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The Impact of Flashing on the Efficacy of Variable Message Signs: A Vehicle-by-Vehicle Approach

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Abstract: A great deal of research has examined the efficacy of variable message signs (VMS) to induce driver behavior changes, improve safety conditions, and decongest the traffic network. However, there is little literature regarding the most effective ways to display this information on VMS. Furthermore, none of the previous contributions have concentrated on analyzing what impact flashing VMS have on drivers by using real traffic data. This article seeks to bridge this gap, analyzing the effect of incorporating intermittent light stimulation to messages on drivers' behavior on a Chilean highway, using vehicle-by-vehicle data obtained in a non-intrusive way. In order to do so, an experiment was carried out to measure the responses of drivers when faced with two types of messages: (1) those intended to induce a speed reduction and (2) those aimed at generating lane changes. From the statistical models we obtained several insights. Our results show that flashing messages may increase the effectiveness of VMS depending on environmental and traffic conditions. In particular, for speed moderation messages, we found 12 significant effects, showing, for example, that a flashing message is most effective in the hours of darkness, with low congestion, small spacing, and low average speeds. Additionally, it has a more significant impact on experienced drivers. On the other hand, for lane change messages, we found five significant effects, showing that flashing messaging reduces its effectiveness in situations where a high cognitive load is required, such as in high flow and high average speeds. No particular effects were identified in either case for specific vehicle types.

Keywords: driver behavior; variable message signs; flashing; automatic vehicle identification; intelligent transportation systems

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1. Introduction

Variable message signs (VMS) are programmable roadside devices that display messages for various events such as accidents, blocked roads, or congestion [1]. In some cases, the VMS include driving recommendations, aiming to reduce travel time and increase road safety [2]. This technology, which has been widely adopted by many countries worldwide [3], is controlled remotely through a central base, using different types of formats and designs, fonts, visual support, and short and extensive text.

This research analyzes the impact that the method of transmitting the message on VMS has on drivers' behavior using an urban highway. In particular, the effect of incorporating intermittent light stimulation (flashing) in messages is studied and compared with a static alternative. Intermittency can increase sensory capacity and increase the likelihood of capturing the driver's attention [4,5] and has been put forward by panels of traffic experts [6].

A great deal of research has looked at the efficacy of variable messaging in bringing about changes in driver behavior [2,7–10]. However, most have focused on off-highway experiences, that is to say, by using surveys or driving simulators. In addition to this, previous contributions have centered in particular on studying drivers' responses in the presence or absence of a message and not on the most effective way of transmitting it.

This article's contribution consists of measuring the differences in driver compliance to VMS prompts that include a flashing message. In order to achieve this, an experiment was designed that considered, in a non-intrusive way, every driver using the *Autopista Central* in Santiago when messages were displayed. To the best of our knowledge, this is the first article of its kind to study the effect of flashing message delivery in VMS that uses comprehensive vehicle-by-vehicle data rather than what-if scenarios or driving simulators.

The rest of the paper is structured as follows. Section 2 is a literature review. Section 3 explains the proposed methodology: experimental design, materials, the participants, and the data. Section 4 analyzes and discusses the results against those of previous studies. Section 5 presents some concluding observations and future lines of research.

2. Literature Review

The literature review is organized into two sections. First, in Section 2.1, we discuss the effectiveness of VMS in inducing changes in driver behavior for a fixed message type, whereas, in Section 2.2, we focus on the impact of the way messages are conveyed on VMS.

2.1. The Efficacy of VMS with Fixed Messaging

Much of the literature related to the impact of VMS on driver behavior has focused on analyzing the differences between showing the message versus not showing it. For this, the vast majority of studies have been based on off-highway experiences, conducting surveys [7,10–15] or using driving simulators [1,16–19].

In the context of using real traffic data, there are fewer contributions. Among these, most obtained data using radar, video, or loop detectors. For example, Levinson and Huo [2] used a loop detector to analyze the travel time of drivers in Minnesota, USA, in a non-intrusive way. The authors found that VMS had a significant effect on reducing delays.

Erke et al. [9] investigated the effects of a message shown on two VMS panels regarding the choice of route and driver speed. The authors used road-speed measurements and analytical videos, concluding that there were more significant speed reductions and more compliance with the choice of alternative routes among those drivers who had seen the messages compared to those who had not.

Romero et al. [20] assessed the influence of VMS on route deviations between a toll highway and a non-toll highway. The authors developed a binary logit analysis using empirical data from Madrid, Spain, obtained through a loop detector. The authors found that VMS were a good tool for managing road traffic as they influenced driver deviations and demonstrated that certain combinations of messages increased these probabilities.

Richards and McDonald [21] investigated the benefits of VMS in an urban network in Southampton, UK. The authors used traffic data collected through traffic detectors and controls during incident scenarios in seven different locations, intending to measure drivers' response to VMS in terms of detour rates. Positive responses were found in drivers, with diversion rates ranging from 2% to 30%, although not all were attributed to the VMS information.

Finally, Basso et al. [22] used a vehicle-by-vehicle approach with real traffic data to measure the impact of VMS on a section of an urban highway in Chile. They studied messages that induced a behavioral change in terms of speed or the lane in which the vehicle was traveling through statistical analysis. The authors found that the vast majority of messages failed to induce the expected behavior change. Their results indicated that drivers less familiar with the road or heavy vehicles were more likely to obey lane-change messages.

2.2. The Effect of the Chosen Method of Transmitting the Message on VMS

Several studies sought to measure how the way a message is displayed on VMS impacts driver behavior. For example, some works focused on evaluating multiphase messages, either to determine an appropriate maximum number of phases [23] or the length of time each phase should be displayed [24,25]. Others sought to study the influence of the color of the text font [5,26–29], the color of the iconography [27,29], the luminance of the text and the background [5], or the use of various color schemes [30,31].

Additionally, other research has focused particularly on evaluating the characteristics of the text and content of the VMS. These include the optimal number of words [32], the number of lines in the message [31,33–35], the size of letter characters [36], the optimal font [37], the kind of abbreviation that works best [38–40] and what information should be included in the message [41–43].

However, few contributions have studied the effects of intermittency in VMS on driver behavior, and none of these used real traffic data. For example, Rämä and Kulmala [8] studied the influence of the "slippery road" message through VMS on the speed behavior of motorists using a driving simulator. In general, an average speed reduction of 2 km/h (1.24 mph) was observed in drivers, compared to those who had not been exposed to the message, although a more significant reduction was observed in cases where the message presented was flashing versus a fixed message.

Dudek et al. [44] conducted an experiment with data obtained through a driving simulator. The authors analyzed 64 test subjects by showing them three-line one-phase messages of a static type (E) and comparing their behavior against two simultaneous types of flashing sequences in the text: on all lines (A) and the first line only (B). The authors found no differences in the average reading time between type A and E messages, but it was more significant in type B. In addition, they did not find significant differences in driving performance but did detect adverse effects related to fully understanding the message for individuals unfamiliar with the flashing mode.

Charlton [45] studied the effectiveness of VMS in the form of danger warning signs of different types, color schemes, and sizes. To study this, the authors conducted a driving simulator with 33 participants from New Zealand, measuring their levels of visibility, understanding, memorability, and primacy. The results showed that the effectiveness of VMS varied according to the type of danger sign. Moreover, for school warning signs, flashing variable messages were more effective than the large static type in terms of sense of danger, visibility, and primacy, while for roadworks warning signs they were slightly more visible, the same in terms of understanding, and perhaps worse in terms of memorability.

Wang et al. [27] evaluated the effects of adding graphic images (GI) to VMS. The authors elaborated a questionnaire to 127 individuals from Rhode Island, which incorporated preferences such as the addition of a GI, the color of the message text, image contrast, alternative GI, flashing, among others, and under a statistical analysis. Their results found that messages with intermittent GI were significantly preferred (76% versus 24%).

Ronchi et al. [4] investigated the design of VMS as a way-finding aid in road tunnel emergency evacuations in Sweden. The authors chose a representative set of eleven VMS systems of varying size, message encoding (text, pictograms, or both), color schemes, and flashing lights. Based on the literature, they selected six types of VMS and compared five different pairs when conducting a declared preference questionnaire on 62 individuals, measuring their perception at a cognitive, sensory, and functional level. The results indicated that the use of flashing lights yielded a better performance.

As discussed in this literature review, there is little evidence regarding the efficacy of intermittency in VMS. Furthermore, the existing evidence is contradictory: Dudek et al. [44], who used a simulator, found adverse effects with flashing displays, whereas Wang et al. [27] and Ronchi et al. [4] found through surveys that subjects preferred flashing lights, and Rämä and Kulmala [8] and Charlton [45] found, through simulators, specific improvements when warning signs were flashing. All of these papers used data gathered from off-road experiments. However, some previous contributions have shown that the analysis of real data may differ from those obtained through simulators or surveys since the experience under these protected scenarios may not be fully replicable on the road [22,46]. This article seeks to bridge this gap by analyzing the effectiveness of flashing through full real-world vehicle-by-vehicle data, obtained in a non-intrusive way, for all drivers using the road during the study periods. To the best of our knowledge, this is the first effort of its kind in the relevant literature.

3. Methodology

3.1. Experimental Design

This experiment was conducted on the *Autopista Central*, one of the most important urban highways in Santiago. This highway extends for 60.5 km (37.6 miles), crossing the Santiago Metropolitan Region from north to south, and connecting with Ruta 5, the main interurban highway in the country. Specifically, the case study was carried out on both lanes of Section B2, which runs from the Mapocho River to Carlos Valdovinos Avenue. This section has four free flow toll gates (PA-14, PA-12, PA-31, and PA-13) from which traffic information is collected, and two VMS (R5S-3 and R5S-1), on which different types of messages are displayed. The distribution of the gates and panels is shown in Figure 1.

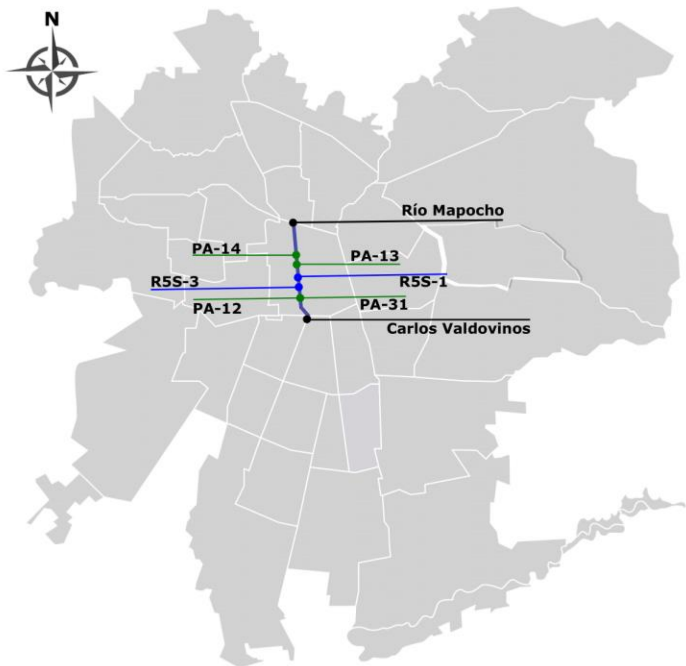

Figure 1. Distribution of toll gates and variable messaging panels on the studied stretch of road.

This study focused on evaluating the response of drivers to a flashing message, comparing it with a static one. Two types of messages were used: (1) those that sought to induce a change in speed: "Moderate your speed," and (2) those that induced a change of lane: "Use center and left lanes." Each one was transmitted in the static and flashing format, the text of the latter flashing at one-second intervals since there is evidence that this frequency improves the degree of perceived urgency (cognitive capacity) without creating an effect that may distract motorists [47].

Thus, a total of four message profiles were used for the analysis of this research. To isolate the effect of the message from the potential announced incident, messages were placed according to a predefined schedule, independent of traffic conditions. In other words, the messages displayed did not refer to a real situation on the road, and therefore, the potential behavioral change was affected only by the message.

The content of the message was composed of a text written in Spanish, in amber, and with three lines of text. In addition, it was accompanied by a red, white, and black illustration for speed moderation, where the suggested maximum speed of 80 km/h (49.7 mph) was shown, with green, white, and red used for the change of lane, indicating that only the left and center lanes were to be used and not the right. Figure 2 shows two examples of the actual variable messaging panels seen by drivers, showing their appearance and design.

Figure 2. Variable messaging panels "Moderate your Speed" and "Use left and center lanes" on the Autopista Central.

3.2. Materials

As shown in Figure 2, the panels cross the road perpendicularly and are supported by metal structures. These panels are made up of a Full Matrix Yellow (Y) zone with 320 × 64 pixel resolution, in addition to three Full Matrix Full color (RGB + Y) 64 × 64 pixel graphic zones. The size of each pixel is 20 mm (0.78 inches). The structure is self-supporting in folded sheet metal, and its material is galvanized steel with a polyurethane paint finish. It weighs approximately 1250 kg, and its dimensions are 7 m (22.97 ft) in length, 1.9 m (6.2 ft) in height, and 0.25 m (0.8 ft) deep.

3.3. Participants

The participants were all drivers using section B2 on any of its lanes, in the 188 sampling intervals, which were carried out in the periods between 11 December 2020 and 29 January 2021 and between 29 March and 9 April 2021. The messages were shown between Monday and Friday at three different times: 11.00 a.m., 3.00 p.m., and 9.00 p.m. The distribution of the intervals of each message, the accumulated duration time, and the number of vehicles under study are shown in Table 1. It can be seen that the number of study vehicles for the message "Use center and left lanes" was significantly lower than for the message "Moderate your speed." The explanation for this is that for messages suggesting a change of lane, the study subjects were only those vehicles on the crowded lane upstream of the messaging panel (in this case, the right lane).

Table 1. Distribution of studied periods, time, and number of vehicles for each message–typology combination.

Message	Typology	Time	Intervals	Accumulated Duration [mins]	Vehicles
Reduce Speed	Flashing	11.00 a.m.	9	115	5949
		3.00 p.m.	14	161	7092
		9.00 p.m.	17	201	7378
	Static	11.00 a.m.	10	102	4698
		3.00 p.m.	10	102	4755
		9.00 p.m.	33	453	15,475
Use Central or Left Lanes	Flashing	11.00 a.m.	8	104	509
		3.00 p.m.	12	115	662
		9.00 p.m.	23	279	1763
	Static	11.00 a.m.	10	132	435
		3.00 p.m.	12	124	609
		9.00 p.m.	30	349	2406

In total, among all the vehicles studied, there were 45,035 unique license plates, of which 42,503 belonged to light vehicles (cars) (94.37%), 165 to motorcycles (0.36%), and 2367 to heavy vehicles (5.25%). The drivers were not informed of the experiment and were not aware that their road behavior was being recorded for a study.

3.4. Description of Raw Data

The raw data received for this research represent real traffic data provided by *Autopista Central*, which contains detailed vehicle-by-vehicle information on drivers passing through each of the highway's four gates. This data were captured through toll gates with Free-Flow Technology (Free Flow) since any vehicle using the highway is obliged by law to have an electronic device called TAG installed on the windshield [48]. This allows the identification of vehicles thanks to Automatic Vehicle Identification (AVI) technology installed in the gates [22,46]. The data are summarized in Table 2.

Table 2. Variables contained in the traffic database.

Variable	Description
License plate	Plate number
Date	Date and time the vehicle passes through the gate.
Lanes	Lane number on which the vehicle travels as it passes through the gate.
Speed	Instantaneous vehicle speed as it passes through the gate [km/h].
Vehicle type	Vehicle Type Number (1 = Automobile, 2, 3 = Heavy vehicle, 4 = Motorcycle)
Gate	Gate number through which the vehicle passes.

Additionally, *Autopista Central* provided us with a series of videos that showed the variable messaging panels operating on the study days, from which exact information was extracted from the messages and is summarized in Table 3.

Table 3. Variables contained in the message database.

Variable	Description
Start Date	Date and time the message began to be displayed.
Stop Date	Date and time the message stopped being displayed.
Message	Message text "Use left and center lanes" or "Moderate your speed"
Message Type	Manner in which the message was transmitted (Static or Flashing)

3.5. Performance Measurement and Data Analysis

The objective of the analysis was to determine whether or not drivers obeyed the VMS more if it was flashing compared to it being static. For each vehicle i that circulated during a speed moderation message, the dependent variable y_i^1 was calculated, according to Equation (1). On the other hand, the variable y_i^2 was calculated for each vehicle that circulated on the right track in the upstream gate during a track change message, according to Equation (2).

$$y_i^1 = \frac{Upstream\ Speed - Downstream\ Speed}{Upstream\ Speed} \tag{1}$$

$$y_i^2 = \begin{cases} 1\ if\ downstream\ lane \neq Right \\ 0\ if\ downstream\ lane = Right \end{cases} \tag{2}$$

In the case of messages that suggested speed moderation, y_i^1 represents the percentage change in speed for each vehicle after viewing the message. In the case of messages suggesting the use of the center or left lane, y_i^2 indicates if the vehicle obeyed the message, that is to say whether it switched to the center or left lane. Intuitively, in both cases, higher values result in a higher degree of compliance with the variable message.

Subsequently, regressions were adjusted considering the y_i^1 and y_i^2 dependent variables, using the typology of the message (flashing/static) and traffic variables as explanatory variables. In the case of speed moderation, linear regressions were used, considering that the dependent variable was continuous. On the other hand, in messages that suggested using the center or left lane, logistic regressions were used while the dependent variable was binary. This analysis aimed to understand the underlying reasons for the change (or not) in the behavior of the study subjects, emphasizing the effect of the typology of the messages. In particular, it also sought to control the traffic conditions faced by each user to differentiate if, for example, drivers faced with a static lane change message did not obey it because they decided not to do so or because the traffic conditions did not allow it. The explanatory variables considered are shown in Table 4, where they were calculated for each study vehicle.

Table 4. Explanatory variables considered.

Variable	Description
Flashing	Takes value 1 if the vehicle faced a flashing message, 0 if it faced a static message.
Darkness	Proxy of darkness on the route, calculated as the inverse of radiation (m^2/W).
Flow previous minute	Number of vehicles circulating during the previous minute on the upstream gate (veh).
Speed previous minute	Average speed of circulating vehicles during previous minute in upstream gate (km/h).
Average km	Average traveled distance by vehicle during the previous year (km).
Category: Motorcycles	Takes value 1 if the vehicle is a motorcycle (Category = 4), 0 otherwise.
Category: Heavy vehicles	Takes value 1 if a heavy vehicle (Category = 2,3), 0 otherwise.
Gap	Separation from the vehicle that passed through the upstream gate in the same lane (s).

4. Analysis and Discussion of Results

4.1. Speed Moderation

Following the methodology set out in Section 3.5, the results of the adjusted linear regression for the case of the messages that suggested a reduction in speed are shown in Table 5. From the signs of the coefficients and reported *p*-values, it was possible to analyze the partial effects of each of the variables incorporated in the model.

Table 5. Coefficient estimates, standard error, and *p*-values for variables in the model. (Speed reduction).

Variable	Coefficient Estimate	SE	*p*-Value
Intercept	−432.33	4.65	<0.01
Flashing	118.00	7.07	<0.01
Darkness	−29.76	1.27	<0.01
Flow previous minute	2.05	0.04	<0.01
Speed previous minute	4.27	0.03	<0.01
Average km.	−0.63	0.18	<0.01
Category: Motorcycles	8.49	9.93	0.39
Category: Heavy vehicles	11.63	2.67	<0.01
Gap	0.48	0.15	<0.01
Flashing × Darkness	13.50	1.95	<0.01
Flashing × Flow previous minute	−1.01	0.06	<0.01
Flashing × Speed previous minute	−0.95	0.06	<0.01
Flashing × Average km.	0.57	0.26	0.03
Flashing × Category: Motorcycles	0.42	15.66	0.98
Flashing × Category: Heavy vehicles	0.21	3.78	0.96
Flashing × Gap	−1.24	0.26	<0.01

4.1.1. Factors Relating to the Surroundings

First, the effects present in both types of typologies were analyzed. According to the results, we found that speed moderation messages lost effectiveness during hours of low light, that is to say, in the dark. Previous experiences have shown that low light has a significant influence on the perception drivers have of the surrounding environment [49]. Additionally, adverse weather conditions reduce driver perception and affect the perceptual judgment of speed and distance [50].

There are also certain traffic conditions that influence the effectiveness of VMS. The results show that drivers tended to reduce their speed more in the presence of high traffic flow in the previous minute. A possible justification for this fact is that in this situation, vehicles were separated by shorter distances, meaning they could be forced to reduce their speed regardless of the message.

Additionally, the effectiveness of the VMS was more significant compared to high average speeds in the previous minute. This behavior is to be expected insofar as drivers driving upstream at a low speed are not able to reduce it further. This effect is relevant, considering that, in high-risk conditions, a slight reduction in average speed can contribute significantly to a reduction in crashes and the severity of injuries [51]. Thus, it is possible that in the face of risky traffic conditions, that is, high flow and high speeds, drivers are more cautious and pay more attention to speed moderation.

Finally, the compliance of drivers with the variable message was lower at low gaps, that is when there is less spacing between vehicles on the same lane. This situation could be due to the fact that with high traffic density, the complexity of driving increases [52], placing a more significant perceptual load on drivers, forcing them to pay more attention to the actual task of driving, otherwise adverse effects on safety may occur [53]. Moreover, if there are conflicting demands for attention, drivers can actually pay less attention to VMS [9].

4.1.2. Factors Relating to Drivers and Vehicles

It can be seen that those drivers more familiar with the Autopista Central were less likely to heed warnings regarding speed moderation. This result is consistent with previous studies, where it was found that more experienced drivers were more likely to display high-risk behavior [54].

In contrast, drivers of heavy vehicles tended to slow down more than drivers of light vehicles or motorcycles. This result is in line with the experiment carried out in Yan and Wu [1], where they suggested that professional drivers were more likely to act on the information shown by VMS, and with the research by Basso et al. [22], where their findings showed truck drivers were more compliant with VMS.

4.1.3. Factors Relating to Message Typology

Now analyzing the effects associated with the presence of flashing messaging, it is possible to conclude that this typology significantly improved compliance with the expected behavior versus static messaging. This fact is consistent with the findings of Rämä and Kulmala [8], while using data in an off-road environment also obtains a more significant speed reduction when the messages are flashing. A flashing display can increase sensory capacity since it draws people's attention to objects [55,56]. Considering that drivers on the Autopista Central had never been exposed to flashing messaging before, the increase in effectiveness could be seen as a contrast to the results of Dudek et al. [44], where adverse effects were found in individuals who were not familiar with the flashing format.

Additionally, it can be seen that a flashing display made for an even more significant improvement in compliance with speed reduction in times of low light. This could mean that drivers perceived the flashing message better when driving in the dark, were more cautious, and treated the message more seriously, thus reducing their speed to prevent accidents. This finding is important because, as mentioned above, VMS are generally less effective in dark environments. Poor night lighting is also one of the main factors contributing to high fatal accident rates, and night traffic accidents tend to decrease as road lighting increases [57–59]. Therefore, these results can be translated into a more suitable configuration in the VMS of the roads, which for example, is variable throughout the day.

Regarding the familiarity of the Autopista Central, it is shown that drivers with more experience tended to comply more with the flashing message. This could be explained by the fact that drivers who use the highway more frequently notice differences concerning their everyday experience with VMS. On the other hand, less frequent users of the Autopista Central may not perceive the relevance of the flashing in the message.

In addition to this, certain traffic conditions counteracted the improvement in the effectiveness of flashing messaging. It was obtained that in situations of high flow and high average speeds the flashing effect decreased. This situation was repeated with high gaps, that is when there is a greater distance between the vehicle and the vehicle that preceded it along the same lane.

Considering the previous analyses, we conclude that flashing messaging is more effective in a dark environment scenario, with low flow, slight gaps, and low average speeds. In the opposite case, in an environment with high levels of flow, speeds, and gaps, which is generally represented in the morning or afternoon hours, the effectiveness of the flashing is reduced.

4.2. Lane Changes

Following the methodology put forward in Section 3.5, the results of the adjusted logistic regression for the case of messages that suggest a change of lane are shown in Table 6. Similar to the previous case, the coefficients and p-values enabled us to analyze the influence of the different variables on the probability of changing tracks.

Table 6. Coefficient estimates, standard error, and *p*-values for variables in the model. (Lane changes).

Variable	Coefficient Estimate	SE	*p*-Value
Intercept	0.17	0.39	0.67
Flashing	0.90	0.49	0.07
Darkness	−0.18	0.08	0.03
Flow previous minute	-1.32×10^{-3}	2.79×10^{-3}	0.63
Speed previous minute	1.43×10^{-3}	3.24×10^{-3}	0.66
Average km.	0.05	0.01	<0.01
Category: Motorcycles	−0.82	0.59	0.17
Category: Heavy vehicles	−0.73	0.15	<0.01
Gap	−0.01	0.01	0.19
Flashing × Darkness	0.09	0.12	0.43
Flashing × Flow previous minute	−0.01	3.80×10^{-3}	0.02
Flashing × Speed previous minute	−0.01	3.80×10^{-3}	0.02
Flashing × Average km.	0.03	0.02	0.16
Flashing × Category: Motorcycles	0.18	0.75	0.81
Flashing × Category: Heavy vehicles	−0.02	0.22	0.93
Flashing × Gap	−0.01	0.01	0.54

4.2.1. Factors Relating to the Surroundings

In the analysis of lane changes, it was found again that variable messages increased the effectiveness in daylight hours. This result is in accordance with Basso et al. [22], where generally, greater visibility increased the probability of lane changes, regardless of whether or not a message was displayed. Furthermore, it is in line with the results of Zhang et al. [49], where the intention to change lanes was significantly higher when respondents drove on roads with public lighting instead of roads without.

4.2.2. Factors Relating to Drivers and Vehicles

In this case, it can be seen that drivers of heavy vehicles were less likely to obey the suggestion of a lane change. This behavior is contrary to what was obtained for speed moderation messages. This could be explained by the fact that, for heavy vehicles, slowing down is an action that could help reduce the risk of having an accident, and this is a relatively easy action to perform compared to lane changes because trucks are longer, wider, heavier, and less maneuverable than cars [60,61].

Additionally, it can be observed that drivers with more knowledge of the Autopista Central tended to comply more with the change of lane indicated. This behavior can occur because more experienced drivers have their preferred lanes or know which lanes are the fastest at any given time, increasing their chances of changing lanes.

4.2.3. Factors Relating to Message Typology

As with speed moderation messages, flashing messaging improved compliance with expected lane change versus static messaging. However, this effect was less significant for this type of message.

Additionally, some traffic conditions impacted the effectiveness of a flashing VMS. We see that this way of transmitting the message induces in a more significant way the changes of the lane in conditions of low flow and low speeds. This can be explained by the fact that the messages flashed at a frequency of 1 Hz. Therefore, it takes a second or two to read and interpret the message, which may not be possible if the driver is travelling at a high speed or in complex traffic conditions. This fact is in line with the results of Dudek and Ullman [62], where they found that the flashing format increased average reading and comprehension time, and also, participants who preferred static messages commented that it was because they found the flashing effect distracting and confusing.

Finally, unlike the case of speed moderation messages, it was found that in the case of lane change messages, although the basal effect of the flash was maintained, there were fewer external factors that differentiated the effects of the static message versus the flashing message.

5. Conclusions

In this research, the effect of flashing on variable messaging has on drivers was analyzed using information from an experiment carried out on the Autopista Central highway in Santiago de Chile. The experiment compared responses to flashing or static messages that indicated moderation of speed or change of lane. In order to analyze the differences between both types of messages, regressions were constructed, which, in addition to quantifying the effect of light flashing, allowed us to isolate and control other traffic and environment variables.

In the literature, numerous efforts have been made to study the impact of VMS on traffic safety. Some experiences affirmed that VMS plays a vital role in transmitting warning information to drivers, affecting their driving behavior [9,50], while others indicated the opposite [22]. However, there are few studies regarding the most efficient ways to deliver this information to VMS, and none of them used full real-world data to analyze the impact of flashing messages on driving behavior. Thus, the main objective of this research contributes to this deficit by comparing static and flashing messages, using vehicle-by-vehicle data from all road traffic.

Several findings were obtained from this study. Overall, the analyses carried out showed that flashing may increase the effectiveness of VMS. However, this efficacy is subject to environmental and traffic conditions. In speed moderation messages, this way of transmitting the message makes it even more effective in dark environments, with low congestion, small spacing, and low average speeds. Additionally, it has a more significant impact on experienced drivers, that is to say, those with higher mileage on the highway. On the other hand, for track change messages, flashing messaging reduces its effectiveness in situations requiring a high cognitive load, namely high flow and high average speeds. For the two types of messages, the type of vehicle had no significant effects.

The results of this research could be used to generate VMS configuration strategies, adaptations to different traffic and environmental conditions, and improvements to safety [63]. Furthermore, the wealth of vehicle-by-vehicle data captured by technologies such as AVI gates could give rise to strategies that use certain information from the group of users that circulate on the roads to design personalized messages that seek to maximize effectiveness. These personalized messages must consider the specific characteristics and idiosyncrasies in the countries where they would be applied so that the results of one country are not directly extrapolated to others. Nevertheless, more research is required to accomplish these objectives. For instance, the data we use could be complemented with the drivers' personal information, such as age or gender, to better reflect the differences in response to VMS messages. Additionally, other experiments that consider in-vehicle data could be performed, such as those based on eye trackers or bio-psychological state detectors.

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