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Evaluation of Digital Alert Systems Associated with Emergency Response Vehicles and Compliance with Move Over Law

Alireza Talebpour
Pengyuan Liu
Mahdi Yousefi
Chun-Chien Hsiao

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16. Abstract

The presence of stationary emergency vehicles on high-speed roadways poses heightened safety risks, and driver compliance with Move Over laws remains inconsistent nationwide. In recent years, digital alert systems, integrated into widely used navigation applications and in-vehicle platforms, have emerged as a potential countermeasure to improve driver awareness and safety. However, limited research has examined the effectiveness of these systems in real-world environments, particularly when combined with traditional visual emergency warnings. To address this gap, two field experiments were conducted in Illinois under multiple operational scenarios involving emergency vehicles and digital alert technologies. High-resolution helicopter-based aerial videography was used to capture detailed vehicle trajectories, offering a unique opportunity to evaluate driver speed adjustments and lane-changing behavior under varying alert conditions. This study offers an empirical investigation of the impacts of digital alerts on driver behavior and compliance with the Move Over law. The findings of this study support transportation agencies and technology developers in designing integrated warning systems to enhance roadway safety.

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Members of the Technical Review Panel were the following:

- Juan Pava, TRP Chair, Illinois Department of Transportation
- Kyle Armstrong, Illinois Department of Transportation
- Victoria Barrett, Chicago Metropolitan Agency for Planning
- Thomas Brengel, Illinois State Police
- Brian Cluever, Village of Carol Stream
- Robin Helmerichs, Illinois Department of Transportation
- Nicholas Jarmusz, Auto Club Group
- Jason Langston, Kendall County
- Joey Lau, Illinois Department of Transportation
- Stephane Seck-Birhame, Illinois Department of Transportation
- Jason Stubler, City of Naperville

EXECUTIVE SUMMARY

This report evaluates the effectiveness of digital alert systems in improving driver compliance with Move Over laws associated with stationary emergency vehicles. Motivated by unfortunate persistent struck-by risks for first responders and the recent deployment of digital alerts through navigation platforms, this study presents the findings of two major field experiments conducted in 2024 and 2025 with high-resolution aerial videography from drivers' responses to stationary emergency vehicles. Together, these experiments offer a multi-day, multi-scenario assessment of how digital and visual warnings individually and jointly shape driver behavior under real-world freeway operations.

The 2024 data collection on I-80 investigated driver responses to a stationary police vehicle under four scenarios: (1) combined digital and emergency light alerts, (2) emergency lights only, (3) no alerts, and (4) normal traffic. The 2025 campaign on I-55 expanded this design in three directions: (1) a high-demand Day 1 experiment with digital alerts, (2) a Day 2 ramp experiment to evaluate potential influence of the presence of emergency vehicles and digital alerts on merging and exiting behavior, and (3) a Day 3 setup with both a police vehicle and an Illinois Department of Transportation (IDOT) maintenance truck, enabling an investigation of the potential differences in driver response to different emergency vehicles. Across these experiments, lane-changing behavior and speed profiles were analyzed.

Results consistently show that digital alert systems encourage earlier and smoother avoidance responses (i.e., drivers change lanes farther upstream and begin decelerating sooner), particularly when visual cues are limited or obstructed. When a large IDOT maintenance truck with emergency lights is present, visual conspicuity becomes the dominant trigger for early avoidance; however, digital alerts still provide an incremental, yet measurable, benefit in digital alert–only configurations. In ramp environments, exit and merge lane choices remain stable across alert conditions, indicating that digital alerts do not alter the lane selection in mandatory lane-changing maneuvers, where geometric constraints and required maneuvers dominate driver decisions. However, digital alerts still meaningfully shape driver behavior in these areas by increasing early awareness of roadside hazards and prompting earlier and smoother speed adjustments as drivers approach the on/off ramp locations.

Several limitations should be noted, including constrained digital alert coverage across navigation platforms, limited manual trajectory cleaning for the 2025 dataset that restricted advanced clustering analysis, and the focus on two freeway corridors under a specific set of operating conditions. Future work can evaluate digital alert deployment across multiple platforms and locations, incorporating more extensive trajectory refinement for microscopic behavioral modeling, and evaluate additional incident types and roadside configurations to further quantify the safety benefits of integrated digital-visual warning strategies.

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CHAPTER 1: INTRODUCTION

An estimated 39,345 traffic-related fatalities occurred in the United States in 2024 (NHTSA, 2025). The National Safety Council (2023) estimated the cost of vehicle crashes in 2023 to be $513.8 billion. Among these crashes, struck-by events are considered a serious safety concern (Klaver Pecheux et al., 2024). Unfortunately, based on analyses by the Federal Highway Administration (FHWA), struck-by events are poorly captured in national data systems, complicating any prevention and evaluation efforts (Klaver Pecheux et al., 2024). Between 2015 and 2024, a total of 160 law enforcement officers in the United States were fatally struck by vehicles while performing their duties (National Law Enforcement Officers Memorial Fund, 2025).

In order to reduce such incidents across the United States, drivers must shift lanes and reduce speed to a safe and reasonable level when nearing stopped vehicles displaying flashing lights, as mandated by the Move Over law. All 50 states have such protections with some variations (NHTSA, n.d.). In Illinois, the Move Over law, also referred to as Scott's Law, makes this requirement explicit: When approaching a stationary vehicle with emergency or warning lights, one must reduce speed, proceed with caution, and move over if it is safe to do so (Illinois Secretary of State, 2025; Illinois State Police, 2023). Illinois extends these protections beyond police vehicles, fire trucks, and ambulances to include highway maintenance and construction vehicles, as well as stopped or disabled vehicles with hazard lights activated (Illinois Secretary of State, 2025; Illinois State Police, 2023).

While prior research has shown that drivers respond to emergency lights, notable noncompliance persists (Carrick & Washburn, 2012). In-vehicle alerts offer a practical way to alert drivers earlier and more consistently as they approach stationary emergency vehicles. Such an approach targets the earlier perception-reaction window, potentially improving compliance with both lane-changing and speed-reduction requirements before drivers reach the emergency vehicle (Carrick & Washburn, 2012). In fact, FHWA guidance under the Next-Generation Traffic Incident Management (NextGen TIM) initiative highlights "digital alerts" (also known as responder-to-vehicle or motorist alerts) as a potential solution to increase compliance with the Move Over law (USDOT & FHWA, 2022; FHWA, 2025). This technology utilizes GPS-based location information from emergency vehicles to send warnings to drivers through navigation apps and compatible infotainment systems (USDOT & FHWA, 2022). Early warnings about the presence of an emergency vehicle or an incident can potentially help drivers respond safely and increase compliance with the Move Over law, improving safety for everyone on the road (USDOT & FHWA, 2022; FHWA, 2025).

Several public agencies have begun operational deployments that deliver real-time move-over notifications to nearby motorists. For example, the Illinois State Police expanded statewide alerts in December 2024 so that drivers in certain vehicles with factory-installed infotainment systems receive an on-screen prompt to reduce speed and change lanes when approaching active police activity, an implementation explicitly intended to increase compliance with the Move Over law (Illinois State Police, 2024). More broadly, FHWA's outreach describes how these alerts can be activated automatically when emergency lights are turned on, minimizing responder workload and ensuring consistent messaging to motorists (USDOT & FHWA, 2022). Despite the aforementioned and other similar initiatives, there has been a very limited number of studies that evaluated the impacts of digital alerts on driver behavior and compliance with the Move Over law. Sakhare et al. (2021) is among the very few studies that evaluated the impacts of digital alerts. They, however, did not isolate the effects of emergency lights from those of alerts. Other studies often either rely on driving simulators or suffer from limited scenarios and sample sizes, making it difficult to generalize findings across freeway environments (Sakhare et al., 2021; Weibull, Lidestam, et al., 2024; Weibull, Kunclová, et al., 2024; Burger & Guna, 2024). Accordingly, whether in-vehicle alerts enhance safety beyond emergency lights under real-world traffic conditions remains an open question, although some simulation studies suggested these technologies may improve driver responses (Sakhare et al., 2021; Weibull, Kunclová, et al., 2024; Burger & Guna, 2024; Masatu et al., 2022).

In order to address this research gap, the primary objective of this study is to assess the effectiveness of digital alert systems in reducing operating speeds and enhancing compliance with the Move Over law. To achieve this goal, this study presents two comprehensive data collection efforts using aerial videography with a helicopter. A comprehensive analysis of drivers' speed patterns, lane selection, and lane-changing behavior is conducted to assess the impacts of digital alert systems on compliance with the Move Over law.

The remainder of this report is organized as follows. Chapter 2 reviews prior studies on digital alert systems, driver compliance, and related safety interventions. Chapter 3 describes the data extraction methodology, including the aerial data collection procedures and trajectory processing techniques used in this study. Chapters 4 and 5 present the experimental designs and results from the July 2024 and July 2025 field data collections, respectively, detailing driver behavior across the corresponding scenarios. Finally, Chapter 6 concludes the report and outlines directions for future research.

CHAPTER 2: REVIEW OF RELEVANT LITERATURE

This chapter examines previous studies on digital alert systems designed to enhance driver compliance. Note that this section does not aim to provide a comprehensive review of the literature and only aims to highlight the existing gaps in the literature. Masatu et al. (2022) proposed a driver alert system aimed at notifying motorists about nearby road signs, which was tested using a smartphone platform. They developed software capable of accurately determining the positions and distances of road signs. By leveraging a smartphone's integrated GPS, accelerometer, gyroscope, and inertial measurement unit, the system could detect when a vehicle approached within 250 m of a sign and subsequently issued a warning to the driver. In addition to this approach, other studies have introduced traffic sign recognition systems that rely on cameras installed on vehicles. These systems detect road signs by analyzing their distinctive shapes and colors, enabling timely alerts to drivers (García-Garrido et al., 2012; Farhat et al., 2019; Hechri et al., 2015). Another similar method utilized a smartphone's back camera instead of a mounted camera for sign detection (Ling & Seng, 2011). Other approaches have relied on in-vehicle mobile devices and communication with the infrastructure on the road (e.g., RFID [radio frequency identification] transmitters) to create road sign notification systems (Rajale et al., 2014; Bhawiyuga et al., 2017). While others have utilized vehicle-to-vehicle communication to broadcast information such as warnings while traveling on the same road (Liang et al., 2015).

Megat-Johari et al. (2021) conducted a series of field experiments to investigate how drivers respond to Move Over laws, particularly in scenarios where law enforcement or road agency vehicles were stationed on the freeway shoulder. The study further examined the impact of upstream dynamic message signs on how drivers respond on the road through specific safety-related messages. Logistic regression models were developed using collected speed and lane data to analyze compliance behavior. The findings showed that drivers were more inclined to either switch lanes or slow down when the vehicle on the shoulder belonged to law enforcement rather than a transportation agency. Driver behavior was largely unaffected by the message type, except when clear move-over alerts were presented instead of regular travel time messages (Megat-Johari et al., 2021). Instead, the present study evaluates GPS-based digital alerts sent directly to drivers through common navigation apps. Additionally, it utilizes high-resolution aerial video to capture continuous vehicle paths. This approach enables the measurement not only of whether drivers follow the law, but also of exactly when and how smoothly they change lanes and adjust their speed in each situation.

A simulator study by Weibull, Lidestam, et al. (2024) tested the effects of true versus false emergency vehicle approaching (EVA) alerts on drivers' behavior. While EVA alerts encouraged faster move-over responses, repeated false alarms led to reduced compliance in later encounters. Interestingly, neither the alert modality (visual vs. auditory) nor driver experience showed significant effects, highlighting the need for minimizing false alerts.

Expanding on strategies to support driver response to emergency vehicles, Weibull, Kunclová, et al. (2024) conducted another simulator study to examine the effect of geofencing-based in-car warnings during interactions with emergency vehicles. The study found that drivers who received such alerts in high-risk scenarios, such as intersections or off-ramps, demonstrated earlier deceleration and higher yielding rates compared to those without alerts. Importantly, drivers reacted to the warnings even before directly seeing the emergency vehicle, suggesting that geofencing alerts may enhance safety.

On the other hand, some studies illustrate the potential of decision support systems to improve driver behavior and avoid collisions (Hirst & Graham, 2020; Werneke & Vollrath, 2013). Ryder et al. (2017) developed a decision support system integrated within vehicles, designed to alert drivers about areas with a high risk of crashes using historical accident data. Their findings indicated that these alerts can significantly improve driving behavior over time. Additionally, the study highlighted that the success of such systems can be influenced by driver personality traits. Complementing these findings, Burger and Guna (2024) evaluated the effectiveness of a Cooperative Intelligent Transport Systems (C-ITS) mobile application called DARS Traffic Plus. Using a realistic driving simulator, the study demonstrated that the app's real-time hazard alerts enabled drivers to adjust their behavior, thereby improving both perceived and actual safety. Notifications delivered with simple auditory signals were especially effective, and average screen-glance durations remained within safe limits, highlighting that mobile alerts can enhance hazard awareness without creating distractions.

While past research has demonstrated that digital alert systems can deliver information to drivers through radio broadcasts, navigation applications, and in-vehicle equipment, the potential safety improvement hinges on the effectiveness of drivers' perceiving and processing of such information. While studies on the safety impacts of digital alert systems are limited, the literature on drivers' response to in-vehicle alerts is rich, with various studies having investigated such a response. For instance, Hanowski et al. (1999) investigated the impact of information on driving behaviors, and their results indicated that the system benefited from in-vehicle safety advisories and warnings. Later, Ben-Yaacov et al. (2002) conducted experiments on the influence of in-vehicle warning systems on drivers' behaviors, and they suggested that such alert systems had both short- and long-term safety implications by encouraging drivers to maintain safe headways. By virtue of the introduction of driving simulators, Whitmire II et al. (2011) evaluated the effectiveness of visual- and audio-augmented warnings on drivers' behaviors in work zones. Their results showed that a combination of in-vehicle warnings in the form of audio and visual messages improves drivers' compliance.

Supporting the importance of alert modality and timing, Haroon et al. (2025) investigated different types of alerts in a simulator-based driving study using eye-tracking. Their findings indicated that drivers responded most quickly and effectively to alerts that included both distance information and specific action instructions. Furthermore, alerts delivered approximately two miles in advance were rated most helpful. These results suggest that carefully designed alerts can significantly improve driver compliance and reduce decision-making time in high-speed environments.

Based on the above literature review, only a few investigations have been conducted on digital alert systems focusing on emergency vehicles and drivers' compliance with the Move Over law. Most of the limited existing studies, on the other hand, only explored normal driving conditions and simple scenarios. Accordingly, there is a critical need to conduct a comprehensive investigation of the effectiveness of digital alert systems in reducing operating speeds and increasing compliance with Move Over law requirements.

CHAPTER 3: DATA EXTRACTION METHODOLOGY

VIDEO DATA COLLECTION

This study aims to evaluate the safety impacts of digital alert systems based on real-world data collection experiments. These experiments were conducted during two data collection events, in which an emergency vehicle was positioned on the shoulder of a freeway, with its emergency lights either activated or deactivated depending on the specific experimental scenario, as described in the following subsections.

The primary objective of the data collection was to obtain continuous video coverage of all vehicles traveling upstream and downstream of the police vehicle. A total of about 10 hours of data were collected using a helicopter. The helicopter hovered at an altitude of approximately 1,000 ft and captured high-resolution 8K video footage. Using a wide-angle lens, the system recorded a roadway segment of roughly 0.5 miles, covering both upstream and downstream of the police vehicle. This coverage fully captured traffic behavior both before vehicles reached the emergency vehicle and after they passed it.

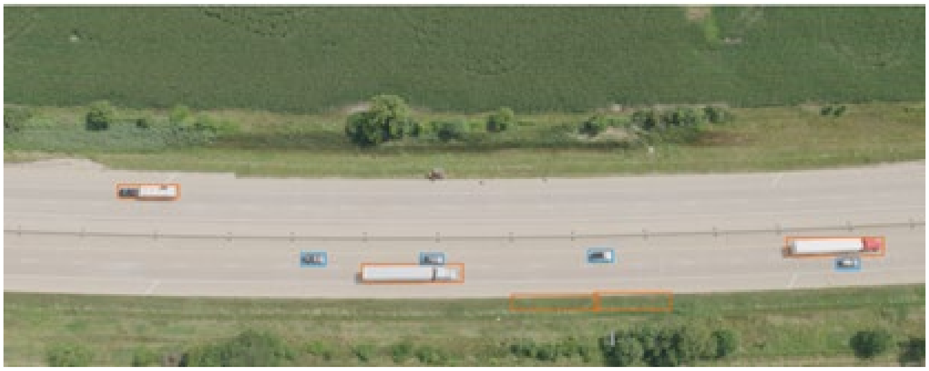
The collected video serves as the raw input for the trajectory extraction process described in the subsequent sections. Experiment details for both data collections are presented separately in Chapters 4 and 5.

TRAJECTORY EXTRACTION PIPELINE OVERVIEW

Building on the video data described above, this subsection outlines the multi-stage methodology used to extract high-resolution vehicle trajectories from the raw footage. The collected video was used to extract the trajectory of all vehicles observed in the video data, using the Third Generation Simulation (TGSIM) methodology for trajectory extraction (Ammourah et al., 2025). These trajectories are characterized based on vehicle ID (a unique number dedicated to each detected vehicle), location (longitudinal and lateral positions), speed, acceleration, lane number, vehicle type, and vehicle length.

Vehicle speed and location data can be extracted from the video recorded from a bird's-eye view camera (via a helicopter). This study utilizes the methodology proposed by Khajeh-Hosseini et al. (2022) as the core of their trajectory extraction method. There are, however, several key modifications to their approach to meet the requirements of this study. This subsection discusses the details of those modifications, while briefly discussing the fundamentals of the method proposed by Khajeh-Hosseini et al. (2022). The trajectory extraction process consists of six steps: (1) data preprocessing, (2) vehicle detection, (3) vehicle tracking, (4) image stabilization, (5) trajectory construction, and (6) data cleaning.

As indicated in Figure 1, after the preprocessing step, vehicles are detected in every image and tracked over the sequence of images. All images are then transformed to match a reference field of view in the image stabilization step. Finally, the vehicles' locations are constructed by converting the image coordinates to the adopted reference coordinates on the ground (Khajeh-Hosseini et al., 2022). The underlying processes in each step are presented below.



(A) Vehicle Detection

(B) Vehicle Tracking

Figure 1. Photo. Vehicle detection and tracking in aerial images.

DATA PREPROCESSING

The first step in the extraction process is to preprocess the collected videos. Data preprocessing requires two steps: raw image extraction and reference image generation.

- Raw Image Extraction: Every video recording is converted to a sequence of images (i.e., frames) separated at a constant rate over time (e.g., ~30 fps). This is done using publicly available RED software, the camera of which was used for video recording. Vehicles will be detected and tracked in these raw images to generate the trajectory data. Accordingly, the extraction rate depends on the frequency of data in the trajectory dataset.

- Reference Image Generation: The key to an effective and accurate trajectory extraction process is that in every video frame, the vehicles' locations should be estimated for a fixed coordinate system and reference point on the ground. This study utilizes satellite images to create the reference image. The reference images were created by carefully selecting a representative high-resolution image from the original videos.

OBJECT DETECTION

Object detection techniques in computer vision have evolved considerably in the past few years, mainly due to recent advancements in deep neural networks. Most of the existing approaches can be used to identify and locate vehicles in the aerial images with a little additional training. There are multiple popular convolutional neural network (CNN) based object detectors, such as R-CNN (Girshick et al., 2014), RetinaNet (Lin et al., 2017), and YOLOv5 (Redmon et al., 2016). The weights and parameters of a pretrained CNN-based object detector can be fine-tuned by training on a dataset of aerial images with known vehicle annotations. The trained model can be used in the vehicle detection process to identify and locate vehicles in the aerial images. This study utilizes RetinaNet (Lin et al., 2017).

OBJECT TRACKING

Tracking is the process of linking the new detections to previous observations. The tracking methodology proposed by Khajeh-Hosseini et al. (2022) includes data association and track maintenance. Data association links the detected vehicles in the current image frame with the vehicles identified in previous ones. This is a critical step considering that not all transformations can be perfect, and some frames must be removed from the data. Accordingly, the process should detect vehicles with some gap in the distance between them in two frames. Track maintenance handles three core functions: (1) creating new tracks with unique IDs for initial detections, (2) updating existing tracks when matches are found through association, and (3) removing inactive tracks that show no matches for multiple frames. Each maintained track preserves the vehicle's unique identifier and its latest detected bounding box coordinates throughout this continuous matching and updating process.

IMAGE STABILIZATION

The location of every vehicle in an image is estimated by converting its position in the image to the fixed coordinate system picked on the ground. Consequently, it is essential to find the mapping function between the image coordinates and the adopted ground coordinate. Image stabilization is the process of converting the field of view of all images (i.e., frames) to a reference image for which the mapping function to the ground coordinate is known. Accordingly, the location of every pixel in the image is mapped to the known ground coordinates. Image stabilization is performed in three steps. The first step is detecting the key features in both reference and input images. There are different algorithms for good key feature detection in images, such as the Harris corner detector (Derpanis, 2004), scale-invariant feature transform (SIFT) (Lowe, 2004), speeded up robust features (SURF) (Bay et al., 2006), and Oriented FAST and Rotated BRIEF (ORB) (Rublee et al., 2011). Following the recommendation by Khajeh-Hosseini et al. (2022), this study adopts SIFT (Lowe, 2004) as the feature detection algorithm. The second step is matching the features between the reference image and the input image. Accordingly, similar to Khajeh-Hosseini et al. (2022), this study utilizes the Fast Library for Approximate Nearest Neighbors (FLANN) matcher to match features between the images (Muja & Lowe, 2013). The final step is finding the perspective transformation, specifically the homography, between the reference and input images, considering the best matching features. Khajeh-Hosseini et al. (2022) realized that despite utilizing state-of-the-art algorithms, some of the feature matchings are incorrect. They instead used Random Sample Consensus (RANSAC), an algorithm to find model parameters from a dataset with many outliers through an iterative process (Derpanis, 2010), to estimate the homography transformation between two images, considering the matched key features. To further improve the transformations (considering that the sizes of the reference images in this study can be significantly larger than those of Khajeh-Hosseini et al. [2022]), this study also removed the matchings that correspond to the vehicles. This is a logical step since the vehicles in the reference image and current image cannot be at the same ground locations, and feature matching using vehicles can result in undesirable transformations.

TRAJECTORY CONSTRUCTION

Detection and tracking steps are based on bounding boxes that represent the vehicle's location in image coordinates (i.e., row and column of pixels). These coordinates need to be converted to a fixed ground coordinate system (e.g., meters) for trajectory extraction. Every pixel is identified by its row and column number in the image map. The pixel coordinate can be transformed into a Cartesian coordinate system by taking axes parallel to the columns and rows of the image map and knowing the pixel size on the ground. Note that the pixel size on the ground depends on the flight elevation and image quality; it is the key to the mapping function between the two coordinate systems. Khajeh-Hosseini et al. (2022) took the front bumper to indicate the vehicles' location, and the trajectory of the vehicle is the list of its location over space and time. Moreover, based on the recommendation by Khajeh-Hosseini et al. (2022), Kalman filter–based smoothing was applied to reduce the noise in the vehicle's location estimates.

DATA CLEANING

Although all the previous steps are automated and result in fairly accurate trajectories, there are still some rare cases that cannot be captured and tagged via the presented process (including parked vehicles on the side of a highway, falsely identified vehicle IDs, etc.). Accordingly, every single trajectory in the dataset is inspected and verified. This process was conducted through the following steps. Problematic trajectories are identified using several filters, such as trajectories that have zero speed values for long durations, trajectory lengths below a minimum threshold, and trajectories that traverse the opposite direction of traffic flow. The IDs of those trajectories are then noted and checked against the original image frames with plotted tracking IDs to verify that they are indeed problematic. Finally, the erroneous trajectories and corresponding IDs are either removed from or corrected in the trajectory datasets.

CHAPTER 4: JULY 2024 DATA COLLECTION

This chapter presents the data collection details and its findings for the July 2024 experiment and provides the corresponding analysis of the observed traffic behavior and safety outcomes.

DATA COLLECTION LOCATION

A section of I-80 near Kendall County, Illinois, was selected for data collection. This segment consists of two lanes in the westbound direction and includes a paved shoulder. The posted speed limit is 65 mph. Figure 2 illustrates the location of the selected roadway section. Data collection was conducted on Friday, July 26, 2024, under sunny weather conditions. The process began at approximately 1:40 p.m. and concluded at approximately 3:25 p.m. The Full Alerts scenario was recorded for about 35 minutes, followed by the Lights Only scenario for about 35 minutes, the No Alerts scenario for about 15 minutes, and the No Vehicle scenario for about 15 minutes.

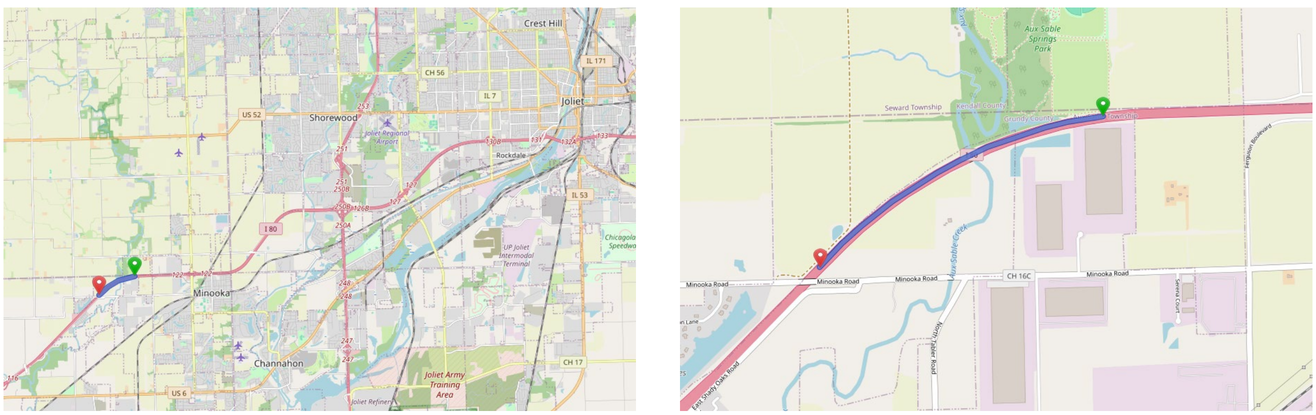


Figure 2. Map. Data collection location (July 2024).

Source: Project OSRM (n.d.)

DATA COLLECTION DETAILS

The key objectives of this data collection effort were (1) capturing the difference between the behavior of drivers in response to a police vehicle in the presence and absence of digital alert systems, and (2) evaluating the effectiveness of digital alert systems in reaching the drivers. In order to evaluate the response of drivers to digital alert systems (e.g., slowing down and changing lanes), the data collection was divided into four scenarios. In the first scenario, a stationary police vehicle was present with both digital alerts activated and emergency lights turned on. In the second scenario, a stationary police vehicle was present with emergency lights activated but without digital alerts. In the third scenario, a stationary police vehicle was present without any active alerts, either digital or visual. In the fourth scenario, no stationary police vehicle was present, and no alert systems were active. As shown in Table 1, we refer to these four scenarios as Full Alerts, Lights Only, No Alerts, and No Vehicle, respectively, in subsequent sections.

Table 1. Data Collection Details (July 2024)

Experiment Configuration	Scenario	Description	Time of Day
Location: I-80 Segment Length: 0.5 miles Number of Lanes: 2 Altitude: 1,000 ft Speed Limit: 65 mph	Full Alerts	Digital Alerts ON + Emergency Light ON	1:40 p.m.–2:14 p.m.
	Lights Only	Digital Alerts OFF + Emergency Light ON	2:27 p.m.–2:54 p.m.
	No Alerts	Digital Alerts OFF + Emergency Light OFF	2:56 p.m.–3:11 p.m.
	No Vehicle	Normal Traffic (No Police Vehicle)	3:11 p.m.–3:25 p.m.

These scenarios were designed to capture driver behaviors while approaching a stationary police vehicle under different alert conditions. The Full Alerts scenario assessed the combined influence of digital alerts and visual emergency warnings on driver behavior, evaluating how the integration of these cues affected maneuvering decisions. The Lights Only scenario served as a comparative baseline to determine the additional benefit of digital notifications beyond traditional visual cues. The No Alerts scenario allowed for the observation of driver behavior in the absence of external warning indicators, while the No Vehicle scenario provided a reference point for assessing the behavioral changes observed under the other conditions. Together, these scenarios provide a comprehensive dataset for analyzing the impacts of digital alert systems on driver behavior.

To capture whether and when the transmitted information reached the drivers, two vehicles were circulated within the section during data collection. GPS locations, along with data from Google Maps, Apple Maps, and Waze, were recorded throughout the process. The collected data indicated that drivers received digital alerts approximately 0.5 miles upstream of emergency response vehicles. However, despite being designed for broader deployment across platforms (including Google Maps, Apple Maps, and Waze), these alerts were only fully operational for Waze users during the data collection, significantly limiting system coverage. This implementation gap and its implications will be further analyzed in the remainder of this section.

ANALYSIS OF LANE-CHANGING BEHAVIOR

Lane-changing behavior is a key indicator of driver response to stationary vehicles and alert systems. Table 2 shows the estimated lane-specific traffic flow at inbound and outbound locations across scenarios, demonstrating that overall traffic patterns remain relatively stable over time. Figure 3 presents the average number of lane changes per vehicle from the outer lane to the inner lane under each experimental scenario. The results show that in the Lights Only scenario, the lane change rate was the highest at 0.41, followed by the Full Alerts scenario at 0.36. In contrast, the No Alerts and No Vehicle scenarios exhibited much lower lane change rates at 0.20 and 0.05, respectively.

Table 2. Lane-Specific Traffic Flow at Inbound and Outbound Locations (July 2024) (veh/hr)

Scenario	Traffic Flow (veh/hr)				Total
	Inner Lane (in)	Outer Lane (in)	Inner Lane (out)	Outer Lane (out)	
Full Alerts	**888**	**729**	**1,408**	**209**	**1,617**
Lights Only	**791**	**742**	**1,371**	**162**	**1,533**
No Alerts	**836**	**676**	**1,108**	**404**	**1,512**
No Vehicle	**943**	**801**	**960**	**784**	**1,744**

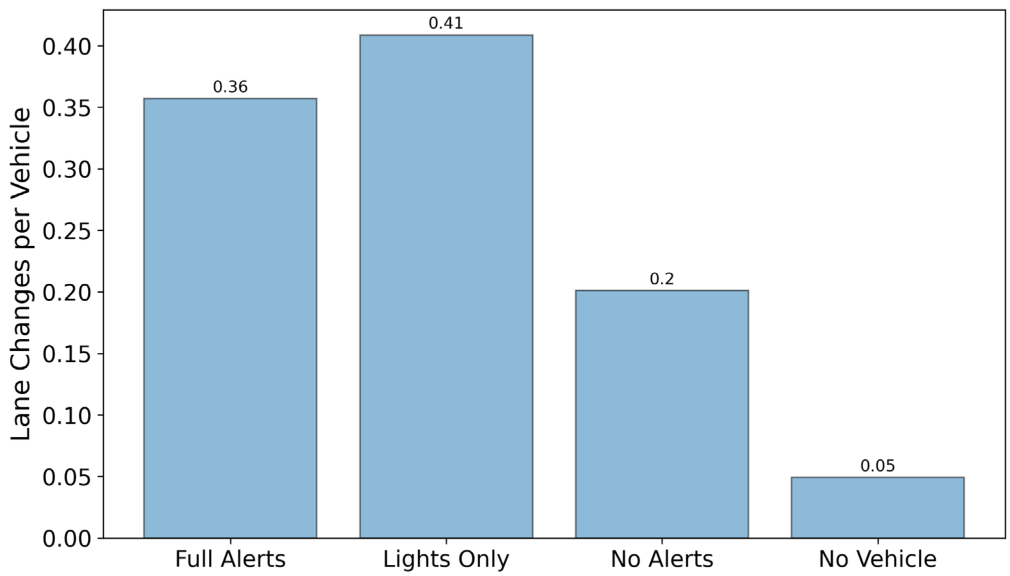
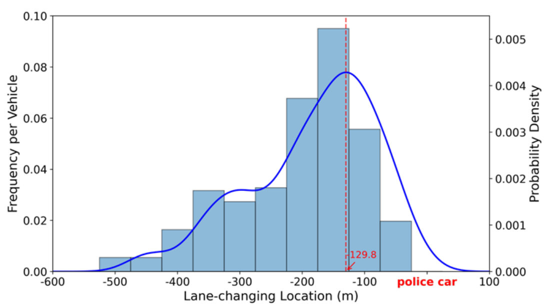


Figure 3. Graph. Lane-changing rate per vehicle from outer to inner lane by scenario (July 2024).

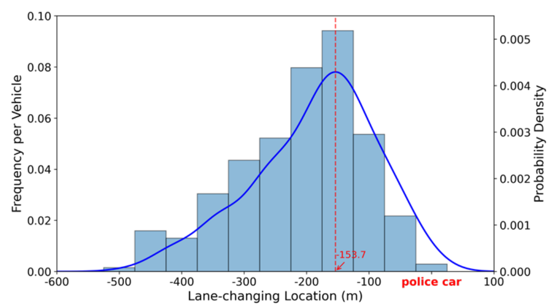
It is important to emphasize that this overall lane change rate should not be interpreted as evidence against the effectiveness of the digital alert systems. The observed difference between the Full Alerts scenario and Lights Only scenario can be explained by the fact that drivers received digital alerts approximately 0.5 miles upstream of the police vehicle, 0.1 mile beyond the boundary of the video recording zone. As a result, some drivers likely initiated lane changes before entering the data collection area. This explanation is supported by Table 2, which shows that a higher percentage of drivers in the Full Alerts scenario were already in the inner lane at the start of the data collection segment compared to the Lights Only scenario. More importantly, the core design objective of the digital alert systems is not merely to increase the number of lane changes but rather to encourage drivers to perform these maneuvers earlier and more proactively, thereby enhancing roadway safety. To further evaluate whether digital alert systems facilitate earlier responses to stationary vehicles, we analyze the distribution of lane-change locations across scenarios in the subsequent paragraph.

To further understand driver response to the presence of emergency vehicles and alert systems, Figure 4 illustrates the distribution of lane-changing locations for each scenario. The No Vehicle scenario exhibits minimal lane-changing activity, and thus its histogram lacks significant analytical value in this context. Comparing the Lights Only and No Alerts scenarios, we observe two key differences. First, the overall volume of lane changing is higher in the Lights Only scenario, which can be attributed to the visual warning provided by the emergency lights. Second, and more importantly, the location of the peak in the histogram shifts further upstream in the Lights Only scenario compared to the No Alerts scenario. This suggests that drivers are more likely to change lanes earlier when emergency lights are visible.

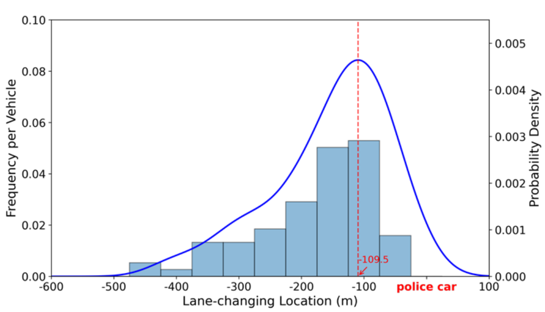
The Full Alerts scenario, which combines both emergency lights and digital alerts, reveals an interesting pattern. Its histogram displays a similar dominant peak to that of the Lights Only scenario, indicating that many drivers still chose to change lanes within a similar range. However, the Full Alerts scenario also exhibits an additional local maximum approximately 300 m upstream of the police vehicle. This secondary concentration of lane changes suggests an incremental influence of the digital alert systems: Some drivers who received early warnings via navigation apps (only Waze during the data collection) reacted by changing lanes earlier than they might have in the absence of such alerts. However, it is important to note that the magnitude of this incremental influence is relatively modest. We propose two possible explanations for this observation. First, the emergency lights already provide a salient early warning, which may reduce the marginal impact of the additional digital alert systems. Second, only a subset of drivers would have been using compatible navigation applications capable of receiving such alerts, limiting the proportion of vehicles exposed to the digital notification. This spatial shift in lane-changing behavior, even if limited, supports the potential of digital alert systems to promote earlier and safer maneuvers when approaching stationary emergency vehicles.



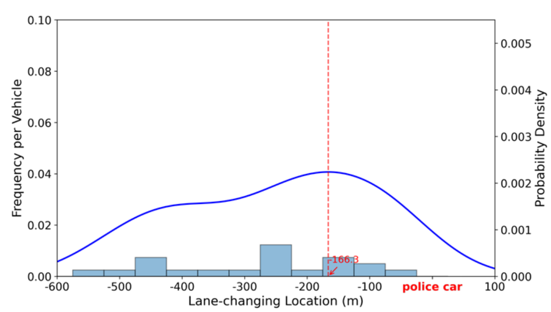
(A) Full Alerts



(B) Lights Only



(C) No Alerts



(D) No Vehicle

Figure 4. Histogram. Lane-changing locations under different alert scenarios (July 2024).

To further quantify the differences in lane-changing behavior under various alerting conditions, a Kolmogorov–Smirnov (KS) test was performed to evaluate whether the lane-changing location distributions differ significantly between each pair of scenarios. The KS test is a nonparametric test commonly used to assess whether two samples come from the same distribution (Massey, 1951). It calculates the largest gap between the cumulative distribution functions of the two samples and provides a p-value to indicate the statistical significance of this difference.

The resulting p-values for all six pairwise comparisons are visualized in a heatmap (see Figure 5). Given that the No Vehicle scenario had very few lane-changing instances, comparisons involving this scenario are less informative. We therefore focus on the comparisons among the other three scenarios. The p-value for the Full Alerts vs. No Alerts scenarios is 0.041 and for the Lights Only vs. No Alerts scenarios is 0.001, both below the 0.05 significance threshold. This allows us to reject the null hypothesis at the 95% confidence level, indicating that the presence of early notification systems, including emergency lights and digital alerts, significantly alters the distribution of lane-changing locations. More specifically, drivers tend to change lanes earlier when they are warned, as reflected in the left-shifted distributions under the Full Alerts and Lights Only scenarios compared to the No Alerts scenario.

On the other hand, the comparison between the Full Alerts and Lights Only scenarios yields a p-value of 0.156, which does not reach statistical significance. This does not necessarily imply that digital alert systems are ineffective, but rather that their incremental influence beyond emergency lights may be partially masked by other confounding factors, such as the limited proportion of drivers actively using digital navigation maps. Moreover, this analysis only considers the impact of digital alert systems on lane-changing behavior. The influence of digital alert systems on vehicle speed profiles, which may offer a clearer signal of early awareness and caution, is examined separately in the remainder of this section. Therefore, it would be premature to conclude that digital alert systems have limited utility based solely on their observed effect on lane-changing locations.

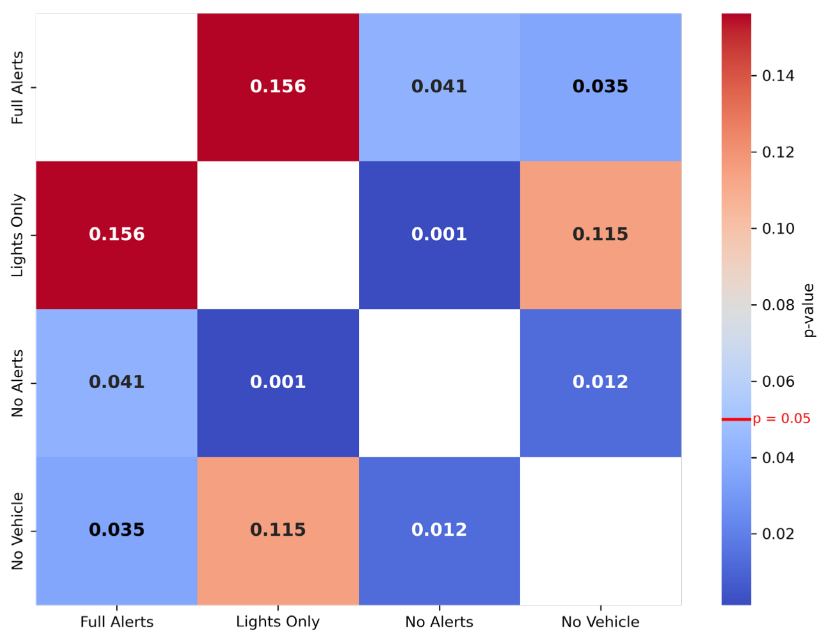
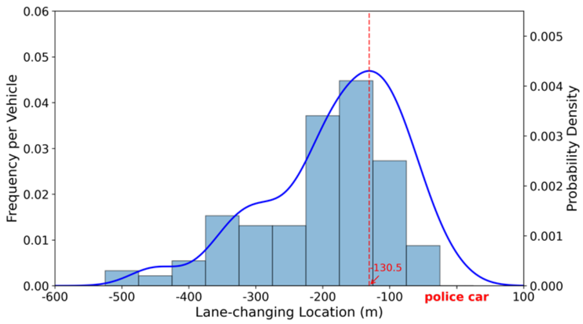
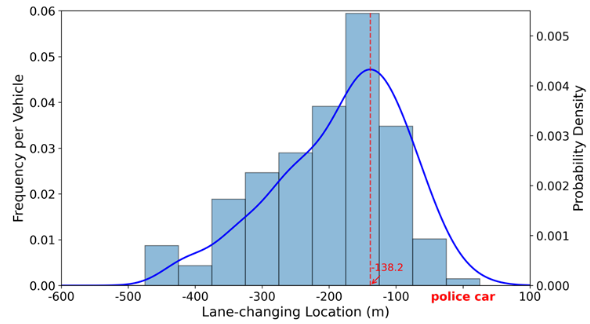


Figure 5. Heatmap. Statistical significance of lane-changing location differences across scenarios (July 2024).

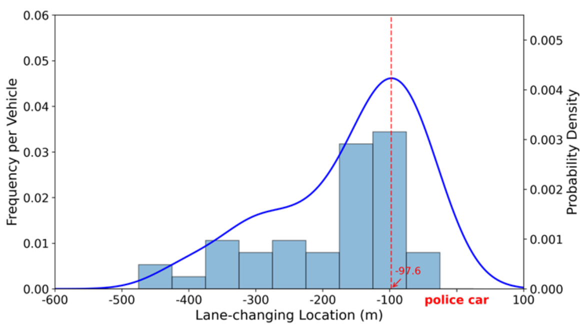
To further examine whether vehicle type plays a role in lane-changing behavior, additional comparisons were conducted between small and large vehicles within each scenario (see Figures 6 through 8). Histograms of lane-changing locations for both vehicle types were generated, and two-sample KS tests were applied to assess the statistical similarity of their distributions. These consistently high p-values indicate that both vehicle classes exhibit similar behavioral trends when approaching a stationary emergency vehicle, regardless of the presence or absence of digital alerts or emergency lights. This further supports the validity of our earlier findings by ruling out vehicle type as a confounding factor. It also suggests that digital alerts and visual cues influence drivers in a generally consistent manner across different vehicle sizes.



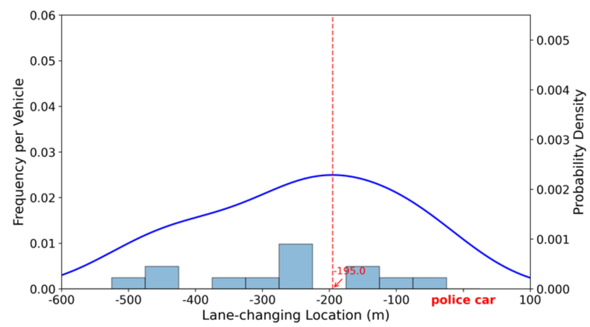
(A) Full Alerts



(B) Lights Only



(C) No Alerts



(D) No Vehicle

Figure 6. Histogram. Lane-changing locations across scenarios (July 2024, small vehicles).

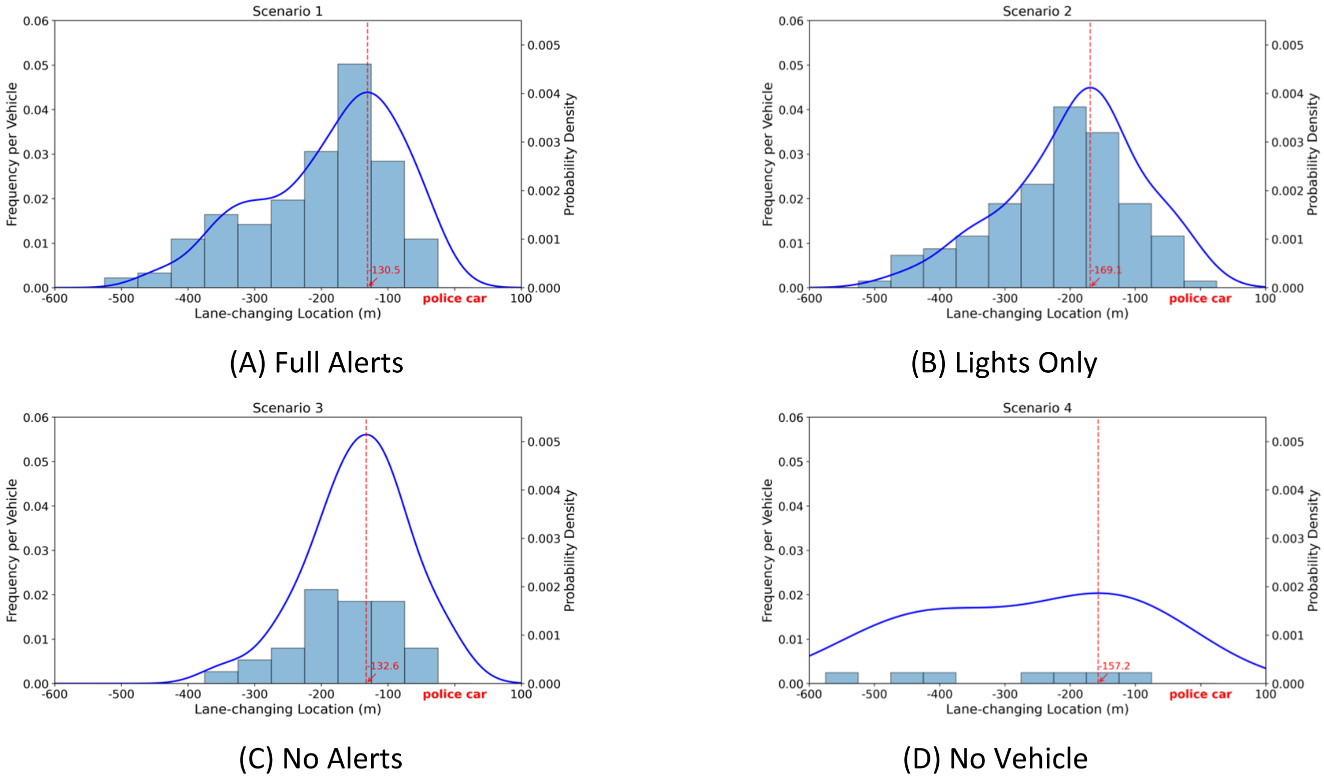


Figure 7. Histogram. Lane-changing locations across scenarios (July 2024, large vehicles).

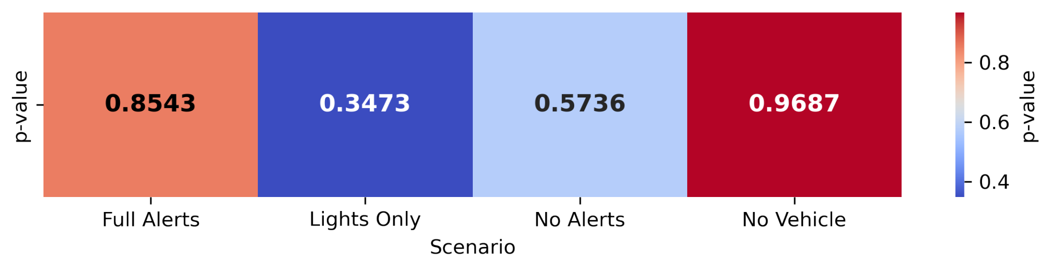


Figure 8. Heatmap. Comparison of lane-changing location distributions between small and large vehicles in each scenario (July 2024).

IDENTIFYING LANE-CHANGING PATTERNS VIA CLUSTERING

To gain a deeper understanding of driver behavior in response to emergency response vehicles and digital alert systems, this section applies clustering analysis to identify distinct patterns in lane-changing maneuvers. By clustering individual lane-change events based on gap-related features, we aim to capture different behavioral strategies that drivers may adopt under varying alert conditions.

Affinity propagation is employed as the primary clustering algorithm. Proposed by Frey and Dueck (2007), affinity propagation does not require prespecifying the number of clusters. Instead, it works by exchanging real-valued messages among data points until a suitable set of exemplars and their associated clusters is formed. Its ability to flexibly determine the number of clusters based on input similarities makes it particularly suitable for exploratory traffic behavior analysis.

In this study, we focus on two key variables for each lane-changing event: the lead gap and the lag gap. This paper follows the definition presented by Yang et al. (2019) of the lead gap and lag gap. These values are calculated as follows in Figures 9 and 10:

$$g^{\mathrm{lead}}(t) = \frac{x^{\mathrm{LV}}(t) - x^{\mathrm{LCV}}(t) - l^{\mathrm{LV}}}{v^{\mathrm{LCV}}(t)}$$

Figure 9. Equation. Lead gap of the lane-changing event.

$$g^{\mathrm{lag}}(t) = \frac{x^{\mathrm{LCV}}(t) - x^{\mathrm{FV}}(t) - l^{\mathrm{LCV}}}{v^{\mathrm{FV}}(t)}$$

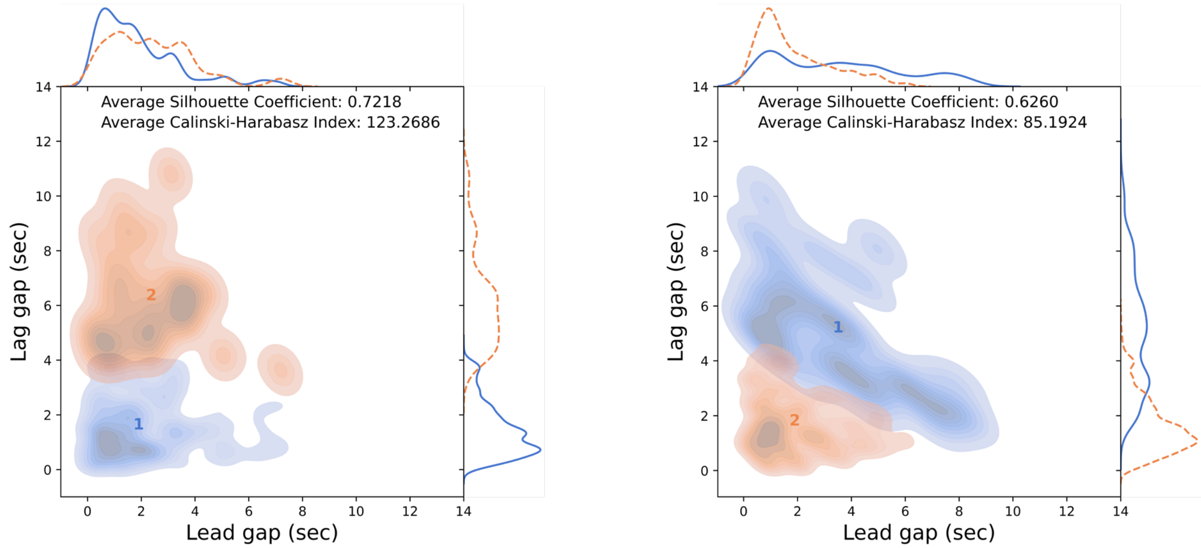
Figure 10. Equation. Lag gap of the lane-changing event.

where g^{lead} and g^{lag} denote the lead and lag gaps, respectively. *LCV* is the changing vehicle, and *LV* and *FV* denote the leading vehicle and following vehicle in the target lane during the lane-changing event, respectively. x and l indicate the location (measured at the front bumper) and length of a vehicle type.

To perform clustering, we construct a similarity matrix using these two features (Zhang et al., 2025) extracted from a 6-second window (3 seconds before and after each lane-changing event, since this is preferable for evaluating lane-changing behaviors according to Ali et al. [2023]), where the similarity between two lane-change events reflects how close their lead and lag gaps are in Euclidean space. Since the number of clusters generated by affinity propagation is sensitive to the preference parameter, we tune this value carefully to obtain clustering results that are both meaningful and stable. To evaluate clustering quality, we adopt two well-known internal validation metrics: the Silhouette Score, which measures the cohesion and separation of clusters (Rousseeuw 1987), and the Caliński-Harabasz Index (1974), which evaluates the ratio of between-cluster dispersion to within-cluster dispersion. A higher value in both metrics indicates a better-defined and more meaningful clustering structure.

Since the No Alerts and No Vehicle scenarios contain relatively few lane-changing events, clustering results for these cases are not particularly informative. Therefore, we focus our clustering analysis on the Full Alerts and Lights Only scenarios, which exhibit sufficient lane-changing activity. As illustrated in Figure 11, both scenarios yield two distinct clusters based on the lead and lag gap features.

In terms of the lag gap, both scenarios show a similar distribution pattern, with most lane changes occurring when the lag gap is less than 12 seconds. This suggests that drivers’ consideration of the following vehicle is relatively consistent across both scenarios. However, when examining the lead gap, clear differences emerge. The Full Alerts scenario resulted in a more consistent gap selection, indicating a more uniform driving condition. Such a consistent gap selection indicates stability in the traffic flow and is often a good indicator of improved safety.



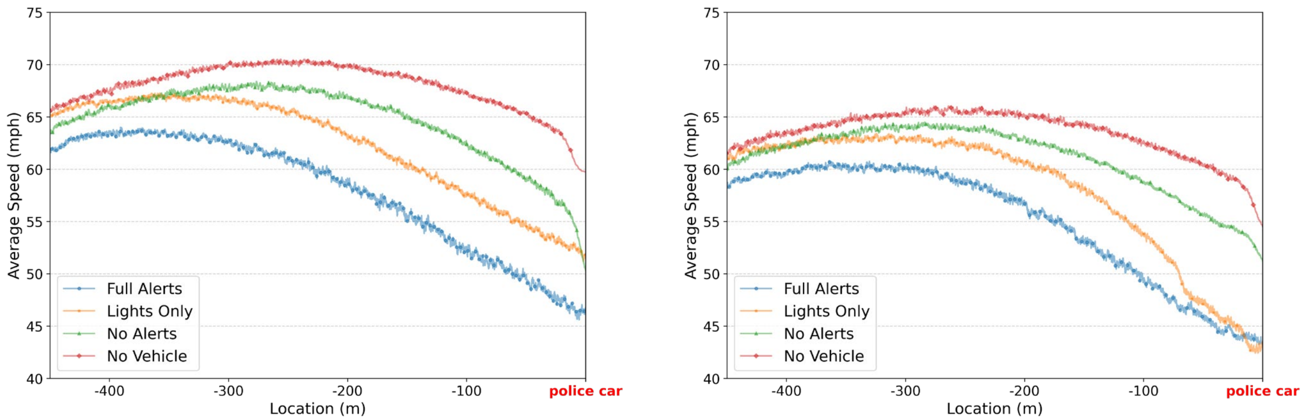
(A) Full Alerts (B) Lights Only

Figure 11. Cluster graph. Clustering of lane-change events in full alerts and lights only scenarios (July 2024).

SPEED PROFILE ANALYSIS ACROSS SCENARIOS

To further understand how drivers respond to emergency vehicles and digital alert systems, this subsection examines the evolution of vehicle speeds as a function of the longitudinal distance to the police vehicle. The analysis is separated by lane (inner vs. outer lanes) to account for different driving behaviors based on proximity to the stationary vehicle. Figure 12 presents the average speed profiles across the four experimental scenarios.

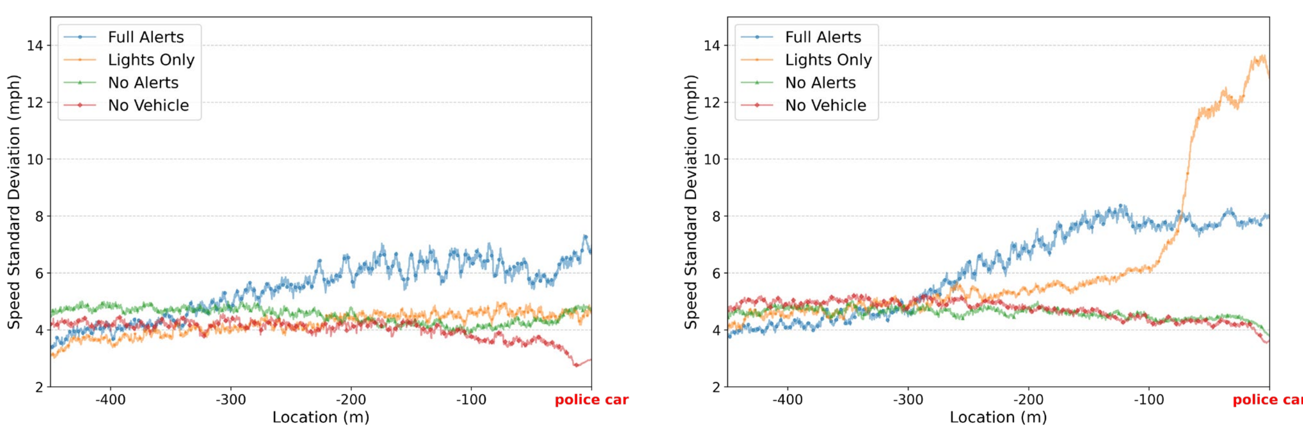
A particularly notable finding emerges from the outer lane analysis. In the Lights Only scenario, there is a sharp drop in speed approximately 70 m upstream of the police vehicle. This sudden deceleration suggests that many drivers executed a last-minute braking maneuver upon perceiving the emergency vehicle. In contrast, the Full Alerts scenario shows a much smoother and more gradual decline in speed. Despite both scenarios reaching similar speeds at the location of the police car, the way in which drivers adjust their speed differs significantly. This smoother deceleration in the Full Alerts scenario implies that digital alert systems allowed drivers to process and react to the emergency response vehicle earlier and more progressively. Rather than making abrupt maneuvers, drivers had more time and space to adapt their driving behavior, leading to a more consistent speed profile. This kind of response is particularly beneficial for traffic safety, as it reduces the likelihood of rear-end collisions, sudden lane changes, and overall traffic disruptions.



(A) Inner Lane (B) Outer Lane

Figure 12. Graph. Average vehicle speed profiles across scenarios in the inner/outer lanes (July 2024).

We further examined the standard deviation of speed as a function of location and scenario, with separate analyses for the inner and outer lanes (Figure 13). The findings reinforce the earlier observations from the average speed plots. In the outer lane, the Lights Only scenario shows a sharp spike in speed variability as vehicles approach the police car—specifically, the standard deviation jumps dramatically at around 100 m upstream, peaking at nearly 14 mph. This pattern indicates that many drivers executed a sudden last-minute maneuver. In contrast, the Full Alerts scenario demonstrates a more gradual increase in speed variability beginning as far back as 300 m upstream. Interestingly, the speed standard deviation stabilizes at a more moderate level, about 8 mph, as vehicles approach the police vehicle. These observations suggest that digital alert systems help distribute drivers' braking behavior more evenly over space, rather than clustering it right before the police vehicle. As a result, traffic in the Full Alerts scenario appears to slow down earlier and more smoothly, reducing the likelihood of abrupt speed changes and enhancing overall safety.



(A) Inner Lane (B) Outer Lane

Figure 13. Graph. Average standard deviation of vehicle speed profiles across scenarios in the inner and outer lanes (July 2024).

CHAPTER 5: JULY 2025 DATA COLLECTION

Building on the July 2024 data collection, three days of data were collected to evaluate digital alerts under a wider range of roadway and operational conditions. While the first experiment focused on a basic freeway scenario, additional scenarios were needed to observe driver responses in more complex environments. The July 2025 data collection, therefore, incorporated another basic freeway section, on-ramp and off-ramp locations, and scenarios in which a large IDOT truck was utilized to compare drivers' responses to different types of emergency vehicles. It is important to note that since the IDOT vehicle did not have the capability to share digital alerts, a police vehicle was positioned immediately downstream of the truck to generate digital alerts. The police vehicle was positioned in a way to not be visible to the drivers approaching the IDOT truck. These additions allow for a more comprehensive assessment of the independent and combined effects of digital alerts across diverse traffic contexts.

It is important to note that the analytical framework used for the 2024 data was not fully replicated in the 2025 analysis. Two approaches applied in the previous study were not repeated here. First, clustering-based analysis of lane-changing behavior was not included since the analysis did not reveal any new findings in addition to what was presented in the previous chapter. Second, the comparative evaluation of lane-changing behavior between small and large vehicles was not repeated. The 2024 results demonstrated no statistically significant differences between vehicle classes, and the 2025 analysis focuses on alert effects rather than vehicle-type heterogeneity. Accordingly, the following sections present only the core behavioral indicators relevant to the evaluation of digital alert effectiveness in 2025.

DATA COLLECTION LOCATION

A section of I-55 in the northeastern area of Springfield, Illinois, was selected for the Day 1 and Day 3 data collection, conducted on July 22 and July 24, 2025, respectively. This segment lies along the southbound direction, extending between coordinates (39.860756, −89.595643) and (39.845831, −89.594451). The location is situated away from nearby airports, allowing uninterrupted aerial operations throughout the data collection period. Figure 14 illustrates the selected roadway section. The same location was used on both days to enable the research team to compare driver responses to a police vehicle and an IDOT vehicle under otherwise similar roadway and traffic conditions.

Data collection for Day 2, conducted on July 23, 2025, was carried out at two adjacent roadway segments on I-55, selected to support the off-ramp and on-ramp experimental scenarios. The segment used for the off-ramp scenarios is located north of the I-55/Adlai Stevenson Dr. interchange, while the segment used for the on-ramp scenarios is located south of the I-55/IL-29 interchange. These segments were chosen due to their consistently high on-ramp volumes and their proximity to one another, which facilitated efficient transitions between experimental scenarios. Figure 15 presents the locations of the selected roadway sections. As with the other data collection days, the selected segments are situated far from airports, supporting continuous, uninterrupted aerial video recording.

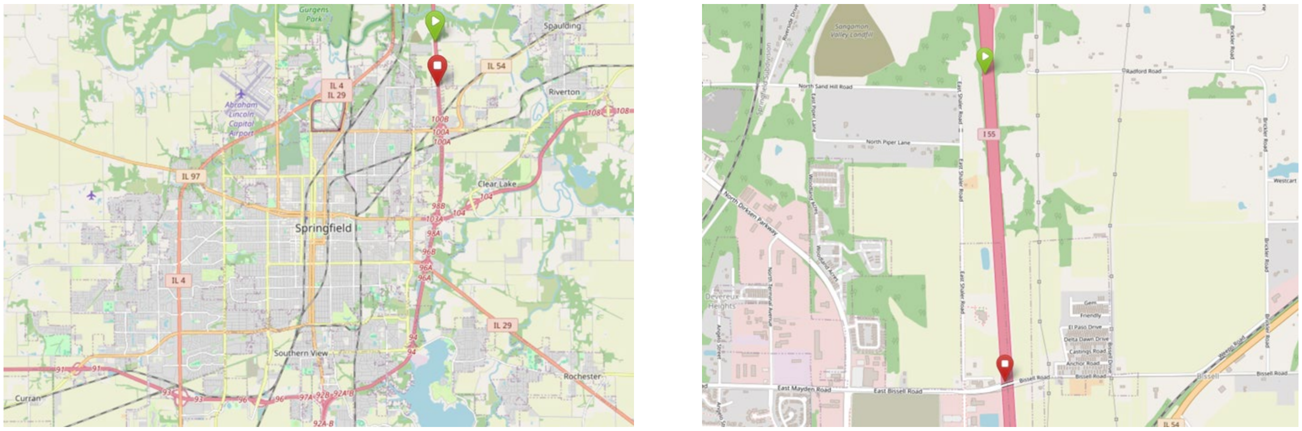


Figure 14. Map. Data collection location (July 2025, day 1 and day 3).

Source: Project OSRM (n.d.)

(A) Off-ramp (B) On-ramp

Figure 15. Map. Data collection location (July 2025, day 2).

Source: Project OSRM (n.d.)

CHANGE IN DIGITAL ALERT SYSTEM BEHAVIOR

During the July 2025 data collection, the research team identified an important change in the operational behavior of the digital alert system compared to the August 2024 experiment. In the earlier deployment, digital alerts and emergency lights could be activated independently. However, in the 2025 deployment, digital alerts were automatically triggered whenever the emergency lights were turned on, making independent control no longer possible. This operational constraint directly influenced the design of the experimental scenarios, as described below.

DATA COLLECTION DETAILS

For Day 1, data collection was designed to systematically examine driver behavior under progressively increasing levels of alert visibility and system activation. The experiment began with the

No Vehicle scenario, recorded at the start of the session to avoid any residual effects from earlier digital alerts that could have influenced baseline conditions in previous studies. This scenario provides an uncontaminated reference for normal traffic flow. Following the baseline, the police vehicle was positioned on the shoulder, and the emergency lights were activated. Because digital alerts were automatically triggered together with the emergency lights in the 2025 system configuration, this scenario represents a Full Alerts condition in which both digital alerts and visual warnings were present. Next, the emergency lights were turned off while the hazard lights remained on, resulting in a Hazard Lights Only scenario. In this configuration, digital alerts remained off, allowing the research team to isolate the behavioral influence of hazard flashers without the presence of digital alerts or emergency lights. Finally, all lights on the police vehicle, including emergency lights and hazard lights, were turned off, creating the No Alerts scenario. This condition reflects a complete blackout in which the stationary vehicle remains visible on the shoulder but provides no external warning cues to approaching drivers. As shown in Table 3, we refer to these four scenarios as No Vehicle, Full Alerts, Hazard Lights Only, and No Alerts, respectively.

Table 3. Data Collection Details (July 2025, Day 1)

Experiment Configuration	Scenario	Description	Time of Day
Location: I-55 Segment Length: 0.5 miles Number of Lanes: 2 Altitude: 1,000 ft Speed Limit: 65 mph Vehicles Involved: Police Vehicle	No Vehicle	Normal Traffic (No Police Vehicle)	12:19 p.m.–1:00 p.m.
	Full Alerts	Digital Alerts ON + Emergency Light ON	1:02 p.m.–2:02 p.m.
	Hazard Lights Only	Digital Alerts OFF + Hazard Lights ON	2:50 p.m.–3:35 p.m.
	No Alerts	Digital Alerts OFF + Black Out	3:36 p.m.–4:21 p.m.

Day 2 focused on evaluating driver behavior in more complex ramp environments, where merging and diverging movements may influence how drivers respond to a shoulder-positioned police vehicle. Unlike the previous experiments, in which the police vehicle was positioned upstream to observe the behavior of the approaching drivers, the vehicle on Day 2 was placed near the center of the data collection segment so that both upstream and downstream trajectories could be examined. This configuration was applied to two roadway contexts: an off-ramp segment and an on-ramp segment. For each context, three scenarios were collected: a No Vehicle baseline, a Full Alerts condition with both emergency lights and digital alerts activated, and a No Alerts condition in which all visual and digital warnings were turned off. Because the effect of hazard lights had already been investigated on Day 1, only these three scenarios were included. Together, the off-ramp and on-ramp experiments allow for assessment of how drivers adjust their speed, lane choices, merging behavior, and diverging movements under different alert conditions, providing insight into how digital and visual alerts function in environments with higher decision-making demands than basic freeway segments. Details are shown in Table 4.

Table 4. Data Collection Details (July 2025, Day 2)

Experiment Configuration	Location	Scenario	Description	Time of Day
Location: I-80 Segment Length: 0.5 miles Number of Lanes: 2 Altitude: 1,000 ft Speed Limit: 65 mph Vehicles Involved: Police Vehicle	Off-Ramp	No Vehicle	Normal Traffic (No Police Vehicle)	9:04 a.m.–9:34 a.m.
		Full Alerts	Digital Alerts ON + Emergency Light ON	9:38 a.m.–10:08 a.m.
		No Alerts	Digital Alerts OFF + Emergency Light OFF	10:10 a.m.–10:40 a.m.
	On-Ramp	No Vehicle	Normal Traffic (No Police Vehicle)	11:14 a.m.–11:44 a.m.
		Full Alerts	Digital Alerts ON + Emergency Light ON	11:51 a.m.–12:21 p.m.
		No Alerts	Digital Alerts OFF + Emergency Light OFF	12:26 p.m.–12:56 p.m.

Day 3 was designed to evaluate the potential safety impacts of installing digital alerts on IDOT emergency vehicles. Because IDOT trucks are not currently equipped to transmit digital alerts, a police vehicle capable of generating alerts was positioned ahead of the IDOT truck to simulate conditions in which the IDOT vehicle itself could broadcast alerts, as shown in Figure 16. The IDOT vehicle was significantly larger than a standard police cruiser, approximately 2.5 times longer and noticeably taller. Due to its larger size, it had a greater visual presence and could partially obstruct drivers' line of sight compared to a typical patrol vehicle. At the same time, this two-vehicle configuration restored independent control of digital alerts and visual warnings. In the 2025 operating environment, emergency lights automatically trigger digital alerts, making it impossible to test digital- or visual-only conditions on a single vehicle. By concealing the police vehicle from upstream traffic and selectively activating emergency lights on either vehicle, the experiment isolated the effect of digital alerts from the strong visual cues of the IDOT truck, while representing a hypothetical scenario in which IDOT vehicles are equipped with digital-alert capability.

Figure 16. Photo. Vehicles involved in the field experiment for Day 3 (from left to right: IDOT truck, passenger vehicle, and police vehicle).

The day began with a No Vehicle baseline to capture normal traffic conditions. In the Full Alerts scenario, both the police vehicle and the IDOT truck had their emergency lights activated, resulting in simultaneous visual cues and digital alert activation. In the Lights Only scenario, the police vehicle's emergency lights were turned off while the IDOT truck's remained on, removing digital alerts while preserving a visual warning. This was followed by the Digital Alerts Only scenario, in which the police vehicle's emergency lights were activated, automatically triggering digital alerts, while the IDOT truck's lights were turned off, creating a condition in which drivers received digital alerts but no visual cues. Finally, both vehicles' lights were turned off in the No Alerts scenario, allowing naturalistic observation of driver behavior when neither visual nor digital warnings were present. This set of scenarios enables direct comparison between digital-only, visual-only, combined-alert, and no-alert conditions, thereby supporting the primary objective of Day 3: assessing the potential effectiveness of adding digital alerts to IDOT vehicles. At the same time, the scenario structure allows a secondary analysis isolating the independent influence of digital alerts by separating it from the strong visual cues of the IDOT truck. As shown in Table 5, we refer to these five scenarios as No Vehicle, Full Alerts, Lights Only, Digital Alerts Only, and No Alerts, respectively.

Table 5. Data Collection Details (July 2025, Day 3)

Experiment Configuration	Scenario	Description	Time of Day
Location: I-55 Segment Length: 0.5 miles Number of Lanes: 2 Altitude: 1,000 ft Speed Limit: 65 mph Vehicles Involved: Police + IDOT	No Vehicle	Normal Traffic (No Police, No IDOT)	8:59 a.m.–9:30 a.m.
	Full Alerts	Digital Alerts ON + Police ON + IDOT ON	9:36 a.m.–10:06 a.m.
	Lights Only	Digital Alerts OFF + Police OFF + IDOT ON	10:10 a.m.–10:40 a.m.
	Digital Alerts Only	Digital Alerts ON + Police ON + IDOT OFF	10:45 a.m.–11:15 a.m.
	No Alerts	Digital Alerts OFF + Police OFF + IDOT OFF	11:18 a.m.–11:48 a.m.

DAY 1 DATA ANALYSIS

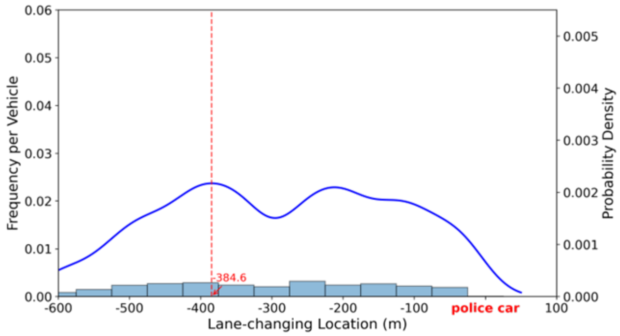
Table 6 summarizes the lane-specific traffic flow for the four Day 1 scenarios. Inbound and outbound flows were broadly consistent across scenarios, indicating stable traffic conditions. Lane-usage patterns clearly reflect the influence of alert visibility. In the No Vehicle scenario, inner-lane outbound flow is slightly lower than inbound flow. Once the police vehicle is introduced, both the Full Alerts and Hazard Lights Only scenarios show substantially higher outbound inner-lane flow, indicating increased lane-changing activity in response to the police car. The No Alerts scenario exhibits noticeably fewer lane changes, indicating that drivers respond much more actively when digital alerts and visual cues are present. Total flow decreases across the four scenarios, primarily due to time-of-day effects and a 50-minute refueling break between scenarios (see Table 3). Thus, the lower flows in the later scenarios reflect normal afternoon demand reductions rather than experimental influences. However, the patterns and percent of flows are consistent across all scenarios.

Table 6. Lane-Specific Traffic Flow at Inbound and Outbound Locations (July 2025, Day 1) (veh/hr)

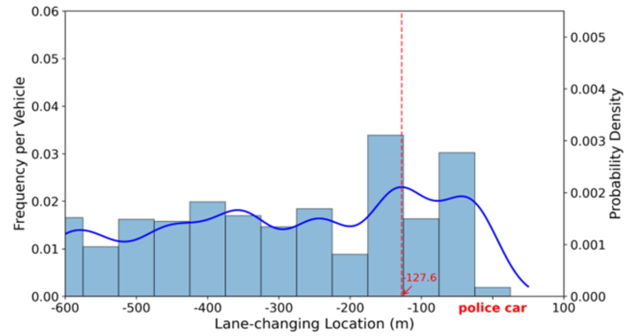
Scenario	Traffic Flow (veh/hr)				Total
	Inner Lane (in)	Outer Lane (in)	Inner Lane (out)	Outer Lane (out)	
No Vehicle	**872**	**458**	**800**	**530**	**1330**
Full Alerts	**782**	**321**	**929**	**174**	**1103**
Hazard Lights Only	**541**	**427**	**619**	**349**	**968**
No Alerts	**377**	**507**	**491**	**393**	**884**

Figure 17 illustrates the distribution of lane-changing locations under all scenarios. Clear differences emerge in both the position and magnitude of the dominant peak across scenarios. Under the Full Alerts condition, the peak lane-changing location occurs approximately 127.6 m upstream of the police vehicle. This distance is substantially greater than the corresponding peak of 74.3 m observed in the Hazard Lights Only scenario. When no alerts are present, the peak shifts even closer to the police vehicle, occurring 63.2 m upstream.

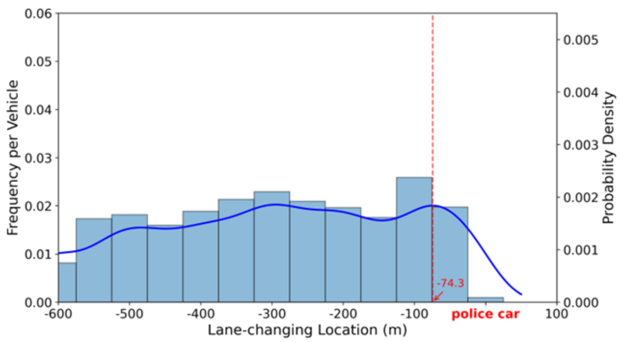
This monotonic shift in peak location provides strong evidence that the level of alert visibility directly influences how early drivers choose to initiate lane-changing maneuvers. The relatively small difference between the Hazard Lights Only and No Alerts scenarios (74.3 m vs. 63.2 m) suggests that hazard lights alone offer only a limited improvement in driver awareness, prompting only a modest upstream shift. By contrast, the introduction of the full alert package (digital alerts synchronized with emergency lights) produces a much more pronounced upstream response, with drivers changing lane nearly 50 m earlier compared to the Hazard Lights Only scenario. This substantial increase in early lane-changing activity highlights the added value of digital alerts when combined with strong visual cues: Drivers receive and act upon the warning earlier, reducing the likelihood of last-second maneuvers near the stationary vehicle. These observations are further validated through statistical comparison using the KS test.



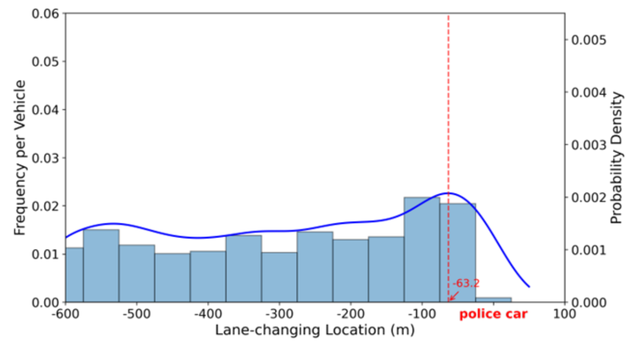
(A) No Vehicle



(B) Full Alerts



(C) Hazard Lights Only



(D) No Alerts

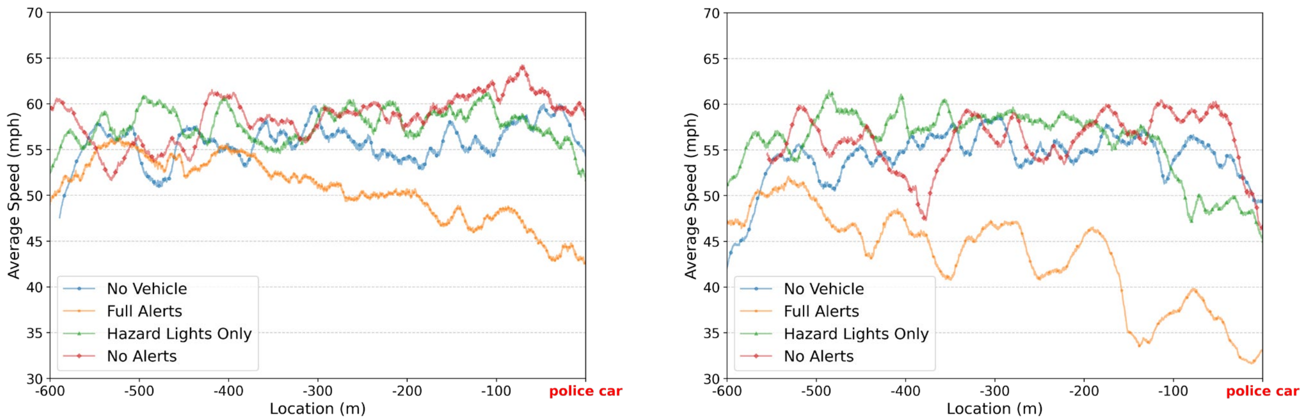
Figure 17. Histogram. Lane-changing locations under different alert scenarios (July 2025, day 1).

To statistically evaluate whether the distributions of lane-changing locations differ across alert conditions, pairwise KS tests were conducted for all Day 1 scenarios. As shown in Figure 18, the resulting p-values reveal several meaningful patterns regarding how drivers respond to different levels of alert visibility. First, all comparisons involving the No Vehicle scenario yield extremely small p-values (0.001 for both Full Alerts and Hazard Lights Only, and effectively 0 for No Alerts), indicating that the baseline traffic behavior is statistically distinct from any scenario in which a police vehicle is present. This confirms that the introduction of the stationary vehicle, regardless of alert type, substantially alters driver behavior.

More importantly, comparisons among the three alert scenarios show a clear, ordered differentiation in behavioral response. The KS test between Full Alerts and Hazard Lights Only produces a p-value of 0.003, indicating a statistically significant difference between these distributions. This aligns with the earlier histogram findings, where Full Alerts prompted lane changes much farther upstream than Hazard Lights Only. The comparison between Full Alerts and No Alerts also yields a statistically significant p-value (0.026), reflecting the strong impact of both visual cues and digital alerts in shifting driver response patterns. By contrast, the p-value for Hazard Lights Only versus No Alerts is higher (0.087), exceeding the conventional 0.05 threshold. This result suggests that although hazard lights do prompt somewhat earlier lane changes, the magnitude of their effect is insufficient to produce a statistically significant shift relative to having no alerts at all. The KS test results therefore reinforce the earlier observations that digital alert systems meaningfully enhance early driver awareness beyond what visual cues alone can achieve.

Figure 18. Heatmap. Statistical significance of lane-changing location differences across scenarios (July 2025, day 1).

Figure 19 presents the location-based speed profiles for the inner and outer lanes under all scenarios. In the inner lane, a clear ordering emerges in how early drivers begin to decelerate. Under the Full Alerts condition, speed reduction begins as far as 400 m upstream of the police vehicle. This early and gradual deceleration aligns with the strong upstream shift in lane-changing activity observed previously. In the Hazard Lights Only scenario, speed reduction occurs much later, beginning at approximately 120 m upstream. When no alerts are present, drivers do not noticeably reduce their speed until they are within roughly 80 m, reflecting a substantially delayed perception of the police vehicle. The outer lane shows a qualitatively similar pattern, though with noticeably greater variability across locations. Speed values in the outer lane fluctuate more widely compared to the inner lane, suggesting that traffic in this lane was less stable and more influenced by interactions among vehicles. Nevertheless, the same hierarchical structure remains evident: Full Alerts consistently produce the earliest speed adjustments, followed by Hazard Lights Only, and finally No Alerts.



(A) Inner Lane

(B) Outer Lane

Figure 19. Graph. Average vehicle speed profiles across scenarios in the inner and outer lanes (July 2025, day 1).

DAY 2 DATA ANALYSIS

Day 2 of the 2025 data collection focused on freeway ramp environments to evaluate whether the presence of the police vehicle and different alert configurations would influence drivers' merging and exiting behavior. Unlike Day 1, where drivers could voluntarily choose when to change lanes, ramp maneuvers represent mandatory maneuvers, and any influence from the alert system would need to manifest through changes in the intended trajectory or speed control. The analysis, therefore, concentrated on two possible behavioral effects: whether the police vehicle triggered lane-changing patterns that deviated from normal ramp behavior, and whether the alert conditions changed how early drivers reduced their speed when approaching the police vehicle.

As illustrated in Table 7, the Day 2 traffic flow results show that the off-ramp demand is consistently lower than the on-ramp demand, indicating that more vehicles are entering the I-55 corridor than exiting it. The flow level is consistent with the Day 1 experiment, which is expected given that both datasets were collected on the same freeway segment under comparable traffic conditions. A clear difference emerges across the three experimental scenarios at the off-ramp: Compared with the No Vehicle baseline, both the Full Alerts and No Alerts conditions exhibit notably higher lane-changing activity, reflected by the redistribution of flows between the inner and outer lanes. In contrast, the on-ramp results show a remarkably stable lane-choice pattern across all scenarios. Nearly all additional inflow from the ramp is absorbed by the outer lane, while the inner lane volume remains largely unchanged. This indicates that neither the presence of the emergency vehicle nor the activation of digital alerts substantially affects the merging lane decision for entering vehicles; drivers tend to complete the merge and remain in the outer lane. This dominant behavioral tendency is further confirmed and discussed in the following analysis.

Table 7. Lane-Specific Traffic Flow at Inbound and Outbound Locations (July 2025, Day 2) (veh/hr)

Location	Scenario	Traffic Flow (veh/hr)					Total
		Ramp	Inner Lane (in)	Outer Lane (in)	Inner Lane (out)	Outer Lane (out)	
Off-Ramp	No Vehicle	49	673	360	627	357	1033
	Full Alerts	41	471	520	555	395	991
	No Alerts	54	412	576	481	453	988
On-Ramp	No Vehicle	86	311	530	300	627	927
	Full Alerts	118	223	554	235	660	895
	No Alerts	83	250	521	241	613	854

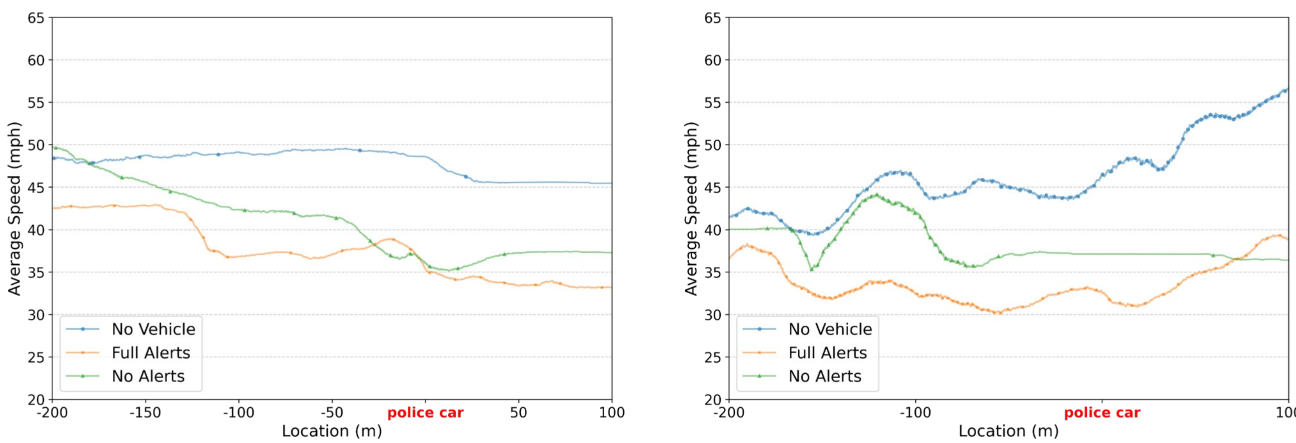
For lane-changing behavior, for off-ramp traffic, we evaluated whether diverging vehicles exhibited forced lane deviation (FLD) behavior, characterized by a temporary move from the outer lane into the inner lane before returning to the outer lane near the exit ramp. For on-ramp traffic, we examined whether merging vehicles performed a rapid secondary lane change, entering the main lanes into the outer lane and then immediately shifting into the inner lane instead of stabilizing in the merge lane. The presence of either behavior would indicate that the police vehicle meaningfully altered drivers' intended merging or diverging trajectories.

A comprehensive review of aerial video recordings across all Day 2 scenarios revealed no instances of rapid secondary lane changes or FLD maneuvers. Vehicles intending to exit at the off-ramp followed normal diverging trajectories without diverting into inner lanes before the exit. Similarly, vehicles merging from the on-ramp consistently entered the mainline and remained in their chosen lane, showing no evidence of avoidance behavior attributable to the police vehicle. These observations held across all alert configurations, including Full Alerts (where both digital notifications and emergency lights were active) and No Alerts (where the police vehicle provided neither visual nor digital cues). Trajectory data confirmed that none of the observed vehicles exhibited lane-change sequences consistent with FLD patterns or rapid secondary lane changes. These observations indicate that the presence of an emergency vehicle near on- and off-ramps does not result in unnecessary high-risk maneuvers.

The absence of these behaviors aligns with well-established traffic behavior principles. First, drivers typically commit to exiting and merging maneuvers before reaching the location of the police vehicle. Exiting and merging involve increased cognitive and operational demands, such as gap assessment and speed adjustment, making drivers less likely to perform additional discretionary lane changes unless necessary. This aligns with existing research (Fuller, 2005) showing that primary navigation tasks dominate driver attention in high-demand environments, reducing sensitivity to secondary stimuli, such as alert systems. Moreover, although some drivers received digital alerts upstream, the notifications did not alter their fundamental merge or diverge plans. This finding suggests that digital alerts may influence anticipatory behavior on basic freeway segments (as demonstrated on Day 1) but have a limited impact on mandatory operational maneuvers in ramp areas.

Because trajectory-based lane-change analysis did not reveal differences in ramp behavior, the analysis turned to speed patterns to evaluate whether the presence of a police car and alert conditions influenced the timing or magnitude of speed reduction. To do so, exiting and merging vehicle trajectories were manually extracted and cleaned to obtain complete records before and after passing the police vehicle location. Figure 20 demonstrates the location-based average speed of exiting vehicles (off-ramp) and merging vehicles (on-ramp) upstream and downstream of the police car.

For exiting vehicles (off-ramp), both Full Alerts and No Alerts scenarios show early speed reduction at least 200 m before reaching the police vehicle, whereas the No Vehicle scenario shows no deceleration until the exit point. Moreover, Full Alerts resulted in lower average speeds than No Alerts, with a reduction of approximately 5 mph over the same distance. For merging vehicles (on-ramp), the influence of ramp geometry is more pronounced: Vehicles initially decelerate on the curved ramp section and then accelerate as they prepare to merge into the main lanes. In the region 100 to 150 m upstream from the police vehicle, all scenarios show a speed increase, but the increase in the Full Alerts scenario is significantly smaller than in No Vehicle and No Alerts scenarios. This produces a distinct behavioral pattern. In the absence of alerts, merging drivers accelerate aggressively to enter the mainline and then brake sharply once they detect the police vehicle, whereas under Full Alerts, drivers maintain a lower and more stable speed throughout the merge zone, delaying strong acceleration until after passing the police vehicle. This indicates that digital alerts combined with emergency lights allow merging drivers to anticipate the roadside hazard earlier, reducing the urgency associated with last-minute acceleration and braking.



(A) Off-ramp (B) On-ramp

Figure 20. Graph. Average speed profiles of exiting and merging vehicles under different scenarios (July 2025, day 2).

Taken together, the Day 2 findings show that alert systems do not alter the path of mandatory merging or exiting maneuvers, but they do influence how drivers manage their speed while performing these maneuvers. Drivers consistently followed their intended merge and exit trajectories, and no avoidance-related lane-change sequences, such as rapid double lane changes or forced lane deviations, were observed. However, the presence of the police vehicle and the associated alert conditions did affect speed control. Full Alerts encouraged earlier awareness of the roadside hazard and produced a smoother speed transition through both the exit and merge zones. By contrast, in the No Alerts condition, merging drivers exhibited a sharper accelerate-decelerate pattern: They accelerated to join traffic and then rapidly reduced speed upon visually detecting the police vehicle. These results highlight a clear contrast with the Day 1 findings. On basic freeway segments, alert systems strongly influence discretionary lane-changing decisions, whereas near ramps, operational necessities dominate lane choice, and the influence of alerts appears primarily in speed management. This pattern is not only consistent with the functional role of ramp areas (where drivers prioritize gap acceptance and execution of mandatory maneuvers) but is also desirable from a safety standpoint, as the alert system enhances hazard awareness without interfering with critical ramp operations.

DAY 3 DATA ANALYSIS

As shown in Table 8, we examined the rate of lane changes per vehicle in the outer lane. The four scenarios showed clear distinctions, with lane-changing rates of 0.57 (Full Alerts), 0.59 (Lights Only), 0.25 (Digital Alerts Only), and 0.14 (No Alerts). The two scenarios with active emergency lights, therefore, produced more than twice as many lane changes as the scenarios without visual cues. This aligns with the results presented in the remainder of this section: When the IDOT truck's lights were visible, drivers detected the hazard earlier and changed lanes more frequently. In contrast, the Digital Alerts Only and No Alerts conditions generated far fewer lane changes, as the truck appeared similar to a standard parked vehicle. Still, the Digital Alerts Only rate was about 80% higher than No Alerts, indicating that digital alerts continued to encourage avoidance behavior even in the absence of visual warnings. Overall, these results confirm that visual conspicuity is the primary driver of behavioral change on Day 3, with digital alerts providing a smaller but measurable contribution when emergency lights are not active.

Table 8. Lane-Specific Traffic Flow at Inbound and Outbound Locations (July 2025, Day 3) (veh/hr)

Scenario	Traffic Flow (veh/hr)				Total
	Inner Lane (in)	Outer Lane (in)	Inner Lane (out)	Outer Lane (out)	
No Vehicle	531	355	492	394	886
Full Alerts	502	336	692	146	838
Lights Only	535	355	743	147	890
Digital Alerts Only	493	327	575	245	820
No Alerts	501	336	549	288	837

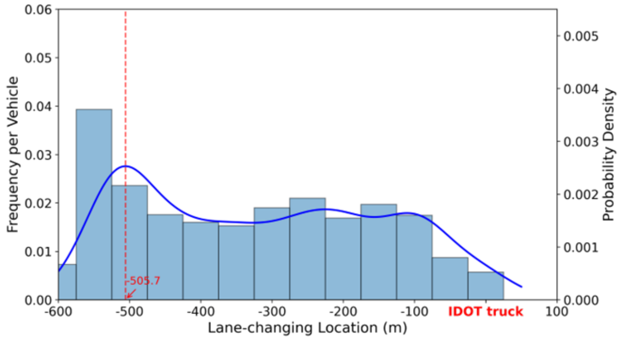
The lane-changing location distributions for the four Day 3 scenarios—Full Alerts, Lights Only, Digital Alerts Only, and No Alerts—are shown in Figure 21. The experimental design allows a direct comparison between scenarios where the IDOT vehicle provides a strong visual warning and scenarios where only digital alerts are available. As a result, a clear behavioral separation emerges between conditions involving the IDOT truck's emergency lights and those without visible cues.

In the Full Alerts and Lights Only scenarios, the peak lane-changing activity occurs approximately 500 m upstream of the police vehicle. This distance is substantially larger than the values observed on Day 1 or in the 2024 data collection, where drivers typically initiated lane changes closer to 120–150 m. The primary explanation lies in the presence of the large IDOT truck, whose size and elevated light bar produce a highly salient visual cue visible from long range. Because the emergency lights of the truck were active in both scenarios, drivers were able to recognize the shoulder-stationary vehicle far earlier than in previous experiments, prompting much earlier discretionary lane changes regardless of whether digital alerts were also active. Although the peak location under the Full Alerts scenario lies slightly closer to the police vehicle than under the Lights Only one, this difference reflects the dominance of the strong visual cue rather than a lack of effect from digital alerts: When the hazard is visible from long range, visual detection drives the modal lane-change point, leaving digital alerts with limited marginal influence on the peak position.

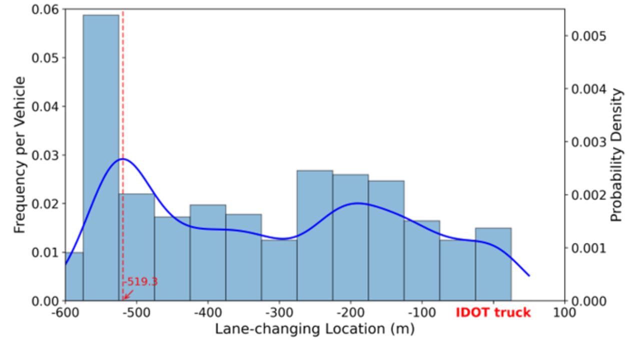
In contrast, the Digital Alerts Only and No Alerts scenarios exhibit markedly shorter lane-changing distances, with peak values at 162.1 m and 147.8 m, respectively. In these configurations, the IDOT truck's emergency lights were turned off, meaning that the only visible roadside object was what appeared to drivers as an ordinary parked maintenance vehicle. As a result, drivers did not perceive an urgent need to maneuver until they were much closer to the vehicle. Nonetheless, the Digital Alerts Only scenario still shows a measurable improvement relative to No Alerts: The digital alert system shifts the peak lane-changing distance upstream by roughly 14 m, indicating that digital alerts continue to provide beneficial anticipatory information even when visual conspicuity is low.

Taken together, the Day 3 results highlight an important interaction between digital alerts and visual cues. When a highly salient visual stimulus, such as the emergency lights on a large truck, is present, it becomes the dominant factor shaping driver behavior, substantially diminishing the incremental influence of digital alerts. However, in the absence of such cues, digital alerts meaningfully improve drivers' responses, reinforcing the system's role as an early warning mechanism. This pattern is consistent with findings from Day 1 and further demonstrates that the relative effectiveness of digital alerts is context-dependent and moderated by the visibility of roadside hazards.

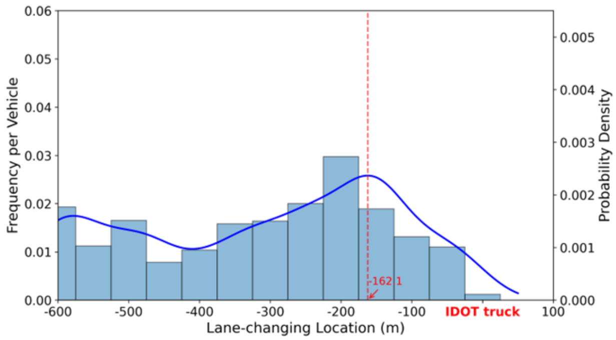
In addition to the distributional patterns, a KS test was also performed to statistically evaluate differences in lane-changing location across the four Day 3 scenarios. The comparison between Full Alerts and Lights Only scenarios yielded a p-value of 0.20, indicating no statistically significant difference in their lane-changing distributions, which is consistent with the finding that emergency lights dominated driver perception in both cases. By contrast, the comparison between Digital Alerts Only and No Alerts scenarios returned a p-value of 0.01, showing a clear and significant difference in where drivers initiated lane changes, further confirming that digital alerts meaningfully shift behavior upstream when visual cues are absent. Finally, both visual-cue scenarios (Full Alerts and Lights Only) showed p-values below 0.001 when compared with both non-visual configurations, confirming that the presence of emergency lights drives a fundamentally different behavioral pattern. Together, these statistical results reinforce the interpretation that highly salient visual cues overshadow the influence of digital alerts in the Full Alerts and Lights Only scenarios, while digital alerts play the leading role in shaping early lane-change behavior when visual warnings are not available.



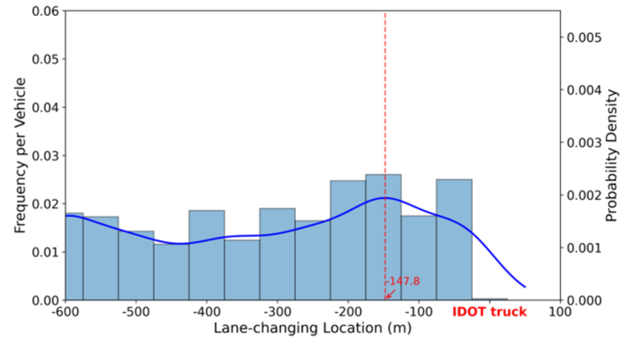
(A) Full Alerts



(B) Lights Only



(C) Digital Alerts Only

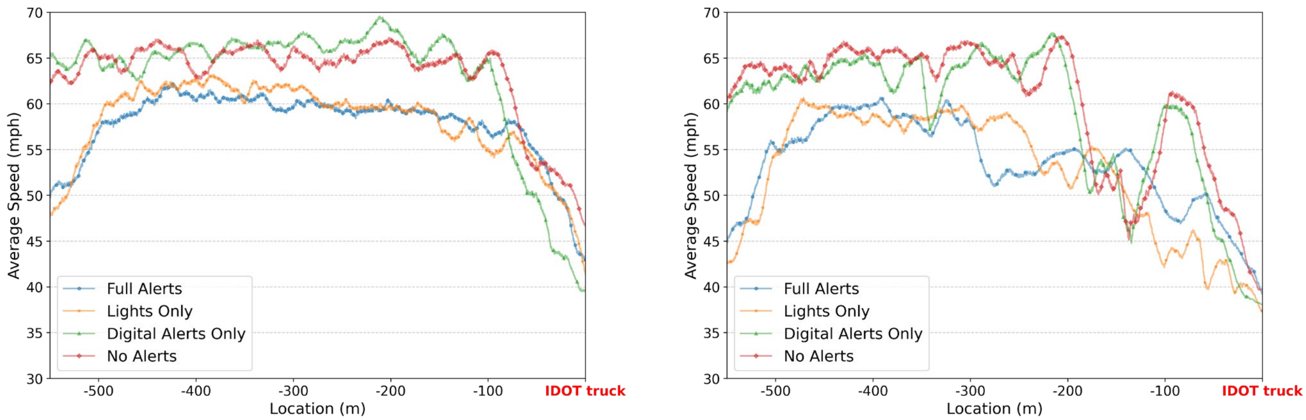


(D) No Alerts

Figure 21. Histogram. Lane-changing locations under different alert scenarios (July 2025, day 3).

As shown in Figure 22, analysis of the location-based speed profiles shows a clear grouping of the four scenarios. For both the inner and outer lanes, the Full Alerts and Lights Only scenarios exhibit nearly identical speed patterns, while the Digital Alerts Only and No Alerts scenarios form a second pair with similar behavior. In both lanes, speeds in the Full Alerts and Lights Only conditions begin to decrease earlier and reach lower values, reflecting the strong visual salience of the IDOT truck's emergency lights.

A closer comparison of the two non-visual scenarios shows that the Digital Alerts Only and No Alerts speed curves have nearly identical shapes; however, the No Alerts curve is shifted downstream, meaning drivers begin to decelerate at a similar rate but only after they are closer to shoulder vehicles. This horizontal shift highlights that digital alerts change when drivers start slowing down. Moreover, under the Digital Alerts Only scenario, the overall speeds remain lower throughout the approach to shoulder vehicles, indicating that even in the absence of emergency lights, digital alerts still prompt drivers to slow down earlier and maintain more conservative speeds, contributing to improved safety margins.



(A) Inner Lane (B) Outer Lane

Figure 22. Graph. Average vehicle speed profiles across scenarios in the inner and outer lanes (July 2025, day 3).

Overall, Day 3 demonstrates that the value of installing digital alerts on IDOT emergency vehicles depends on visibility conditions. When the IDOT truck's emergency lights are active and highly visible from a long distance, most drivers detect the roadside hazard through visual cues alone, and the behavioral effect of digital alerts is effectively overshadowed (i.e., lane-changing timing and speed adjustments are largely determined by the emergency lights rather than by alert information). However, when visual cues are absent or limited, digital alerts serve as the primary mechanism that shifts driver responses upstream, encouraging earlier lane-change locations and earlier speed reduction. This indicates that digital alerts are especially effective for smaller roadside vehicles or situations where emergency lights cannot be easily seen (e.g., curves, occlusion instances, and adverse weather conditions). For large IDOT trucks under ideal daylight conditions, digital alerts function as a redundant safety layer, ensuring protection for drivers who may not immediately notice visual cues.

CHAPTER 6: CONCLUSION, LIMITATIONS, AND FUTURE WORK

This study presents a comprehensive multi-day data collection evaluating digital alert systems as a safety measure for roadside emergency operations on high-speed freeways. Collecting data in Kendall County, Illinois, for one day in 2024 and Springfield, Illinois, for three days in 2025, the research provides a comprehensive view of how digital alerts and traditional visual cues jointly shape driver behavior under real traffic conditions and influence compliance with the Move Over law. Unlike controlled driving simulator studies, the experiments were conducted entirely in live operating environments with naturalistic traffic, generating high-resolution trajectory data for thousands of vehicles.

Across all four days, the results reveal a clear and reproducible behavioral pattern: Digital alerts shift both lane-changing locations and speed-reduction points upstream relative to a stationary roadside emergency vehicle. This effect is observed under a wide range of roadway geometries, traffic demands, and emergency vehicle types (i.e., police vehicles and IDOT vehicles). The findings demonstrate that digital alerts act as an independent early warning channel, enabling drivers to anticipate roadside hazards earlier than visual cues alone allow.

The experiments also show how alert effectiveness interacts with visual conspicuity. When the large IDOT emergency truck was present, its emergency lights generated a strong visual signal that prompted many drivers to change lanes at very long distances (up to 400–500 m). In these cases, visual conspicuity dominated driver reaction, and the added value of digital alerts was largely masked by the highly salient visual cue. However, when emergency lights were absent or visibility was limited, digital alerts became the primary mechanism, encouraging earlier lane changing and speed reduction. This suggests that the safety benefit of installing digital alerts on IDOT vehicles depends on the visibility of the emergency vehicle (i.e., digital alerts offer limited additional effect when strong visual cues are present but provide meaningful value as an early warning mechanism when visual detection is delayed or obstructed).

In addition to the observed speed and lane-changing patterns, the 2025 ramp experiment provides an important observation related to mandatory lane-changing maneuvers. In exiting and merging environments, lane-choice outcomes remain stable across alert conditions, since those maneuvers are dictated primarily by ramp geometry, gap availability, and traffic flow rather than by secondary cues. However, the absence of discretionary lane changes does not imply a lack of influence. In fact, digital alerts still affect speed-control strategies near the ramp influence area. Exiting drivers reduced speed earlier when full alerts were active, and merging drivers exhibited smoother speed profiles that avoided the abrupt merge-zone braking commonly triggered by late awareness of the police vehicle. This distinction is crucial since on basic freeway segments, drivers have discretion both in whether and when to change lanes and in how early they begin decelerating. On near ramps, however, lane selection is dictated by drivers' path choice as well as geometric and operational requirements. The only remaining form of discretionary behavior is speed management, which is heavily influenced by digital alerts.

Taken together, the findings show that digital alert systems can meaningfully enhance compliance with Move Over laws without disrupting essential navigational decisions. They provide a new layer of protection for first responders, especially in cases where the line of sight is limited (e.g., where vehicles block the view of the police car or where digital alerts can reach drivers before they exit a curve or ramp). The experimental evidence supports the role of digital alert systems as a complementary safety technology alongside emergency lights, expanding the upstream safety buffer, where early decisions prevent unsafe maneuvers downstream.

STUDY LIMITATIONS

Several limitations should be considered when interpreting the findings of this study. First, the traffic demand observed during the 2025 data collection was substantially higher than in the 2024 experiment, reflecting normal weekday afternoon conditions on I-55. Although the analysis controlled for relative lane-change frequency and normalized distributions, differences in flow levels may still influence the magnitude of lane-changing and speed-adjustment behavior captured across scenarios. From a traffic-flow perspective, this is an expected outcome: Higher demand creates denser car-following interactions and reduced gap availability, which naturally dampen lane-changing frequency and compress the distance over which drivers adjust speed. Additional data collection in more congested conditions (e.g., stop-and-go traffic) can help create a comprehensive model of drivers' behavior when approaching an emergency vehicle (even though such conditions are mostly low-speed instances and already satisfy the Move Over law requirements).

A key missing factor from all the presented analyses is the actual penetration rate of digital alerts. We were not able to acquire any information regarding how many vehicles received the digital alerts. Although the research team ensured that digital alerts could be reached by popular navigation apps during the data collection, navigation apps presented the alerts differently and at different locations upstream of the emergency vehicle. In fact, except for one navigation app, the remaining apps did not provide consistent alert coverage, which means the observed effects reflect only a subset of the traveling population that was exposed to the digital alert system. Those factors were not considered in the analyses due to the lack of information on the penetration rate of digital alerts.

FUTURE RESEARCH

Future research can build upon this work in several ways to better quantify the safety benefits of digital alert systems. A natural extension is to deploy alerts across multiple navigation platforms, enabling higher penetration rates and improved measurement of user heterogeneity, including differences in vehicle types and driver familiarity with digital alerts. Additional data collection under nighttime, low-visibility, or adverse weather conditions would also be valuable, as digital alerts may have greater influence when visual cues are less reliable or partially obscured. With full trajectories, the observed distributions of lane-change distance, speed adjustment, and merging behavior can be used to calibrate microscopic models of car following, lane selection, and gap acceptance, enabling controlled evaluation of digital-alert timing and message design across different traffic environments. Finally, beyond experimental data, a before-and-after evaluation on real operational corridors, where digital alerts are deployed continuously, would provide evidence of how alert systems affect compliance with the Move Over law and reduce struck-by risk over time, complementing the controlled experimental approach presented in this report.

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