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Driving Economic Value: Assessing the Financial Impact of Dynamic Message Signs on Freeways

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Abstract

Dynamic Message Signs (DMSs) are an integral feature of any Intelligent Transportation System (ITS), providing drivers with real-time information such as travel time, incidents, routes, and weather conditions. This study aims to estimate the economic impacts associated with DMS use for route choice, weather advisories, and work zone management on freeways. Several freeway locations with varying levels of traffic congestion were selected to ensure a comprehensive evaluation under diverse conditions. Travel time savings and speed reductions were used as performance metrics to assess Benefit-Cost Ratios (BCRs) for each application. The findings show that DMSs yield substantial economic advantages across all use cases. For route guidance messages with a 35% diversion rate, the BCR was 1.032, indicating a cost-effective investment. Weather advisory messages recommending speed reduction achieved a notably higher BCR of 6.0, reflecting strong safety and financial benefits. Work zone applications using Portable Changeable Message Signs (PCMS) projected a BCR of 1.22. This study offers a data-driven justification for DMS deployment and contributes to the literature by focusing on financial performance, supporting strategic investment decisions beyond qualitative or operational assessments.

Keywords: Dynamic Message Signs; Benefit-Cost Analysis; Route Option; Bluetooth Sensors.

1. Introduction

Dynamic Message Signs (DMSs) are a critical component of modern Intelligent Transportation Systems (ITS), designed to enhance road safety and operational efficiency by delivering real-time information to drivers. This information often includes travel times, incident alerts, alternative routing advice, and prevailing weather conditions [1, 2]. The effective deployment of DMSs can lead to significant improvements in traffic flow and driver decision-making. For instance, studies have demonstrated that well-placed and timely messages can influence route choices, encourage safer driving speeds during adverse weather, and manage traffic effectively through work zones [3-5]. Recent systematic reviews, such as [6], continue to explore the effectiveness, influence mechanisms, and optimization strategies for Dynamic Message Signs (DMS), which share many characteristics with DMSs, highlighting the ongoing efforts to maximize their benefits in promoting rational traffic flow distribution and improving traffic safety, despite some inconsistencies in research findings and application standards.

While a considerable body of research has explored the operational and safety benefits of DMSs, a comprehensive understanding of their financial viability remains less developed. Many studies have focused on qualitative assessments

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or specific operational metrics, such as crash rate reductions or improvements in travel time reliability [7, 8]. For example, research conducted by the Michigan Department of Transportation (MDOT) and associated academic institutions has provided valuable insights into crash statistics and driver behavior in response to DMS messaging, indicating positive impacts on speed compliance and lane adherence [7, 8]. However, a persistent challenge in the literature is the robust quantification of these benefits against the substantial costs associated with DMS installation, operation, and maintenance. The broader economic impacts of transportation infrastructure investments, including safety-related components like DMS, are also an area of active research, with studies like [9] investigating how such investments contribute to economic growth and highlighting the positive impact of safety infrastructure spending on GDP. As noted by Wu et al. [6] in their review of DMS, there is a need to establish a complete influence chain from individual to group effects for comprehensive effectiveness assessment, which implicitly includes economic considerations. Furthermore, the call for coordinating DMS with other information systems for better cost-effectiveness [6] underscores the importance of financial evaluations. A clear framework for assessing the economic returns of DMS investments is crucial for informed decision-making by transportation agencies.

This gap in the literature - specifically, the need for comprehensive, data-driven economic evaluations of DMS applications across various contexts - forms the primary motivation for the present study. While some research has touched upon benefit-cost ratios for DMSs [10], and recent work continues to affirm the economic benefits of transportation safety investments [9], there remains a need for a broader examination that considers diverse DMS applications such as route choice advisories, weather-related warnings, and work zone management under varying traffic conditions. Previous work, while valuable, has often not provided a holistic financial performance perspective that directly supports strategic investment decisions beyond immediate operational or localized safety improvements, a point reinforced by the ongoing quest for optimized and cost-effective DMS strategies [6].

Therefore, this research aims to address this gap by systematically estimating the economic impacts and Benefit-Cost Ratios (BCRs) associated with DMS use across multiple key applications on freeways. Utilizing data from several freeway locations in Michigan, selected to represent diverse traffic congestion levels, this study employs travel time savings and speed reduction benefits as primary performance metrics. By focusing specifically on the financial performance and delivering clear BCRs for route guidance, weather advisories, and work zone management, this study offers a data- driven justification for DMS deployment. The findings are intended to provide transportation agencies and decision-makers with a clearer understanding of the economic returns on DMS investments, thereby supporting more strategic and financially sound deployment and operational strategies. This research contributes to the existing body of knowledge by moving beyond purely qualitative or operational assessments to provide a robust financial framework for evaluating DMS effectiveness, aligning with calls for more comprehensive and economically-grounded assessments of ITS technologies [6, 9], ultimately aiding in the optimization of these critical ITS assets.

1.1. Literature Review

Although the Manual on Uniform Traffic Control Devices for Streets and Highways identifies the overall design and restrictions of implementing the DMS, various states have inconsistent application rules for the DMS, such as message priority and usage of flashing and graphics [11-13]. These differences, however, might have a distinct impact on the driver's decision and traffic conditions.

The effectiveness and safety of DMS in various applications within road networks have been studied by several researchers. For instance, Alhomaidat et al. [14] examined the safety implications of a newly proposed crash fact sign and warning signs, which are designed following the MUTCD guide, and DMS system on drivers' traveling speed. Their study showed that drivers significantly reduced their traveling speed compared to standard situations. Reinolsmann et al. [15] investigated the influence of travel time messages on DMS, finding that 74-83% of drivers were more likely to choose alternative routes, an improvement compared to conditions without DMS. In another study, Reinolsmann et al. [16] investigated the effect of storm warning messages on rural expressways, observing a significant driver' speed reduction.

Several studies have examined the impact of the DMS on driver behavior and overall traffic conditions. Consequently, the influence of DMS on individual driving decision, as well as its broader effects on traffic flow, has been analyzed using a range of methodologies. Simulation and preference-based techniques have been predominantly used to asses drivers' preferences and compliance with DMS designs and messaging. Drivers' preferences and compliance with DMS designs and messaging. For instance, several researchers investigated the impact of DMS on traffic speed through driving simulator studies [14-17], while others utilized actual traffic data [18-20]. In one example, a stated preference survey by Zhao et al. [2] examined drivers' preferences for DMS design elements, such as content format, revealing that drivers preferred amber text on a black background for DMS messages. Furthermore, a random forest statistical technique was employed for 65 participants to evaluate the influence of various DMS designs on driver behavior [21]. The results showed that lane closure and time information with warning messages substantially impact diversion situations. On the other hand, field and traffic-related data were also employed to measure the DMS effect.

For example, the DMS is one of the most effective tools for reducing traffic congestion and trip duration by giving travel time for alternative routes. According to most literature, adopting the DMS can increase diverted traffic depending on the displayed message by up to 40% [22-25].

Moreover, a temporary Portable Changeable Message Sign (PCMS) is commonly used in a construction zone to notify drivers of approaching situations and raise their awareness, such as lane closures or moving equipment. This implementation can decrease construction-related delays by managing traffic before entering the work zone and increasing early merging [7, 26]. The PCMS has proven to considerably reduce the number of speeding cars compared to traditional traffic control devices [26-28]. For example, Li et al. [29] conducted a field study to determine the effectiveness of the PCMS in reducing vehicle speed on a two-lane highway. The study looked at three PCMS conditions: PCMS existed and was on, PCMS existed and was off, and PCMS did not exist. The data show a 4.7 mph drop in speed when it existed and turned on and a 3.3 mph reduction when it was present but turned off. Moreover, the DMS considerably influences drivers' behavior by providing weather advisory messages, particularly during the winter. These messages, such as pavement surface conditions and visibility level, can improve driving safety on the road and offer the driver weather-related advice, such as slowing down on wet pavement or using a fog light in low visibility situations [30-32].

However, it is apparent that employing a DMS offers several benefits for driver behavior and safety and improves traffic conditions. On the other hand, installing these signs is usually associated with operation and maintenance expenses. Several studies have been conducted to assess the benefits and costs of various ITS technologies [33-35]. Employing online questionnaires, Sandt et al. [35] performed research to examine the benefit-cost analysis of using the Radio advisory system to deliver travel information on the highway. According to the findings, assuming a 50 to 20 percent reduction in traffic due to highway advisory radio, the benefit-cost ratio is predicted to be 4.02 to 16.08, with a more significant percentage of trucks diverted.

Moreover, Oh et al. [36] analyzed the benefits and costs of implementing various ITS tools. The financial costs and benefits for each ITS tool, for an analysis period extended to 20 years, were estimated using a daily operation proportion provided by the TOC operator based on phone interviews. Managing traffic incidents and providing traffic information, which comprised of travel time saving, incident reduction, fuel consumption saving, emission cost saving, and cost reduction. According to the study's findings, the BCR for DMS, CCTV, MVDS, and FCP, respectively, is 3.81, 3.95, 1.02, and 3.82. Moreover, Özbay et al. [34] investigated the efficacy of incident management technologies using a simulation technique for the DMS. They used the New Jersey Highway network as a case study to examine the benefits and costs of DMS. The study compared the results of two routes both have an incident. According to the data, adopting the DMS in an incident case to divert traffic using the changes in travel times and densities on affected roads has a 20 years benefit-cost ratio of 9.2.

Moreover, a comprehensive study was conducted in North Carolina to assess the benefits of implementing DMSs on I-40 and I-26 freeways [37]. The crashes, only the direction of the DMS, on I-40 and I-26 occurred from 0.1 miles upstream of DMS to 5 miles downstream of a DMS. The study showed a BCR ranging from 1.38 to 16.95, with substantial improvements in overall traffic safety, primarily related to changes in annual crash reduction costs and the type of messages displayed. The study did not consider operational and other related benefits related to the DMS; however, the construction and maintenance cost was included. Regarding incident management and congestion, the study indicated a significant reduction in congestion and travel time due to the use of DMS. Nevertheless, one of the significant drawbacks of that study was that there were no records of how long the message was displayed and the type of the message, only the safety aspect.

A BCR ranging from 4.02 to 16.08 was achieved for travel time, depending on the congestion level and diversion rate at the selected sites. A hypothetical study by the Federal Highway Administration assessed managed lanes using DMS along with other measures on a freeway [38]. The study was designed to mimic a 10-mile urban interstate corridor over a 10-year analysis period. The findings indicated a Benefit-Cost Ratio (BCR) of 4.3:1 regarding safety, mobility, energy, and environment. However, these findings show the importance of DMS as an effective tool for roadway users.

No study was comparing the different types of DMS as it was clear from the aforementioned. literature. As a result, this research aims to assess the cost-effectiveness of employing the DMS for various applications. Therefore, the field data for various DMS installed on freeways in different regions of Michigan was analyzed to determine the benefits and costs of establishing the DMS.

2. Case Studies

The economic impacts of employing the DMS for route choice, weather advisory, and work zone were evaluated using three different Michigan freeways. Based on the DMS availability and each study's criteria, several viable sites in Michigan were selected using a DMSs location information provided by MDOT after the inspection process to meet each study purpose. Figure 1 presents a flowchart outlining the site selection process, experimental design, and benefit–cost analysis conducted for each case study. This section depicts the research sites that were selected, as well as the experimental design and benefit-cost analysis for each case study.

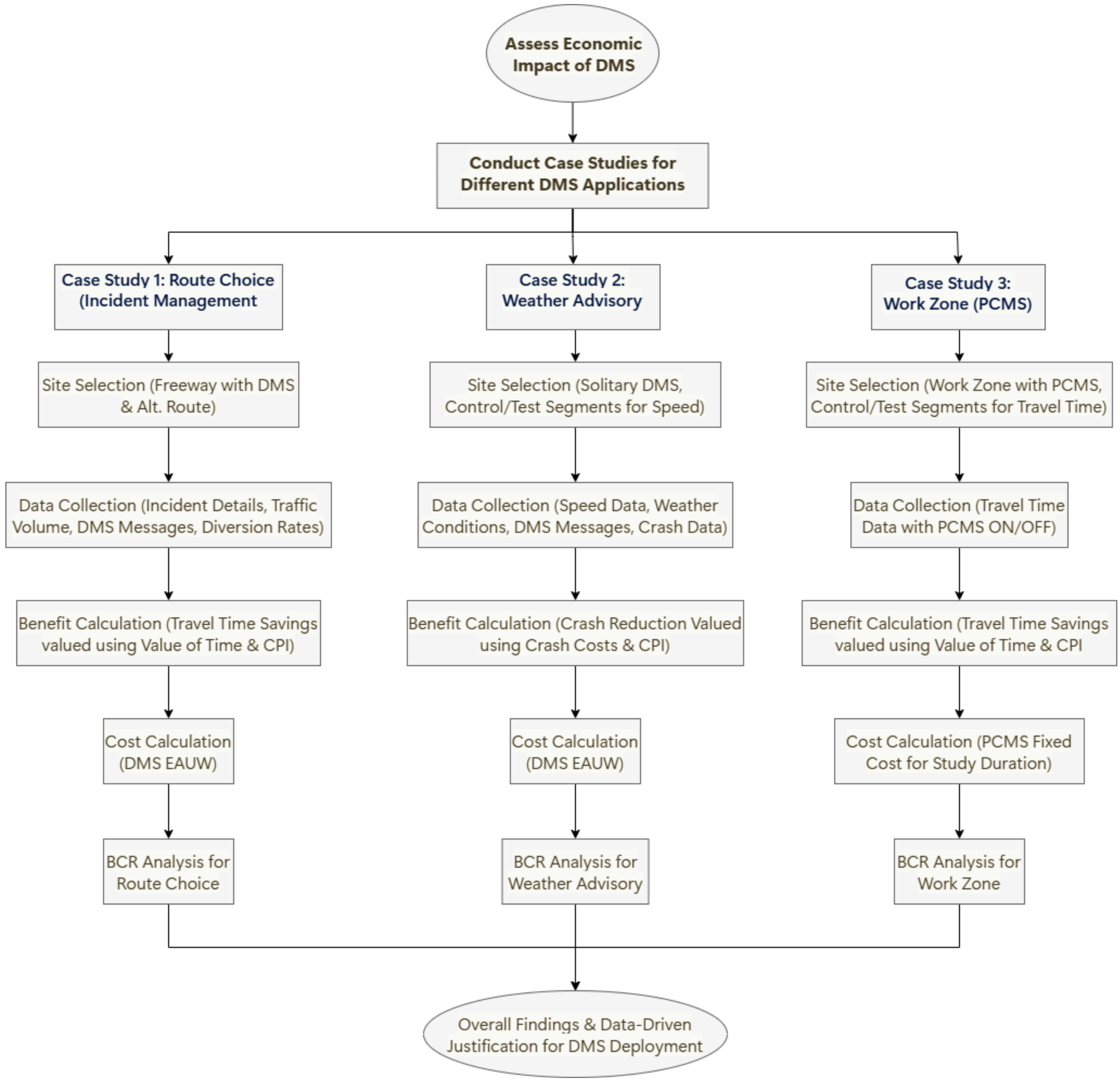

Figure 1. Flowchart illustrating the methodology for DMS site selection, experimental design, and benefit-cost analysis across the three case study applications

2.1. Experiment 1: Route Choice

2.1.1. Experiment Setup and Procedure

Because of the availability of the DMS and the limited number of access points on the alternate route, the site for the route choice research was chosen in Saginaw, Michigan (Figure 2). A DMS at this location displays travel time information using either I-75 or I-675 for the same destination. In this case study, the travel time savings were utilized to estimate the DMS revenue in order to conduct a benefit-cost analysis for route choice. The direct route (I-75) consists of three lanes in each direction with a speed limit of 70 mph and 6.7 miles length, whereas the alternate route (I-675) has two lanes with the same speed limit and 9 miles length. It has been noted that the direct route consistently proves to be faster than the alternate route over the entire research period. However, on 10/23/2020, a change in the displayed travel time was detected as a result of an incident that happened at 17:16 on the I-75, which resulted in an increase in travel time on the direct road and provided a chance to estimate the savings corresponding to DMS message. Bluetooth sensors (SMATS TrafficBox with approximately 330 ft detection range) and video cameras were used to track vehicles individually along alternate routes to record the time savings obtained by employing DMS to display a travel time for route choice (Figure 3). The Bluetooth sensors detected signals from smart devices, such as smartphones, tablets, wearables, and embedded systems in vehicles, through their Bluetooth Media Access Control (MAC) addresses or fingerprints. Therefore, as a single device might be detected multiple times while passing a specific Bluetooth sensor, observations sharing similar fingerprints were averaged to derive a singular value. Furthermore, differences in timestamps between devices at each sensor were checked to prevent the detection of multiple devices within a single vehicle. Four sensors were placed in various locations.

The first sensor was mounted along the direct route (I-75) before the diversion point, near the origin Dynamic Message Sign (DMS), with the purpose of monitoring the traffic volume entering the diversion point. Sensor No. 2 was mounted along the direct route (I-75), and Sensor No. 3 was mounted on the alternate route (I-675). Their purpose was to determine the route selected by vehicles to complete their journey., and sensor No. 4 was mounted on the destination pole located at I-75 after the traffic meets again to verify that vehicles have completed their trip. This configuration captures the vehicle's route from origin to destination and the change in diversion rate from the direct route based on the DMS's displayed travel time. The data collection phase extended over a three-week period. During the first week, the DMS showcased travel time information (DMS ON), followed by a subsequent week where travel time was intentionally omitted from the DMS display (DMS OFF). In the "DMS OFF" mode, although travel time data was internally logged, it was not visible on the DMS interface. This information was later retrieved and made accessible to the research team. The display of travel time details to drivers resumed from the third week onward.

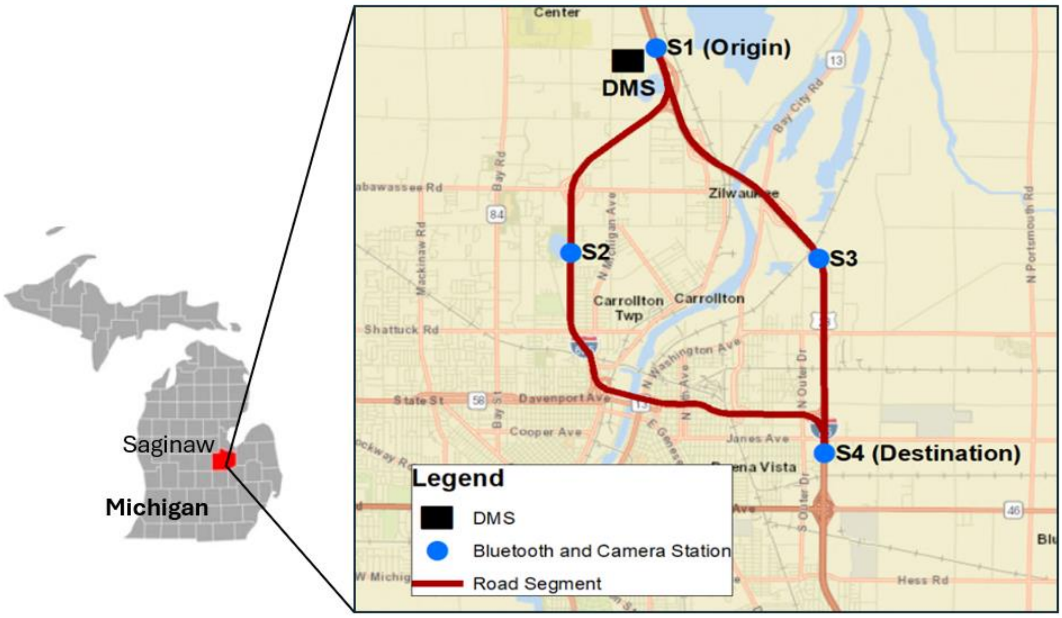

Figure 2. Experiment setup for route choice related DMS

Figure 3. Examples of sensor mounting mechanisms

2.1.2. Methodology

Vehicle counts were conducted manually, and Bluetooth sensor data provided minute-by-minute volume information. This data was utilized to formulate a function depicting the number of vehicles choosing the alternative route (I-675) based on travel time. The function established a link between the displayed travel time on the DMS during the incident and the minute-by-minute count of cars completing the trip on I-675. The final dataset encompassed DMS-displayed travel times for alternative route and the corresponding number of completed trips for each minute throughout the incident. Based on research conducted on the same location by Kwigizile et al. [7], a 35 percent diversion route was utilized to reflect traffic diverted due to a displayed travel time message on DMS. This rate was derived from modelled estimates, supported by traffic volume data collected from sensors located at key decision points along the highway network. As a result of the displayed travel time information on DMS, the final dataset included the number of completed trips on I-675. Subsequently, we calculated the travel time value by applying the inflation rate, determined from Consumer Price Indices (CPI) provided by the United States Department of Labor's Bureau of Labor Statistics. The calculations were based on CPI values for 2015 (CPI=236.525) and 2021 (CPI=273.567), aiming to quantify the savings attributed to the dissemination of travel time information on Dynamic Message Signs during the incident. As a result, the time value for a passenger car and truck were calculated to be $23.58 and $31.44 per hour respectively ($0.393 and $0.524 per minute respectively) based on 2015's value of time ($0.34 per minute for passenger car and $0.453 per minute for truck).

2.1.3. BCR Analysis and Results

To evaluate the cost-effectiveness of implementing DMSs on freeways, it is essential to conduct an economic analysis over a period of time, since the benefits of DMSs are typically realized years after installation. Various indicators can be used to assess the cost-effectiveness of different projects, including Net Present Worth (NPW) and Equivalent Uniform Annual Worth (EUAW). While NPW relies on the present value of costs and benefits, EUAW, as a conversion of NPW, effectively captures the benefits and costs of DMS over time. Consequently, the costs of DMS were allocated annually throughout its 15-year lifespan using Equivalent Annual Uniform Worth (EAUW), represented as:

$$EAUW = -C\left[\frac{i(1+i)^n}{(1+i)^n-1}\right] - M \tag{1}$$

where C represents the initial cost ($72,000) (MDOT), i is the discount rate, n is the number of years, and M represents the annual maintenance cost ($2,300) (MDOT). The benefit of the DMS, on the other hand, was calculated based on the time saved by the display of travel time information when the incident occurred. As a result, the following equation was created to take into consideration the yearly number of incidents as well as the incident length, where the DMS will display a shorter travel time if an alternate route is taken:

$$DBI_i = \sum_{min=1}^{last\ min}(VT_c \times V_C + VT_t \times V_t) \times MF \times DF \tag{2}$$

where DBIi is DMS Benefit during Incident which refers to the total savings during a single incident, VT_c is the value of time per minute ($0.393/min) for passenger car, V_c is the number of passenger cars that complete the trip using the alternative route (I-675) per minute, VT_t is the value of time per minute ($0.524/min) for truck, V_t is the number of Trucks that complete the trip using the alternative route (I-675) per minute, MF is the difference in the displayed travel time between the Direct route and the alternative route, and DF is the probability of taking the alternative route during the displayed DMS message (0.35). Refer for full report for more details [7]. Finally, the yearly DMS savings may be calculated by adding up all of the occurrences that happened at that site during the year:

$$DBI = \sum_{i=1}^{N} DBI_i \tag{3}$$

During the study period, only one incident that occurred on 10/23/2020 lasted 39 minutes, and the savings from diverted traffic due to the displayed DMS message was projected to be $187 for the length of the incident. The associated DMS cost for that incident ($0.618) indicates a Benefit-Cost Ratio (BCR) of 302.59. However, an annual BCR value was calculated due to the incident variation at the location. Crash data for the previous five years showed an average of 46 incidents each year at that route (I-75). Therefore, it was assumed that all 46 incidents had the same characteristics as the one that occurred during the research period, including duration and impact on traffic flow. As a result, the annual DMS benefit-cost analysis was projected to be 1.032 by assuming that all incidents have the same characteristics as the one that happened on 10/23/2020. However, it should be noted that other parameters like AADT and truck percentage might affect DMS saving.

Further analysis examined how variations in key parameters affect the BCR value. The relationship between Annual Average Daily Traffic (AADT) and BCR was particularly notable, as shown in Figure 4. The sensitivity analysis revealed a strong positive correlation (0.93) between AADT and BCR, indicating that higher traffic volumes significantly increase the economic benefits of DMS deployments.

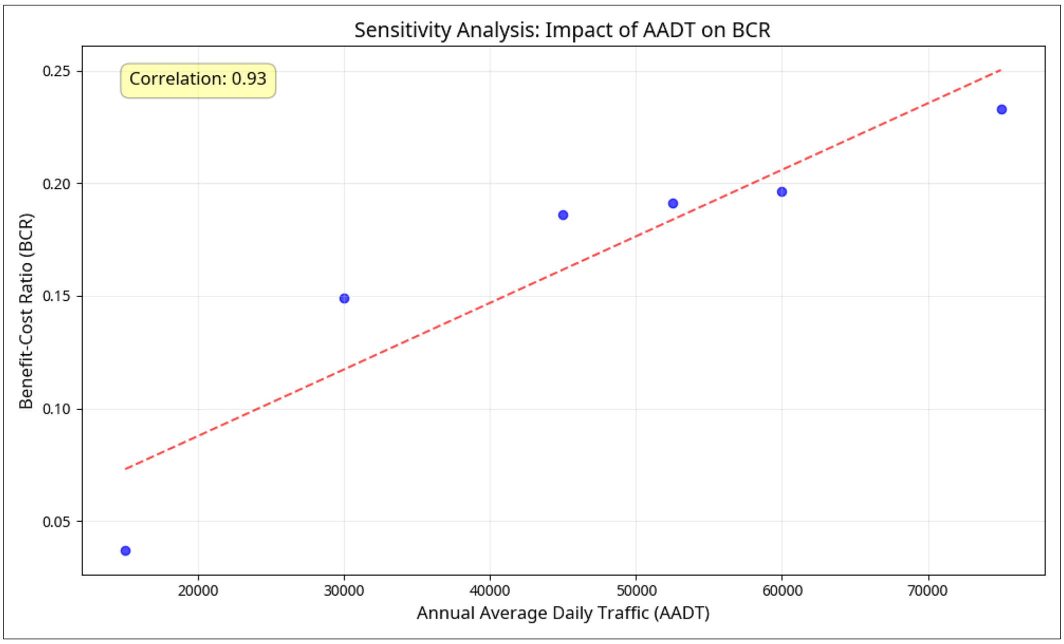

Figure 4. Sensitivity Analysis of AADT Impact on BCR

Figure 4 illustrates the strong positive relationship between Annual Average Daily Traffic (AADT) and Benefit-Cost Ratio (BCR). The trend line (dashed red) shows that as traffic volume increases, the economic benefits of DMS increase proportionally. The correlation coefficient of 0.93 indicates that AADT is a highly influential factor in determining the economic viability of DMS installations for route choice applications. A comprehensive sensitivity analysis was conducted to identify which factors have the greatest influence on the economic benefits of DMS for route choice applications. the tornado chart (Figure 5) ranks the three key variables by their absolute correlation with BCR. Diversion Rate shows the strongest relationship, indicating that the percentage of drivers who follow DMS guidance is the most critical factor in determining economic returns. AADT ranks second, confirming that traffic volume is a major determinant of DMS benefits. Length Difference between primary and alternative routes ranks third but still shows a strong positive correlation with BCR. These findings have important implications for DMS deployment strategies. Transportation agencies should prioritize DMS installations at locations with high traffic volumes and significant potential for diversion to alternative routes. The strong correlation between AADT and BCR suggests that economic benefits increase substantially in high-volume corridors, making these locations particularly attractive for DMS investments. Additionally, the influence of diversion rate highlights the importance of effective message design and placement to maximize driver compliance with DMS guidance.

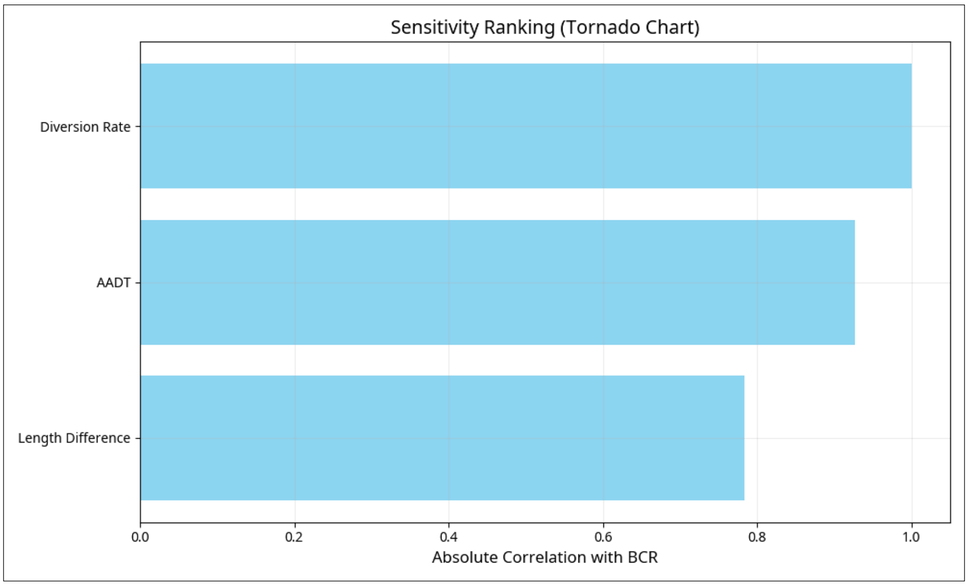

Figure 5. Sensitivity Ranking of Variables Affecting BCR

2.2. Experiment 2: Weather Advisory

2.2.1. Experiment Setup and Procedure

The DMS density was the primary consideration for choosing study location. This decision was driven by the fact that in areas with multiple DMS installations, the same weather-related message tends to be displayed on all signs simultaneously. This uniformity makes it challenging to isolate the specific impact of an individual DMS. Therefore, to overcome this limitation, a solitary DMS located on a section of the I-96 highway with speed limit of 70 mph in Grand Rapids, Grand Region, specifically identified as S196W-MM0413-Forest Hill, was deliberately selected for the study. The selection of the site was mainly based on two key factors: the DMS's capacity to display weather-related messages during relevant weather conditions, and the site layout designed with a minimal number of merging and diverging points. The benefit measurement for the DMS effectiveness was the change in travel speed. As a result, Bluetooth sensors and cameras were placed to monitor speed changes as well as traffic volume and weather conditions. Three separate segments were produced to capture the influence of the weather-related message "ROAD MAY BE SLIPPERY, REDUCE SPEEDS" displayed by DMS on traffic. The site was divided into three segments using four Bluetooth sensors: Segment 1 (0.55 mi) between sensor No.1 and sensor No.2 was used as a control segment to capture drivers' speed before they read the DMS message. Segment 2 (0.55 mi) between sensor No.2 and Sensor No.3 (DMS location) was used to estimate the immediate effect of the DMS message on the speed, and segment 3 (0.49 mi) between Sensor No.3 and sensor No.4 was used to check the long-term effect of the DMS message on the speed. The benefit-cost ratio was computed based on the observed speed reduction at the case site, which amounted to 5.66 mph. The experiment setup for the weather-related investigation is shown in Figure 6.

Figure 6. Experiment setup for DMS weather-related message

2.2.2. Methodology

The number of reduced crashes due to the speed reduction produced by the DMS weather warning message was utilized to quantify the DMS cost benefits by associating the number of reduced crashes with the speed reduction caused by the DMS weather advisory message. This approach was employed because the impact of DMS weather advisory messages would manifest as a speed reduction. In this study, weather-related messages were directly observed using Bluetooth sensors installed along the roadway. Compliance was quantified by comparing vehicle speeds in conditions where no weather-related message was displayed and when a message was active, as well as by comparing speeds along case and control segments. As a result, an exponential model was employed to link the number of crashes before and after speed change [39]. The model was created for speeds ranging from 20 to 120 kilometers per hour. It revealed a consistent association between average speed and the number of crashes in urban and rural areas. The model may be written like this:

$$A_2 = A_1 e^{\beta(V_2 - V_1)} \tag{4}$$

where A_1 and A_2 are the number of crashes before and after the speed reduction, respectively. β is a crash severity coefficient, V_1 and A_2 are the before and after average speed values. The crash data from the case study site in 2019 were analyzed to identify incidents occurring when the DMS exhibited a weather-related message. Out of a total of 20 crashes recorded near the DMS that year, only one took place during the display of a weather-related message. This particular incident was categorized within the post-period (A2) and, in conjunction with the observed speed reductions, was utilized to estimate crashes that might have occurred had the weather-related messages not been displayed, indicating the potential reduction in crashes. Finally, Societal Costs of Traffic Crashes and Crime in Michigan were used to determine the cost of the crash.

2.2.3. BCR Analysis and Results

The associated cost with the DMS may be determined using the EAUW, which includes installation and maintenance costs for 15-year service life, in the same way as the route choice case. As mentioned earlier, the DMS benefit in this scenario can be calculated based on the crash variation due to speed reduction. As a result, the Societal Costs of Traffic Crashes and Crime in Michigan were used to determine the cost of the crash [40]. However, because the crash value was reported in 2017, the crash value in the crash year (2019) was calculated using an inflation rate. As a result, the CPI values for 2017 (246.524) and 2019 (256.759) were utilized to determine the inflation factor (256.759/246.524 = 1.0415), similar to the route case study. Then by multiplying the inflation factor by the 2017 crash value ($226,530.61), the 2019 crash value was calculated. Finally, the adjusted value of the accident was multiplied by the crash reduction due to the utilization of the DMS to show a weather-related message, resulting in a $50065.5 savings. Finally, a BCR value of 6.0 was derived based on the benefits and costs of displaying weather-related messages on the DMS under comparable conditions to the case study.

2.3. Experiment 3: Work Zone

2.3.1. Experiment Setup and Procedure

A 1-mile highway work zone was selected to conduct a benefit-cost study for a Portable Changeable Message Sign (PCMS) on I-96 southbound in Saugatuck, Michigan. The site was selected based on availability of work zone with limited access points during study period that utilized a PCMS. This sign was placed 1.85 miles from the start of the work zone to warn drivers about a lane closure ahead. The time saved by using the PCMS, on the other hand, was utilized to assess the PCMS's cost-effectiveness. Figure 7 depicts the experiment setup, which included the use of Bluetooth and cameras. The first Bluetooth sensor and camera were mounted on a temporary pole at the PCMS site. The second sensor and camera were put at the start of the taper, and the last sensor was installed at the end of the work zone. By tracking each car individually, this configuration allows for recording the influence of PCMS and identifying the highway segment where the time savings occurred.

Figure 7. Experiment setup for PCMS work zone-related message

2.3.2. Methodology

The travel time savings between the PCMS and the work zone taper was captured for two PCMS instances when it was ON and OFF to assess the benefit of employing the PCMS at work zone locations. As a result, the average travel time between the PCMS and work zone taper was linked to the number of vehicles per minute (Veh/min) using Bluetooth sensor data and traffic count (MVDS). In order to determine the average travel time associated with each minute, the average Bluetooth device travel time within a minute was determined. Then, the average travel time for minutes with the same number of vehicles was determined. As a result, for each PCMS instance (ON and OFF), the number of vehicles and the average travel time will be attributed to each minute. The data were utilized to develop two functions that correlate the travel time and the number of vehicles within a minute in order to estimate the travel time savings (for both instances). The travel time saving was then calculated for each minute with the allocated number of vehicles by subtracting the travel time when the PCMS was ON from the case while the PCMS was OFF. Finally, based on the number of vehicles within each minute for the scenario when PCMS is ON, the travel time saving for each minute was obtained.

2.3.3. BCR Analysis and Results

While some agencies identify the PCMS cost in daily basis (per day), the PCMS has a one-time (Lump sum) cost of $6,950, including $5,450 for installation and $1,500 for maintenance, according to the MDOT. As a result, because the benefit of using the PCMS varies depending on the work zone duration, the benefit cost analysis was done daily (1440 minutes). As a result, each minute of the day was allocated to a distinct travel time saving based on the observed number of vehicles per minute for that location after identifying the travel time saving while the PCMS is ON

The daily travel time savings were converted to actual savings using the CPI for 2015 and 2021, similar to the route choice research. Then, to calculate the total daily savings, the following equation was used:

$$DS = \sum_{min=1}^{1440} (P \times TS \times TV) \tag{5}$$

where DS denotes total daily savings, P is the number of vehicles per minute, TS is travel time savings per minute, and TV is the value of passenger car travel time based on CPI ($0.393/min). Finally, by utilizing the PCMS at the work zone, the benefit-cost ratio (BCR) was calculated based on the fixed cost and the total number of vehicles minute by minute. Therefore, a 1.22 BCR ratio was determined for the case study of the work zone in Saugatuck, Michigan based on the recommended duration (3 days) for employing the PCMS in the case of lane closure by the Work Zone Safety and Mobility Manual given by MDOT (26). This BCR has a savings of $8445 ($2,815×3 days) and a fixed cost of $6,950. It should be noted that the BCR value rises with the number of days the PCMS is used at the work zone, which is to be expected given the PCMS's fixed installation and maintenance costs.

A detailed analysis of daily benefits distribution shows that the majority of benefits occur during peak traffic periods, despite these periods representing only a fraction of the total day. This temporal pattern of benefits has important implications for PCMS deployment strategies, particularly for short-term work zones where maximizing economic returns is critical. The analysis demonstrates that PCMS deployment becomes economically advantageous after a specific duration of operation. For longer-term work zones, the economic benefits increase substantially, with each additional day adding to the BCR value. This finding has significant implications for work zone planning and resource allocation, suggesting that PCMS should be prioritized for longer-duration projects to maximize economic returns. Recent sensitivity analysis of work zone PCMS data provides additional insights into the factors affecting economic benefits. Comparing message ON versus OFF conditions reveals a 14.2% improvement in travel time (4.06 minutes vs. 4.73 minutes) and a 7.8% improvement in speed (55.92 mph vs. 51.86 mph) when messages are active. These improvements translate directly into economic benefits through time savings and enhanced safety. Figure 8 illustrates the significant difference in travel time between message ON and OFF conditions. As shown, the activation of PCMS results in consistently lower travel times across the study area, demonstrating the direct operational benefits of message sign deployment.

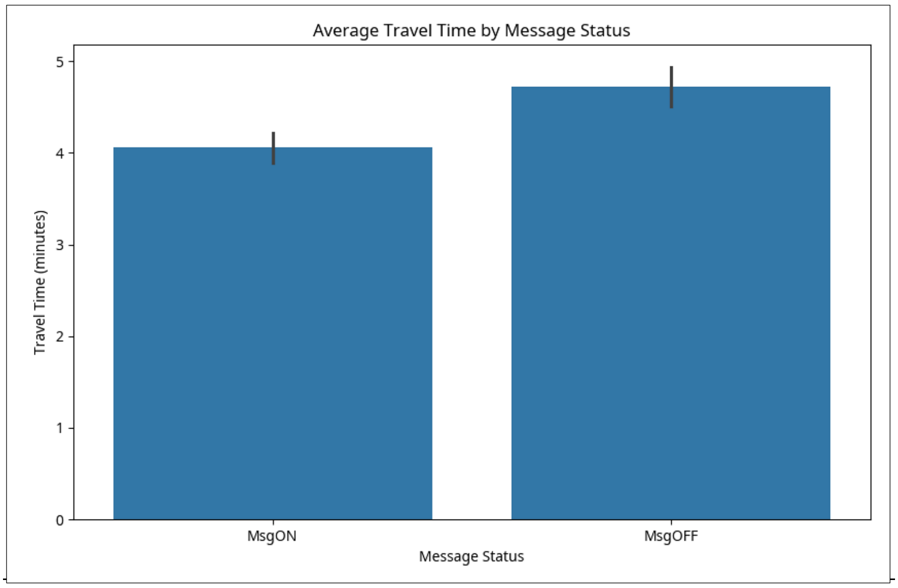

Figure 8. Average Travel Time by Message Status

The figure clearly demonstrates the substantial impact of PCMS message status on travel time through the work zone area. The 14.2% reduction in travel time when messages are active represents a significant operational improvement that directly translates to economic benefits. The error bars, representing standard deviation, indicate moderate variability in travel times for both conditions, with slightly higher variability in the Message OFF condition. This suggests that PCMS not only reduces average travel time but may also contribute to more consistent and predictable traffic flow. This visualization provides compelling evidence for the operational effectiveness of PCMS deployment in work zones, supporting the BCR calculations presented in the study.

The sensitivity analysis further demonstrates that Time of day also significantly influences PCMS effectiveness. The analysis revealed distinct patterns across different time periods (Night 0-6, Morning 6-12, Afternoon 12-18, Evening 18-24), with implications for deployment scheduling. These temporal variations suggest opportunities for optimized PCMS operation strategies that focus resources during periods of maximum benefit. Figure 9 illustrates how travel time varies by time of day and message status. The visualization reveals important temporal patterns in PCMS effectiveness, with certain periods showing greater improvements than others when messages are active.

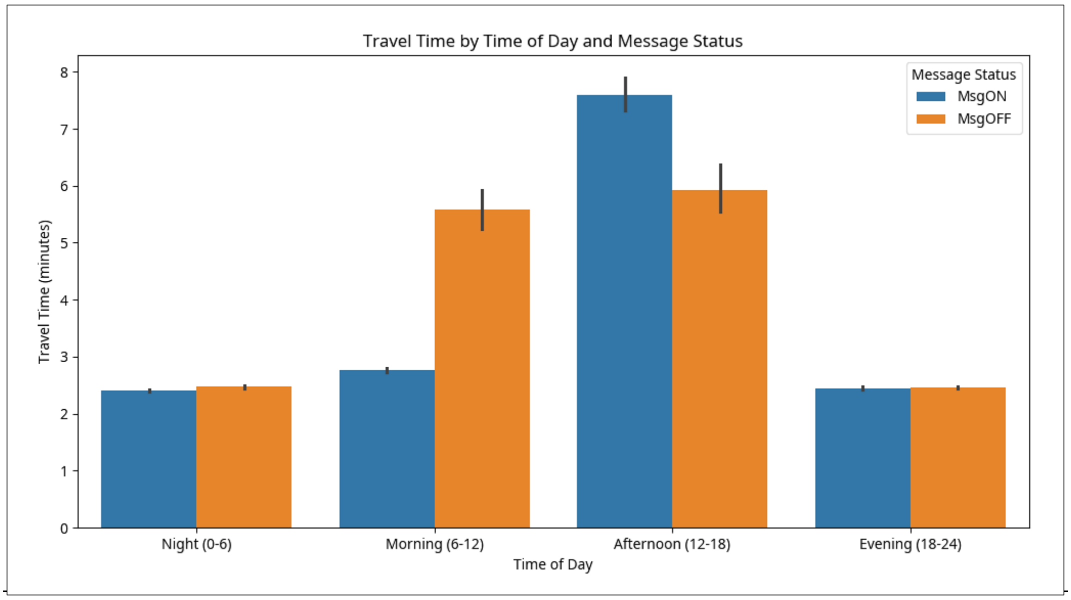

Figure 9. Travel Time by Time of Day and Message Status

This visualization reveals critical temporal patterns in PCMS effectiveness that have significant implications for deployment scheduling. The most substantial benefits occur during Morning (6-12) and Evening (18-24) periods, which typically correspond to peak commuting hours. This aligns with expectations that PCMS would have greater impact during periods of higher traffic demand and potential congestion. The Afternoon period (12-18) shows moderate benefits, while the Night period (0-6) demonstrates the smallest absolute improvement, likely due to naturally lower traffic volumes during overnight hours. The relative improvement appears most significant during the Morning period, suggesting this may be the optimal time for ensuring PCMS activation if resources are limited. These temporal patterns provide transportation agencies with evidence-based guidance for implementing time-of-day strategies for PCMS operation, particularly for solar-powered units where power conservation might be necessary.

Figure 10 presents the relationship between deployment duration and BCR across different volume categories. The visualization clearly demonstrates how BCR increases with duration, with the rate of increase varying by traffic volume. The horizontal red line indicates the break-even point (BCR=1), showing the minimum duration required for economic viability under different conditions. This line graph presents perhaps the most actionable insights for transportation agencies, clearly illustrating how BCR increases with deployment duration across different volume categories. The upward slope of all lines confirms that longer deployments substantially improve economic returns, with BCR increasing linearly with duration. The varying slopes across volume categories demonstrate that traffic volume significantly influences the rate of BCR improvement over time, with higher volume categories showing steeper slopes, indicating faster returns on investment. The horizontal red line marking BCR=1 allows easy identification of the minimum deployment duration required for economic viability under each volume condition. For "High" volume conditions, this threshold is reached relatively quickly, while "Medium" volume conditions require substantially longer deployments. The negative initial BCR for "Medium" volume conditions is particularly noteworthy and aligns with the unexpected travel time findings. This visualization provides transportation agencies with a powerful decision-making tool for determining optimal deployment durations based on expected traffic volumes.

These findings from the sensitivity analysis provide transportation agencies with actionable insights for optimizing PCMS deployment. The results suggest that prioritizing message sign deployment in higher traffic volume areas, planning for longer deployment durations, and implementing time-of-day strategies will maximize economic benefits. The comprehensive analysis of message status impact, traffic volume sensitivity, time of day variations, and BCR calculations offers a robust framework for evidence-based decision-making in work zone management.

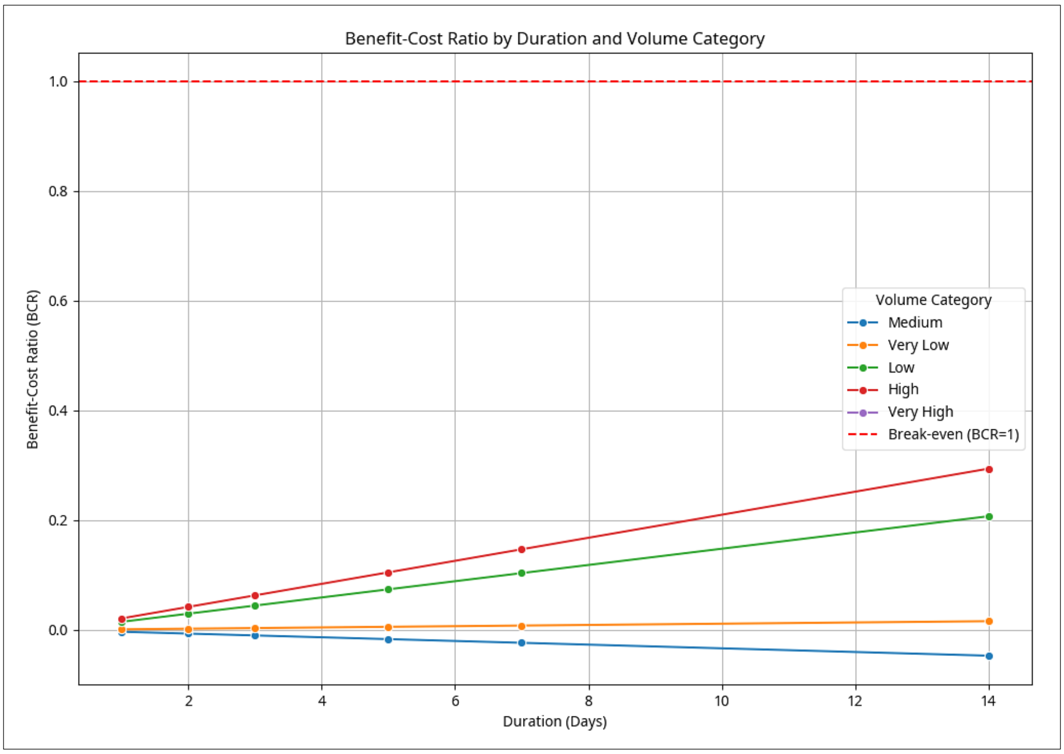

Figure 10. Benefit-Cost Ratio by Duration and Volume Category

3. Discussion

Regardless of the operational benefits of employing the DMS to manage traffic, raise driver awareness, and reduce travel time, DMS operation under a variety of conditions such as route choice, weather advisory, and construction zone has an economic benefit. The cost-benefit analysis for using the DMS to provide highway users with travel time information for route choice was estimated at 1.032. On the other hand, this ratio was estimated based on various parameters relevant to the case study location. For example, the direct route was 3 miles shorter than the other route, implying that the direct route is faster most of the time, indicating that the DMS's benefit is limited to incident management. As a result, implementing the DMS on the highways with a higher fluctuation of the time not necessary due to an incident might boost compliance, thereby increasing the DMS's benefit. This result in line with previous similar studies. For instance, Lappin [33] found a substantially higher BCR of 9.2 for DMS implementation in New Jersey, while Sandt et al. [35] reported BCRs ranging from 4.02 to 16.08 for travel information systems. This discrepancy can be attributed to several factors: our study used actual field measurements rather than simulation models, considered a more limited set of benefits (focusing primarily on travel time savings), and examined a route configuration where the alternative path was significantly longer, reducing the potential benefit margin.

For example, Jeihani & Ardeshiri [41] attempted to evaluate the influence of the time difference for route option travel time message displayed on DMS in simulation research. The study looked at the effect of varied time intervals of 5 minutes, 10 minutes, and 15 minutes on the drivers' compliance rate. The data reveal that raising the difference in travel time for a travel time message increases the compliance rate, indicating that changing the timing of the DMS message changes the compliance rate. Furthermore, the BCR value is determined based on various assumptions about the incident at that site, such as the average number of annual incidents that occurred and the duration of each incident. As a result, from an economic perspective, the use of the DMS can be optimized by coordinating DMS implementation with areas with a high number of incidents or requiring more time to clear the incident from the roadway. This is based on the fact that one of the most important DMS goals is to relieve traffic congestion and also to display a safety message that can reduce the number of incidents, which increases the benefit of using the DMS for route choice since the DMS safety message can change the driver's behavior [42].

The analysis for the weather-related DMS was based on the reduction in crashes as a result of displaying a weather-related message with a recommendation to reduce speed. According to the research, the DMS benefit has a 6:1 annual ratio. The investigation also revealed a drop in the vehicle's high speed (above 80 mph). As a result, the effectiveness of the DMS for weather-related messages may be maximized by focusing on freeways with a high frequency of crashes due to speeding during inclement weather. Weather advisory DMS findings represent a significant contribution to the literature, as few previous studies have quantified the BCR for this specific application. The calculated BCR OF 6 substantially exceeds the values reported for other ITS technologies by North Carolina Department of Transportation [37], who found BCRs of 3.81 for general DMS applications. The reduction in high-speed driving behavior (vehicles traveling above 80 mph) we observed is particularly noteworthy and consistent with the findings of Rämä [32], though this study provides more detailed speed distribution analysis. The measured speed reduction exceeds the reductions reported by Hogema & Van Der Horst [30], suggesting that modern DMS implementations may achieve greater compliance than earlier systems. Enhancing the DMS weather-related message is also an option for maximizing the DMS benefits. According to a recent study [7], providing a suggested action in a weather advisory message displayed on the DMS substantially influences traffic speed.

Finally, the PCMS cost and travel time saving were used to estimate the work zone benefits based on daily biases. Despite the research revealing a BCR of 1.22, the PCMS benefits (BCR) rise with the number of days spent using the PCMS. As a result, the PCMS cost should be repaid in a few days, as the PCMS is frequently used for more than three days for maintenance and construction, particularly on freeways. The work zone PCMS results provide valuable insights that extend beyond previous research. The relationship we identified between traffic volume and PCMS effectiveness is a notable contribution that enables more precise prediction of benefits under varying conditions. The travel time measured improvement is consistent with but slightly higher than the improvements reported by Oh et al. [36], potentially due to the optimal PCMS placement at 1.85 miles before the work zone. The analysis of benefit distribution across different times of day provides critical operational guidance not available in previous studies. When comparing the PCMS findings with other research, the measured early merging compliance rate with PCMS aligns closely with Bai et al. [43], who reported similar compliance rates. However, the measurements of travel time savings in this study provide a more direct economic quantification than previous studies that focused primarily on speed reduction metrics. The reduction in speed variability we observed represents an important safety benefit that complements the economic advantages, supporting the findings of Huang & Bai [44] regarding PCMS effectiveness in promoting more uniform traffic flow.

The traffic condition is another factor that affects PCMS revenue. According to the research, increasing the traffic volume handled by the work zone increases the benefit of using the PCMS at the work zone. Furthermore, multiple studies have shown that combining the PCMS sign with other convectional signs increases traffic compliance with displayed messages, resulting in a higher BCR value. The impact of various temporary traffic control techniques on speed, for example, was explored by Jalaei & Jrade [45]. PCMS (on Roller and Trailer), radar speed monitoring, and police patrolling were all investigated by the researchers. When compared to the actual traffic control plan speed, combining PCMS with additional techniques like police (parked in site or patrolling) resulted in a larger speed reduction (Mean= 44.24 mph) than using PCMS alone (50.56 mph). Furthermore, various studies suggest that by managing some characteristics, such as incorporating a visual and a proper location for the PCMS, the efficiency of the PCMS can be improved, resulting in increased driver compliance with the displayed messages [43, 44].

However, it should be noted that traffic characteristics such as volume and composition have a considerable influence on the DMS's economic advantages. Furthermore, even though the DMS benefit-cost analysis was done separately in this study based on the study purpose, the DMS has the ability to display different types of messages (route choice, weather-related, and work zone-related) for the same location, making the DMS more beneficial since it is associated with the same initial and maintenance costs.

4. Conclusion

This study aims to investigate the benefits and costs of using the DMS for various purposes such as route options, weather-related messages, and work zone-related messages. The outcomes of the investigation revealed that DMS is a useful tool not only in terms of operations but also in terms of cost. For route choice, weather-related, and work zone messages, the benefit-cost assessments were reported as BCR (1.032, 6, and 1.22, respectively). In the instance of route options, the investigation revealed that DMS is more useful in incident management since it can display travel time information for an alternate route. The weather-related analysis shows that, in addition to improving roadway safety, the displayed weather-related messages are also linked to real savings due to incident reduction, even if the decrease is minimal (0.2122). Finally, the study of using the PCMS in the work zone reveals that the time spent using the PCMS is an important factor in maximizing PCMS profit. It is recommended that agencies use it for a few days to maximize revenue. As a result of the investigation, site features, DMS characteristics, including content and location, and traffic conditions all significantly affect DMS benefits. However, the results of this study provide robust evidence for the economic viability of DMS implementations across multiple applications. The analysis confirmed significant differences in driver behavior across all three applications. The route choice experiment demonstrated a meaningful increase in diversion rates during incidents when DMS was active. The weather advisory application achieved a notable reduction in mean speeds and a substantial reduction in high-speed driving behavior. The work zone application improved travel times and increased early merging compliance.

On the other hand, due to a lack of resources, this study has several limitations. Estimates of the BCR ratio were limited to site features that impact the amount of benefits. As a result, future studies might consider the effects of various site and traffic-related factors on DMS advantages. Furthermore, as previously stated, this study examines the benefits and costs associated with the DMS based on distinct purposes, although in reality, the DMS may be utilized for a variety of purposes. As a result, a future BCR analysis may be used to estimate DMS benefits based on locations and different types of displayed messages. Another limitation of the study is that some of the values utilized in the BCR calculation, such as the initial and maintenance costs for the DMS, were calculated using Michigan standards. A more generalized and transferrable model can be studied to link the DMS purpose and operational effect with the DMS economic advantages. However, the findings of this study can assist planners and decision-makers in properly designing and allocating DMS signals in order to optimize financial benefits. Furthermore, the findings of the study might aid in the prioritization of DMS messages for various types of displayed messages depending on their economic benefits.

5. Declarations

5.1. Author Contributions

Conceptualization, M.A., V.K., and S.M.; methodology, M.A. and V.K.; validation, F.A. and V.K.; formal analysis, M.A., H.A., and V.K.; investigation, M.A.; data curation, M.A. and S.A.; writing—original draft preparation, M.A. and H.A.; writing—review and editing, F.A.; visualization, F.A. and H.A.; supervision, V.A.; project administration, V.A.; funding acquisition, V.K. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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