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The Comparison of Data Collection Methods in Evaluating Drivers' Responses to Speed Message Signs

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Table of Contents

List of Tables

List of Figures

INTRODUCTION

As part of Advanced Traffic Management Systems (ATMS), Variable Message Sign (VMS) or Dynamic Message Sign (DMS) was introduced and deployed across the nation with an intention to augment the safety and efficiency of transport networks (Ermagun et al., 2021a). DMS is an electronic traffic sign that disseminates route guidance information (Erke, 2007), work zone warnings (Huang and Bai, 2019), advertisements (Harms et al., 2019), and speed advisories (Jomaa et al., 2016). It can be switched on or off and display multiple slides of information (Nygårdhs, 2011). The large deployment of DMS in American and non-American transport networks led to detecting areas in need of implementation, prioritizing investments, and evaluating the effectiveness of dynamic message signs. Research has then evolved to study the response and, in most cases, the compliance of drivers with the messages displayed on the electronic sign. Depending on the context of the message, the intention may be to divert traffic flow (Mahmassani and Liu, 1999), to create a homogeneous speed pattern (van Nes et al., 2010), to decrease traffic speed (Garber and Patel, 1995), or to warn drivers of adverse weather conditions (Rämä, 1999).

The response of drivers to road sign messages has been examined by conducting stated preference surveys (Bakhsh Kelarestaghi et al., 2020, Ma et al., 2014), by running simulators (Dutta et al., 2004), and by conducting field studies (Erke et al., 2007). Stated preference surveys involve participants answering a set of questions and can be distributed and completed manually or digitally. For example, Gan and Xe (2011) distributed a survey that asked 171 drivers about their responses to theoretical diversion information in Shanghai. They found that saving travel time and more years of driving experience increase the likelihood of obeying the DMS, while more traffic lights, higher use of urban freeways, being a mid-age driver, and having an employer-provided car decrease the likelihood of diverting in response to the DMS. Driving simulator studies involve creating a virtual reality where participants sit on a driver's car seat and look at a monitor projecting a driver's view through a windshield. There are controls for the participant to steer, brake, and accelerate, and these actions affect what the participant sees in the monitor. Reinolsmann et al. (2021) conducted a simulator study with 63 participants to understand the response of drivers to two different DMS graphics communicating a "Sandstorm" warning in Qatar. They found that both graphics were equally effective at reducing speeds before the low visibility condition. Field studies involve collecting observed data from the real world. There are various methodologies used to conduct a field study, but a few examples include using loop detectors to track drivers' route choice behavior, observing brake lights from a video, and using a radar speed gun to collect speed data. Kim et al. (2014) conducted a field study with 859 drivers to understand what DMS information causes drivers to detour in South Korea. They found that additional travel time is the most influential variable for increasing detours.

An untapped research avenue is to compare the responses of drivers to dynamic message signs in the three different environments of field study, simulator, and questionnaire. The overarching goal of this thesis is to compare these three data collection methods by conducting a scoping literature review to understand how questionnaires, simulators, and field studies vary in results and application. By summarizing and analyzing the existing literature related to drivers' response to DMS, we can draw conclusions about the consistency between various data-collection methods. The scope of the thesis is limited to studies examining the behavior of drivers to speed change messages when the DMS explicitly asks for a change in the speed. The contribution is therefore twofold. <u>First</u>, much of the previous research has focused on exploring the drivers' response to DMS by conducting stated preference surveys, using simulators, or conducting a field study. Little is known about whether and to what extent the response of drivers is a function of the data collection method. This thesis compares the responses of drivers to variable message signs when studied through a questionnaire, simulator, and field study. <u>Second</u>, this thesis presents the similarities and dissimilarities between these three data-collection methods by synthesizing 35 peer-reviewed articles published between 1997 and 2021. In particular, this thesis answers the following questions:

- Are results obtained from surveys, simulations, and field observations consistent when considering drivers' responses to DMS?
- What are the similarities and dissimilarities between surveys, simulators, and field studies?

The remainder of this thesis is structured as follows. First, we discuss the methodology of the review. Second, we summarize the statistics of 35 research papers extracted from the 1,826 papers collected through our scoping method. Third, we review the extracted papers considering the data collection method used and the results obtained from each study. Finally, we present our conclusions and their implications for existing and future research.

METHOD

Literature reviews are typically classified as either systematic or scoping reviews. Systematic reviews are often identified by their focused research questions, detailed data extraction, and set inclusion and exclusion criteria. In contrast, scoping reviews can have broader research questions, may or may not have data extraction, and inclusion and exclusion criteria can be developed *post hoc* (Armstrong et al., 2011). Scoping reviews can have broad goals such as identifying gaps in the research, presenting key findings, and making a general conclusion about a population (Peters et al., 2015). A previous literature review studied the relationship between driver behavior and variable message signs and followed a scoping review methodology limited to European studies from 2000-2005 (Nygårdhs, 2011). Similarly, this thesis is classified as a scoping review due to its broad application.

This scoping literature review follows the five stages outlined by Arksey and O'Malley (2005):

- *Stage 1*: identifying the research question
- *Stage 2:* identifying relevant studies
- *Stage 3*: study selection
- *Stage 4*: charting the data
- *Stage 5*: collating, summarizing, and reporting the results

To retrieve all the relevant studies, we conducted an electronic search on Google Scholar. The key searches were "dynamic message sign," "variable message sign," "field data," "field study," "observed," "questionnaire," "simulator," and "survey." The "dynamic message sign" and "variable message sign" terms were used interchangeably along with the other terms joined with a plus sign (e.g., "dynamic message sign" + "field data," "variable message sign" + "survey"). Only the peer-reviewed journals in English were kept for further review, totaling 1,826 manuscripts. Duplicates were then removed, resulting in 1,338 remaining papers. We then read each abstract for relevance, checking specifically for articles relating to drivers' response to variable message signs. After removing irrelevant papers, we were left with approximately 900 manuscripts. Because of the high number of relevant papers, we narrowed our search further to only include studies that had a DMS displaying a message related to speed.

Only articles utilizing questionnaires, simulations, or field observations to study a DMS instructing drivers to slow down were kept for analysis. Also, the DMS had to explicitly mention speed. Existing research studying the speed change behavior of drivers falls into two distinct categories. First, there are studies examining the response of drivers to speed change messages. The DMS wording in this category explicitly asks for a change in the speed. For example, "Reduce Speed" (Hildebrand and Mason, 2014), "Slow Down" (Sui and Young, 2014), and "Slow Down Your Speed Is…" (Monsere et al., 2005) are all examples of messages explicitly instructing a change in speed. Second, there are studies measuring the speed change of drivers implicitly under different messages such as "800 Meters Ahead - Traffic Congestion" (Yan and Wu, 2014), "Caution" (Guattari et al., 2012), "A31 closed after Bergdorp. Accident. Oostdorp follow Bergdorp" (Harms et al., 2019), and

"Minimum headway 80m" (Rämä and Kulmala, 2000). The former is included in our analysis as it directly examines the compliance level of drivers to speed change messages. To avoid skewed data, any articles that studied DMSs in the presence of outside influencing factors such as inclement weather (Belz and Gårder, 2009) were not included. However, a DMS warning about outside factors approaching such as "Fog Ahead-Speed Reduced" (Hassan et al., 2012) and "Work Zone Ahead/Reduce Speed" (Rahman et al., 2017) were included. A total of 35 articles remained after this extraction process. A flowchart showing this methodology is depicted in Figure 1.

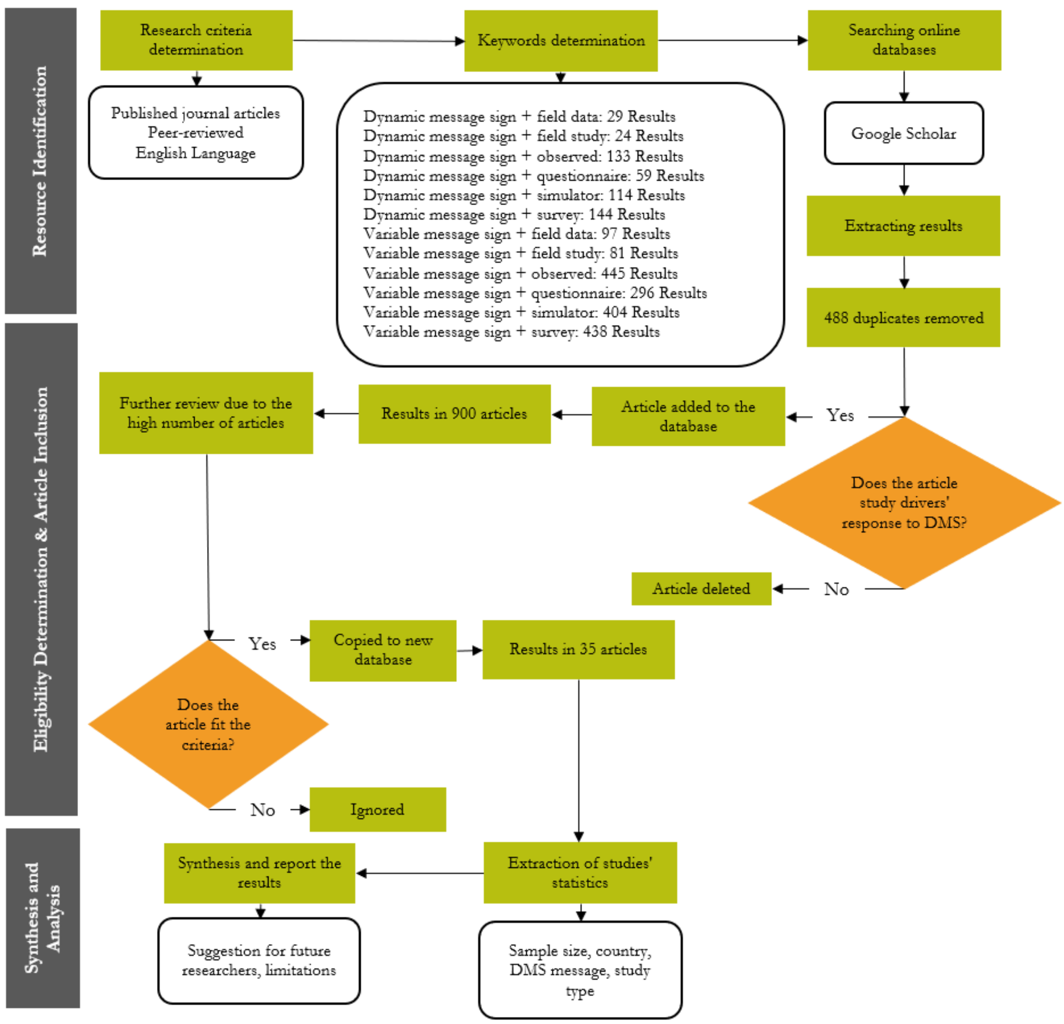

FIGURE 1 Flowchart of the data extraction process

REVIEW STATISTICS

Some articles presented more than one method to retrieve drivers' response to DMS and were dually accounted for in those respective categories. Specifically, three studies (Monsere et al., 2005; Richard and De Barros, 2010; Huang and Bai, 2019) employed field observations and questionnaires, one study (Reinolsmann et al., 2019) utilized a simulator and a questionnaire, and one study (Rahman et al., 2017) used a simulator and field study. It is worth noting that although many simulator studies utilize questionnaires to obtain demographic or socioeconomic data, these articles were not considered to have multiple data collection methods because the questionnaire was not used to obtain drivers' responses to DMS. There are 35 distinct articles that will be analyzed in this review: 16 papers use field studies, 15 use simulators, and 9 use questionnaires as depicted in Figure 2. Table 1 summarizes the key features of each study retrieved for the synthesis in this thesis.

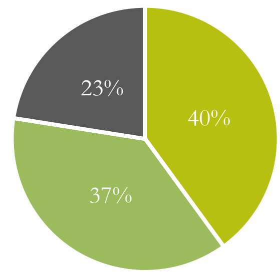

FIGURE 2 Distribution of data collection methods used in the relevant studies

TABLE 1 Summary of literature

No.	Study	Location	Type of Data	Sample Size
1	Basso et al. (2021)	Chile	Field	22
2	Bertini et al. (2006)	Germany	Field	1 day
3	Chaurand et al. (2015)	France	Field	6,486
4	Hildebrand and Mason (2014)	Canada	Field	120
5	Huang and Bai (2014)	USA	Field	712
6	Huang and Bai (2019)*	USA	Field	712
7	Jomaa et al. (2016)	Sweden	Field	7 months
8	Kamyab et al. (2003)	USA	Field	5,522
9	Megat-Johari et al. (2021)	USA	Field	4,520
10	Monsere et al. (2005)*	USA	Field	11,591
11	Rahman et al. (2017)*	USA	Field	13,002
12	Richard and De Barros (2010)*	Canada	Field	90,912
13	Sui and Young (2014)	USA	Field	1,400,000
14	Ulfarsson et al. (2005)	USA	Field	5,896
15	Van et al. (2018)	USA	Field	10,000
16	Zovak et al. (2017)	Croatia	Field	57,000
17	Ermagun et al. (2021b)	USA	Survey	4,302
18	Glendon and Predergast (2019)	Australia	Survey	81
19	Glendon et al. (2018)	Australia	Survey	60
20	Hassan et al. (2012)	USA	Survey	566
21	Huang and Bai (2019)*	USA	Survey	149
22	Rämä and Luoma (1997)	Finland	Survey	590
23	Richard and De Barros (2010)*	Canada	Survey	97
24	Monsere et al. (2005)*	USA	Survey	87
25	Reinolsmann et al. (2019)*	Qatar	Survey	66
26	Almallah et al. (2020)	Qatar	Simulator	66
27	Banerjee et al. (2019)	USA	Simulator	65
28	Boyle and Mannering (2004)	USA	Simulator	51
29	Comte and Jamson (2000)	UK	Simulator	30
30	Domenichini et al. (2017)	Italy	Simulator	42
31	Hussain (2021)	Qatar	Simulator	60
32	Jamson et al. (2005)	UK	Simulator	24
33	Kang and Momtaz (2018)	USA	Simulator	31
34	Kolisetty et al. (2006)	Japan	Simulator	10
35	Lee and Abdel-Aty (2008)	USA	Simulator	86
36	Rahman et al. (2017)*	USA	Simulator	44
37	Reinolsmann et al. (2019)*	Qatar	Simulator	66
38	Sharples et al. (2016)	UK	Simulator	81
39	Strawderman et al. (2013)	USA	Simulator	39
40	Wu et al. (2018)	USA	Simulator	72

*Articles mentioned twice in the table because it uses multiple data collection methods.

Table 2 details what messages are presented on the DMSs in each study. The messages in quotations reflect the exact wording presented to drivers in the corresponding study. Some DMSs did not display a worded message but rather displayed a variable speed limit (VSL) (Bertini et al., 2006; Ulfarsson et al., 2005; Van et al., 2018; Rämä and Luoma, 1997). A VSL displays a speed limit number and can change according to the weather, congestion, and road work presence. Other studies did not specify the exact wording of a DMS message but rather outlined what information was presented on the DMS (Banerjee et al., 2019; Comte and Jamson, 2000; Jamson et al., 2005). Finally, one study presented eighteen anti-speeding messages that are not included in Table 2 for the sake of space (Glendon et al., 2018).

TABLE 2 Summary of messages

Study	Message or DMS
Basso et al. (2021)	"Moderate your speed"
Bertini et al. (2006)	Variable Speed Limit
Chaurand et al. (2015)	"Respected Speed Limit = Less Crashes"
Hildebrand and Mason (2014)	"Reduce Speed"
Huang and Bai (2014)	"Work Zone Ahead Reduce Speed"
Huang and Bai (2019)*	"Work Zone Ahead Slow Down/Flagger And Prep To Stop"
Jomaa et al. (2016)	"40 km/hr/REDUCE SPEED"
Kamyab et al. (2003)	"Slow"
Megat-Johari et al. (2021)	"Move-Over And Slow Down For Service Vehicles"
Monsere et al. (2005)*	"Slow Down/Your Speed Is"
Rahman et al. (2017)*	"Work Zone Ahead/Reduce Speed"
Richard and De Barros (2010)*	"Speeding Will Catch Up To You/Don't Save Time Save Lives"
Sui and Young (2014)	"Slow Down/Reduce Speed"
Ulfarsson et al. (2005)	Variable Speed Limit
Van et al. (2018)	Variable Speed Limit
Zovak et al. (2017)	"100km/hr" OR "80km/hr"
Ermagun et al. (2021b)	"Work Zone Ends - Speed Limit 60mph"
Glendon and Predergast (2019)	"Keep Your Mates Safe/Reduce Your Speed"
Glendon et al. (2018)	Anti-speeding messages
Hassan et al. (2012)	"Fog Ahead-Speed Reduced/40 mph"
Huang and Bai (2019)*	"Work Zone Ahead Slow Down/Flagger And Prep to Stop"
Rämä and Luoma (1997)	Variable Speed Limit
Richard and De Barros (2010)*	"Speeding Will Catch Up to You/Don't Save Time Save Lives"
Monsere et al. (2005)*	"Slow Down/Your Speed Is"
Reinolsmann et al. (2019)*	"80 km/hr"
Almallah et al. (2020)	"80"
Banerjee et al. (2019)	Initial Speed/Visible Area/Readable Area/Lost Legibility/Post DMS Area
Boyle and Mannering (2004)	"Fog Ahead Slow Down 45 Mph," and "Curvy Road Drive Slowly/Snowplow Ahead Slow Down 35 mph"
Comte and Jamson (2000)	Advisory speed and number plate
Domenichini et al. (2017)	"Reduce the Speed"
Hussain (2021)	"Slow Down"
Jamson et al. (2005)	Varying units of information
Kang and Momtaz (2018)	"Reduced Speed Ahead 50 mph"
Kolisetty et al. (2006)	"Fog - Suggested Speed"
Lee and Abdel-Aty (2008)	"Speed Limit Reductions Next 3 Miles," "Caution: Speed Limit Reduction Strictly Enforced," and "Speed Limit Reduced High Accident Risk"
Rahman et al. (2017)*	"Reduce speed to 55 mph"
Reinolsmann et al. (2019)*	"80km/hr"
Sharples et al. (2016)	"Congestion Slow Down" and "Incident Slow Down/Accident Slow Down"
Strawderman et al. (2013)	"Reduce Speed/To 55 mph"
Wu et al. (2018)	"Fog Ahead Reduce Speed"

*Articles mentioned twice in the table because it uses multiple data collection methods.

Interestingly, almost half of the studies (48.6%) were conducted in the United States followed by western Europe (25.7%), Qatar (8.6%), Australia (5.7%), Canada (5.7%), Chile (2.85%), and Japan (2.85%). A graphical representation of the distribution of where the studies were conducted is shown in Figure 3.

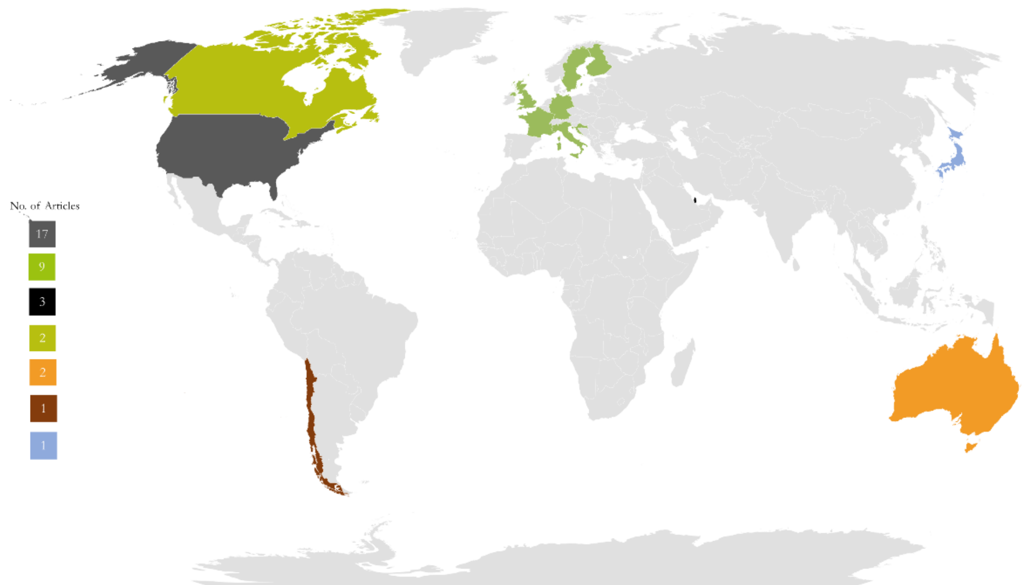

FIGURE 3 Distribution of where studies were conducted

None of the studies exceed 25 years old. The distribution of the years of publication is shown in Figure 4. Studies published between 2015 and 2019 had the highest percentage (40%) followed by 2005-2009 (17.1%), 2010-2014 (17.1%), after 2019 (14.3%), 2000-2004 (8.6%), and before 2000 (2.9%).

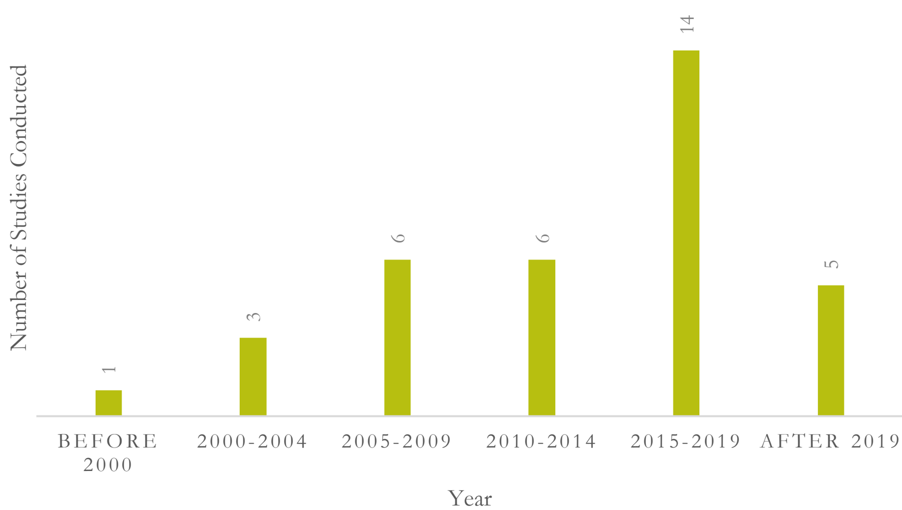

FIGURE 4 Distribution of publication years

Retrieved articles have sample sizes ranging from 10 subjects to 1,400,000. This distribution is shown in Figure 5. Note that two field studies (Jomaa et al. 2016; Bertini et al. 2006) were excluded from this distribution because they did not have a specified sample size but rather a specified time frame of data collection. As evident from the figure, the majority (71%) of studies use a sample size of 1000 or less. Of this majority, 55.6% are simulator studies, 29.6% are questionnaire studies, and the rest are field studies. Note that 100% of simulator studies analyzed in this paper had sample sizes less than 1,000. The sample size 1001-10,000 is 83.3% field studies and 16.7% questionnaires. Finally, all studies with sample sizes greater than 10,000 are field studies. This reveals the tendency for field studies to have large sample sizes and simulators to have small sample sizes. This is likely due to the time and cost associated with simulator studies. Because simulator equipment can be expensive, there is often just one simulator available that can accommodate one participant at a time. Participants are also mostly paid for their time (Rahman et al., 2017). Therefore, sample sizes tend to be the smallest in simulator studies due to the time commitment and cost. On the other hand, field studies do not require any recruitment for participation because they involve observing reactions to real-world situations. Therefore, large sample sizes are much easier to obtain in field studies.

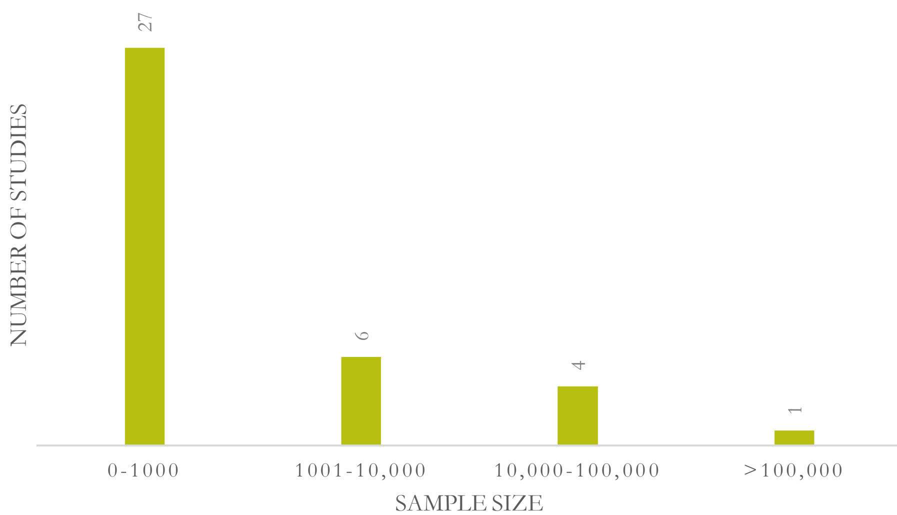

FIGURE 5 Distribution of sample sizes used in studies

ADVANTAGES AND DISADVANTAGES OF DATA COLLECTION METHODS

The strengths and weaknesses of these three data collection methods were revealed when attempting to compare results because the type of data collected across each method varies. One advantage of questionnaires is that they can collect a wide variety of characteristics such as demographics, reported responses, preferences, experience, and perspectives (Glendon et al., 2018). In addition, researchers can control the "environment" or scenario participants are exposed to, eliminating unintentional outside influences. However, participants' responses may not reflect their real-world behavior as they are in an imaginary scenario. There is also always a chance for bias or ambiguity in the survey questions, which may result in skewed data. Finally, questionnaires are better suited to retrieve general rather than specific responses.

As stated in the Review Statistics section, field studies tend to have large sample sizes. Large sample sizes help reduce bias and often show a normal distribution. Because field study data is collected by observation and researchers do not have to recruit participants for their study, large sample sizes are much easier to obtain compared to questionnaires and simulator studies. Also, the data collected from field studies shows actual responses of drivers, not just reported responses. However, field studies do have extensive limitations. They cannot retrieve internal reactions such as preferences or attitudes because only physical reactions can be observed. Field studies occur in an uncontrolled environment, so it is difficult to eliminate any outside influences. Depending on the type of field study conducted, the equipment could be expensive.

As shown in Table 3, simulators can collect the widest variety of data. Simulator studies often conduct a survey prior to or after the simulation to collect information on demographics, comprehension, and driving experience (Hussain, 2021; Sharples et al., 2016). Simulators are also made to feel realistic within a controlled environment to reduce bias and produce accurate results. However, drivers are still subject to behaving differently within a simulator because there are no real-world consequences in virtual reality. Many studies reported participants experiencing simulator sickness due to the appearance of motion in a still setting (Kolisetty et al., 2006). In addition, creating a realistic, virtual world can be very expensive. Not only are researchers responsible for the equipment, but participants are also often paid for their time (Rahman et al., 2017). Most participants commit at least an hour of their time total to get familiar with the equipment before taking part in the study (Lee and Abdel-Aty, 2008). Therefore, sample sizes tend to be the smallest in simulator studies due to the time commitment and cost. Moreover, all participants in a simulator study must "drive" the same "vehicle" provided, so the effect of vehicle type of driver behavior cannot be observed. A summary of the advantages and disadvantages of using each data collection method is presented in Table 3.

TABLE 3 Advantages and disadvantages of three data collection methods

	Field	Simulator	Questionnaire
Advantages	Large sample size Realistic data	Widest variety of data Feels realistic Controlled environment	Wide variety of data Controlled environment
Disadvantages	No demographic data No internal reactions Uncontrolled environment Expensive equipment	May not reflect real world behavior Simulator sickness Not in personal vehicle Small sample size Expensive Time consuming	May not reflect real world behavior Misunderstood questions General responses

SPEED, VEHICLE TYPE, AND DEMOGRAPHIC ANALYSIS

The type of data collected in these studies is shown in Table 4. As evident from the table, the only variables that all three data collection methods observe are lane position, message type, traffic, and weather. Simulator studies can collect the most amount of data, followed by questionnaires and then field studies. Variables were analyzed from each group of studies to make a logical comparison between the three data collection methods. The variables "speed," "vehicle type," and "age and gender" were chosen based on availability and prevalence of overlap across more than one data collection method as seen in Table 4.

TABLE 4 Number of studies collecting various data for each study type

Variable	Field	Simulator	Questionnaire
Speed	**16**	**14**	**0**
Lane Position	3	1	1
Message Type	4	1	1
Vehicle Type	**3**	**0**	**2**
Headway	1	1	0
Traffic	1	1	1
Weather	2	1	1
Acceleration	0	5	0
Demographics	**0**	**10**	**6**
DMS Preferences	0	1	4
Driving Experience	0	2	2
Comprehension of DMS	0	1	1
Roadway Type	0	1	1
Familiarity with DMS	0	0	1
Distance from DMS	1	2	0

Because the speed variable was studied in 16 field studies and 14 simulator studies, drivers' speed reduction in response to DMS was analyzed for all relevant field and simulator studies. Speed reduction was not analyzed for questionnaire studies because the questionnaires reported general rather than specific responses of drivers to DMS. For example, the questionnaire from Hassan et al. (2012) revealed that 37% of drivers reported that they would slow down immediately in response to a DMS, but the field study from Chaurand et al. 2015 revealed that on average, drivers reduced their speed by 2 km/hr. Because questionnaires cannot retrieve specific speed reduction data, questionnaires were not included in the speed analysis. Vehicle type was analyzed for three field studies and two questionnaires. Specifically, we are interested in how vehicle type affects drivers' response to DMS. Simulator studies were not included in the vehicle type analysis because in a simulator study, each participant is required to sit in the same vehicle seat. Since simulator studies did not consider vehicle type as a variable, simulator studies were not included in the vehicle type analysis. Demographic data was collected in ten simulator studies and six questionnaires. However, only seven simulator studies and four questionnaire studies considered the effect of drivers' demographics on their response to DMS. Field studies were not included in this analysis because no field studies were able to collect demographic data from drivers. Because field studies are mostly observational, it would be nearly impossible to collect accurate information on gender, ethnicity, age, or income based solely on drivers' appearance.

Field Studies: Speed Analysis

The only variable that was analyzed across every field study was speed. For the sixteen field studies evaluated in this review, the average speed reduced by 9.4% in response to seeing a variable message sign, and no study showed an average increase in speed. Figure 6 shows a breakdown of the speed reduction results from these field studies.

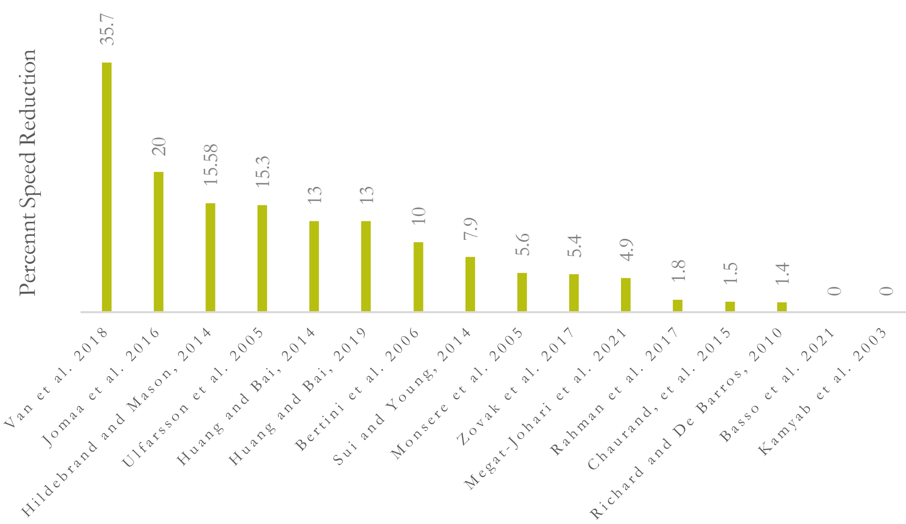

FIGURE 6 Speed reduction in response to a DMS for each field study

Field Studies: Vehicle Type

Three field studies observed vehicle type as an independent variable (Kamyab et al., 2003; Megat-Johari et al., 2021; Monsere et al., 2005). Kamyab et al. (2003) observed the effect of a DMS reading "Slow" on a two-lane highway serving approximately 1,500 vehicles per day. The results revealed that passenger vehicles increased their compliance with the speed limit only on a short-term basis. In fact, not only was there no significant long-term speed limit compliance, but there was also a long-term increase in mean speed. On the other hand, non-passenger vehicles showed a decrease in mean speed long-term but did not have any change in speed compliance. Overall, this study revealed no significant changes in mean speed among passenger and non-passenger vehicles.

Megat-Johari et al. (2021) observed the effect of a DMS reading "Move over and Slow Down for Service Vehicles" on a limited access freeway serving 68% passenger cars and 32% larger vehicles (trucks and non-passenger vehicles with a trailer). The results indicated that on average, passenger cars drove 3.4% faster than larger vehicles. Also, in response to the DMS, passenger cars slowed down to 5.6% below the speed limit while non-passenger vehicles only slowed down to 3.4% below the speed limit. Both vehicles had a higher downstream speed variability compared to the upstream speed variability. To test drivers' compliance with the DMS message, a Michigan Department of Transportation (MDOT) truck was placed on the side of the road after the sign. In response, 38% of passenger vehicles changed lanes while only 33% of non-passenger vehicles moved over. Overall, non-passenger vehicles are less likely to move over and tend to slow down less dramatically than passenger vehicles. As mentioned by that study, this could be due to the difficulty of changing lanes for a larger vehicle rather than lack of compliance.

Monsere et al. (2005) looked at Interstate 5 in Oregon on a curve serving 32,000 vehicles per year where 73% are passenger vehicles and 27% are non-passenger vehicles. There was a posted speed limit of 65 mph for passenger cars and 55 mph for trucks preceding the curve. Preceding the curve, there was an advisory speed of 45 mph and a DMS reminding drivers what their speed was. The results indicated that passenger cars had a mean speed of 52 mph at the curve while non-passenger vehicles had a mean speed of 46 mph. Also, the maximum speed reduction was 3.3 mph and 3.0 mph for passenger vehicles and non-passenger vehicles, respectively. The DMS successfully reduced the number of drivers in the high-speed category across all vehicle types. Non-passenger vehicles had more vehicles near the mean speed but did not have a consistently significant difference between before and after DMS speeds. Overall, both vehicle types reduced their speed by about 5% in response to the DMS. However, non-passenger vehicles tended to be less effected by DMSs.

The analysis of the three studies listed above reveals a few general conclusions about the role of vehicle type in affecting drivers' response to DMSs:

- Non-passenger vehicles tend to be less compliant with DMS messages than passenger vehicles.
- All vehicles tend to slow down immediately in response to a DMS.

Simulator Studies: Speed Analysis

Every study involving simulators collected speed data except for one (Sharples et al., 2016). On average, drivers reduced their speed by 6.5% after passing a DMS sign with a speed-related message. Average speed reductions from individual studies can be seen in Figure 7.

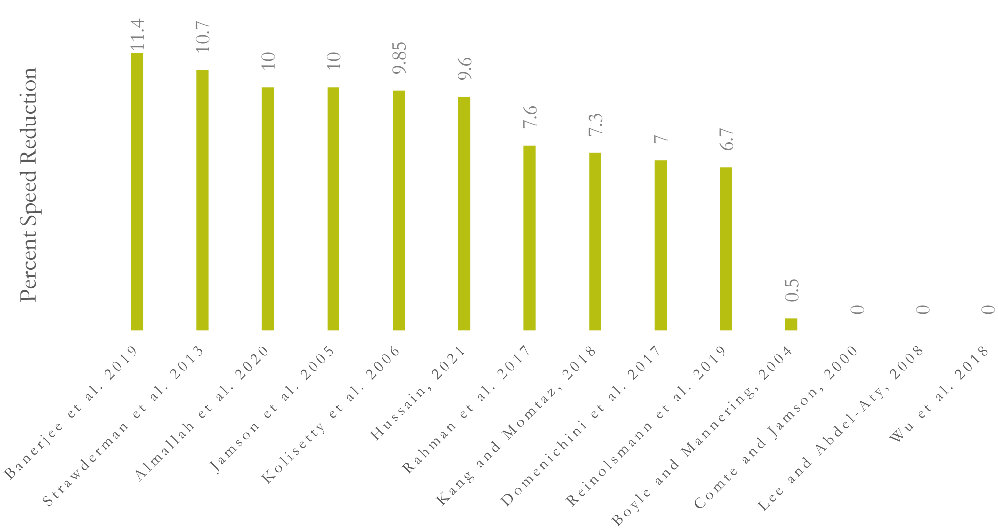

FIGURE 7 Speed reduction in response to a DMS for each simulator study

Simulator Studies: Demographic

Seven studies (Banerjee et al., 2019; Boyle and Mannering, 2004; Hussain, 2021; Kang and Momtaz, 2018; Lee and Abdel-Aty, 2008; Rahman et al., 2017; Wu et al., 2018) considered age and gender as possible explanatory variables for drivers' response to variable message signs. Banerjee et al. (2019) found that older participants (> 55 years) slow down significantly when they see a DMS with 6-7 words. In contrast, drivers 26-35 years old tended to increase their speed when passing a DMS with only 2-4 words. The reduction in speed from older drivers is likely due to their slower reading and comprehension time as well as poor eyesight. Similarly, Kang and Momtaz (2018) observed that participants aged 45-65 years old are the most compliant with DMSs. Wu et al. (2018) also supported this idea and found that young drivers drove faster and were less sensitive to fog than older drivers. These studies all suggest that older drivers tend to drive slower and exercise more caution than younger drivers.

Concerning gender, Boyle and Mannering (2004) found that on average, males drove faster than females. Hussain (2021) found that when considering a DMS, LED lights, and road markings with a pedestrian encircled, males prefer warnings from a DMS more than females. Rahman et al. (2017) and Lee and Abdel-Aty (2008) both found that neither age nor gender were statistically significant factors affecting drivers' response to DMSs.

Questionnaire Studies: Vehicle Type

Two questionnaire-related papers (Monsere et al., 2005; Ermagun et al., 2021b) studied the effect of vehicle type of drivers' response to DMS. As mentioned previously for the field study (Monsere et al. 2005), this study took place on Interstate 5 in Oregon on a curve serving 32,000 vehicles per year where 73% are passenger vehicles and 27% are non-passenger vehicles. Approaching the curve, there was an advisory speed of 45 mph and a DMS displaying one of three messages. "Caution Sharp Curves Ahead" was displayed for vehicles driving less than 50 mph, "Slow Down Your Speed is xx mph" was displayed for vehicles driving between 50 mph and 70 mph, and "Slow Down Your Speed Is Over 70 mph" was displayed for vehicles driving over 70 mph. Surveyors set up a table 26 mi and 35 mi from the curve in the southbound and northbound directions, respectively. Willing motorists were asked to complete an eleven-question survey pertaining to the recognition, importance, visibility, and placement of the DMS. The results from the survey revealed that 85% of the respondents were in passenger vehicles and 76% of respondents said that the DMS displayed their speed, implying that those drivers were driving anywhere from 50 to 70 mph when passing the DMS and approaching the curve. Finally, 76% of respondents reported slowing down in response to the DMS.

The second study (Ermagun et al., 2021b) surveyed 4,706 people across ten states and the District of Columbia about their socioeconomic characteristics, attitudes and preferences, and behavioral responses to a theoretical compromised DMS. The results revealed that single unit trucks, vans, and motorcycles were the most likely vehicle type to be distracted by a phone when passing a compromised DMS. In contrast, suburban drivers were the least likely to be distracted by their phones. This implies that non-passenger vehicles are more likely to be distracted by compromised DMSs than passenger vehicles.

Questionnaire Studies: Demographic Impacts

While almost all the questionnaire studies collected data on age and gender, only four studies (Glendon and Predergast, 2019; Glendon et al., 2018; Hassan et al., 2012; Ermagun et al., 2021b) considered age and gender as explanatory variables for drivers' response to variable message signs. Glendon and Predergast (2019) found that both males and females perceived threatening messages to be more effective than coping messages for drivers in general. Glendon et al (2018) concluded that signage relating to friends or "mates" as a reason to reduce speed was effective for young males. Hassan et al. (2012) discovered that older drivers are 5.1 times more likely to obey a variable limit sign than younger drivers, and females are 3.7 times more likely to reduce speed in medium traffic conditions than male drivers. Finally, Ermagun et al. (2021b) concluded that females are less likely to be cognitively distracted (i.e., let their mind wander) by DMSs and are more likely to obey DMSs than males.

A ONE-ON-ONE COMPARISON OF DATA COLLECTION METHODS

This section compares the results pertaining to speed, vehicle type, and demographics for field and simulator studies, field and questionnaire studies, and simulator and questionnaire studies, respectively. Specifically, this section discusses whether the conclusions made across the data collection methods are consistent.

Field Studies vs. Simulator Studies

As stated previously, both field studies and simulator studies looked extensively at the effect of variable message signs on changing drivers' speeds. Questionnaires were not included in the speed reduction comparison because they only revealed general behavior (e.g., 40% of participants reported that the DMS would influence their behavior) (Rämä and Luoma, 1997) rather than specific behavior (e.g., average speed reduced from 111.7 km/hr to 100.7 km/hr) (Kolisetty et al., 2006).

Drivers' speed reduction (in percent) in response to a DMS sign was calculated or retrieved for all possible field and simulator studies. We tested the potential relationship of the speed reduction with the initial speed, the number of observations, the data collection methodology, and the place of the study. The results indicated that there is no statistically significant association. This means that the speed reduction reported in the studies synthesized in this thesis is not a function of the initial speed, the number of observations, the data collection methodology, or the place of the study.

Simulator Studies vs. Questionnaires

The ten studies analyzed for their insights pertaining to the effect of age and gender on drivers' response to dynamic message signs produced conclusive results. Because demographic variables are nearly impossible to collect due to the observant nature of field studies, field studies were not included in the age and gender comparison. The simulator studies from Banerjee et al. (2009), Kang and Momtaz (2018), and Wu et al. (2018) aligned with the questionnaire from Hassan et al. (2012), confirming that compliance with DMSs increases along with age.

In addition, the simulator study from Boyle and Mannering (2004) coincided with the questionnaires from Hassan et al. (2012) and Ermagun et a. (2021b) in concluding that females tend to drive slower and be more compliant with DMSs than males. Therefore, the simulator and questionnaire studies produce similar results when considering drivers' response to DMS.

Field Studies vs. Questionnaires

Four studies (Kamyab et al., 2003; Megat-Johari et al., 2021; Monsere et al., 2005; Ermagun et al., 2021b) analyzed the effect of vehicle type on drivers' response to DMS. Simulator studies were not included in the vehicle type comparison because simulators require all participants to use the provided vehicle in the simulated environment. Monsere et al. (2005) presented both a field study and a questionnaire, and both sets of results revealed that the mean speeds of passenger and non-passenger vehicles entering the curve were greater than the advised 45 mph speed. In addition, field studies from Megat-Johari et al. (2021) and Monsere et al. (2005) aligned with the questionnaire from Ermagun et al. (2021b) revealing that non-passenger vehicles tend to be more reckless. In the field studies, non-passenger vehicles were less willing to comply with the safety-related instructions on the DMS. Similarly, when the DMS was compromised in the questionnaire, the non-passenger vehicles were more likely to be distracted by their phones.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Dynamic Message Signs are critical components of the Intelligent Transportation System (ITS). They can warn, inform, and advise drivers about congestion, Amber alerts, and speed reductions to improve the safety and efficiency of traffic. To study how drivers react to variable message signs, researchers have often used one of three data collection methods: field studies, simulators, or questionnaires. This thesis has analyzed the similarities and dissimilarities between the results obtained from these three methods as well as the limitations of each method.

The main findings of this thesis are encapsulated in the following:

- Simulators can collect the widest variety of data in a controlled, realistic environment, but the results may not reflect real world behavior, simulator sickness may arise, vehicle type cannot be analyzed, and sample sizes are often small due to the expense and time required.
- Questionnaires can collect a wide variety of data in a controlled environment, but the results may not reflect real world behavior, questions could be misunderstood, and only general responses are obtained.
- Field studies can obtain realistic data in large sample sizes, but demographic data and internal reactions cannot be recorded. Equipment can be expensive, and the environment is impossible to control.
- There is no correlation between initial speed, the number of observations, the data collection methodology, and the place of the study.
- Simulator studies and questionnaires revealed that older and female drivers tend to drive slower and be more compliant with DMS.
- Field studies and questionnaires suggested that all vehicles tend to drive faster than the posted advisory speed, and non-passenger vehicles tend to drive more recklessly than passenger vehicles.
- Results from field studies, simulator studies, and questionnaires are relatively consistent when considering drivers' speed reduction in response to a DMS speed change message.

Future researchers can utilize this study to determine which data collection method is most appropriate for them to observe drivers' response to speed-related variable message signs, depending on the type of data needed and the availability of resources. The results presented from these 35 articles can be used to understand and improve work zone safety, reduce crashes, and improve driver efficiency. Three variables were analyzed in this thesis: speed reduction, vehicle type, and demographics. Other variables such as driving experience, comprehension of DMS, and DMS preferences can be studied for consistency in future research. Also, this thesis only considers speed-related variable message signs. There are many articles available that explore drivers' response to DMS displaying route guidance (Peeta and Gedela, 2001), travel time (Gan and Ye, 2012), and advertisements (Harms et al., 2019). Future research can expand on these findings to see if questionnaires, simulators, and field studies have consistent results when considering drivers' response to various kinds of DMS. On limitation of the current thesis is the lack of in-depth comparison between explanatory variables due to the varying types of data collected in questionnaires, simulator studies, and field studies. Another limitation is inconsistency of the speed change messages on the DMS across studies.

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