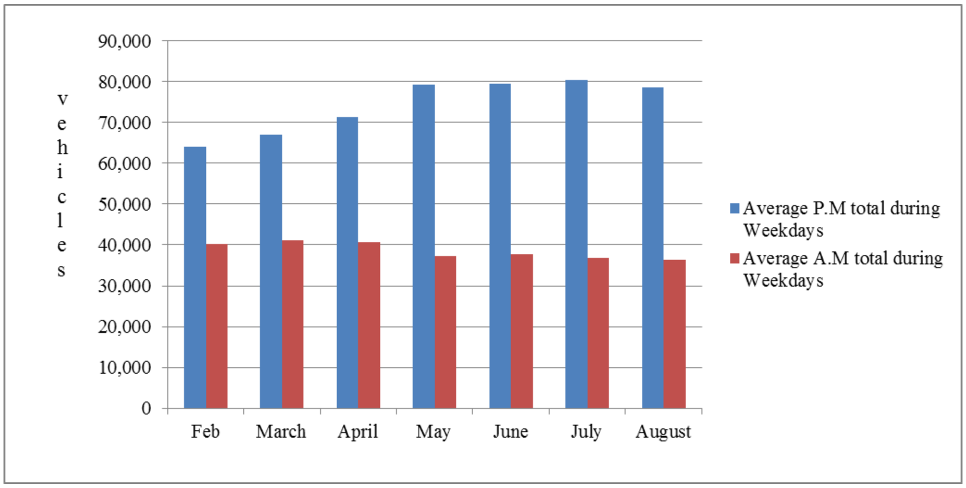

Figure 20. ADT during weekdays (A.M vs. P.M.)

- Average Daily Traffic (ADT) during weekdays at A.M and P.M. peak periods: Table 23 shows the total A.M. (7 a.m. to 9 a.m.) and P.M. (4 p.m. to 6 p.m.) peak average daily traffic during weekdays for each month from February 2010 to

August 2010. Figure 21 shows the variations for total A.M. and P.M. peak totals during weekdays.

Table 23. Average A.M and P.M peak totals

Serial number	Month	Average A.M peak total	Average P.M peak total
1	Feb	13,266	16,477
2	March	13307	16947
3	April	12723	18086
4	May	10104	21454
5	June	9878	21205
6	July	9467	21704
7	August	10242	21777

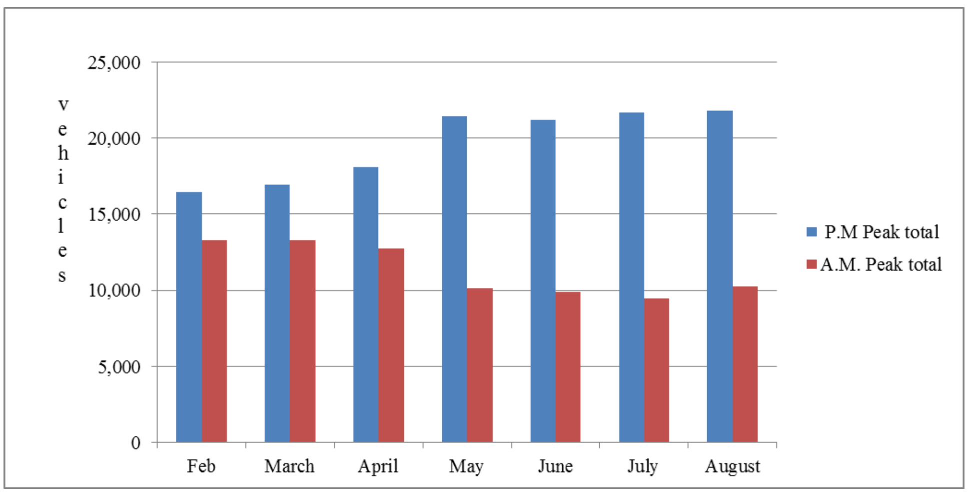

Figure 21. Average A.M. peak vs. P.M. peak totals

- Average Daily Directional Traffic (ADT) during weekdays for peak periods: Table 24 shows the total A.M. peak average daily directional traffic during weekdays (7 a.m. to 9 a.m.) where station 136 which is I-40 westbound was considered and P.M. peak average daily directional traffic during weekdays (4 p.m. to 6 p.m.) where station 135 which is I-40 eastbound was considered for each month from February 2010 to August 2010. Figure 22 shows the variations for total A.M. and P.M. peak directional totals during weekdays.

Table 24. Average A.M. and P.M. peak directional total

Serial number	Month	Average A.M peak directional total (St 136)	Average P.M peak directional total (St 135)
1	Feb	8323	10283
2	March	8039	10227
3	April	7736	10842
4	May	5,077	10,731
5	June	4923	10617
6	July	4629	10863
7	August	5116	10894

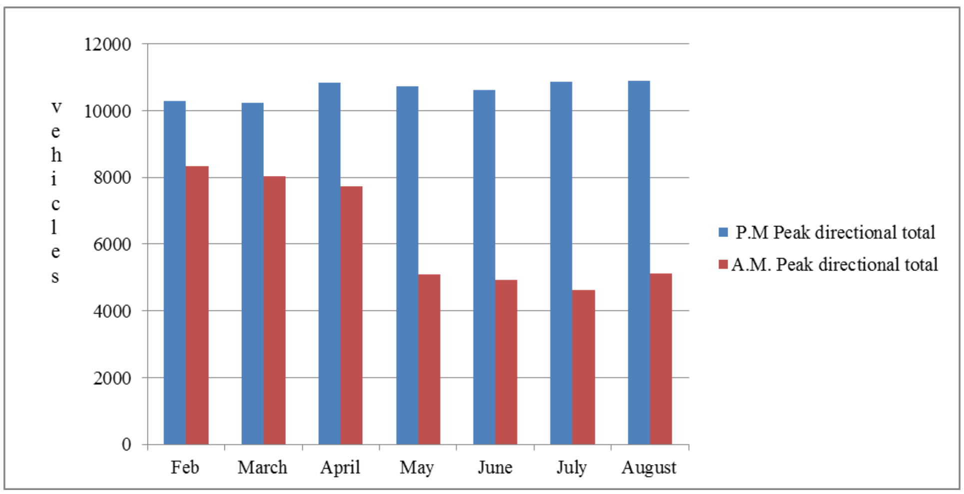

Figure 22. A.M. vs P.M. peak directional total