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Driver's deceleration behaviour according to infrastructure

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Abstract

This study is part of the SURCA French project, which goal is to identify relevant scenarios for interaction between autonomous vehicles (AV's) and other road users. Observations from current AV deployment in real traffic have raised that braking situation are a major source of conflict. The objective of this study is to collect human driven vehicle's deceleration profiles, and explore the link between their characteristics and the reason to stop. Existing studies on drivers' braking behaviour investigated data either from controlled experiments or driving simulators. Few studies have explored data from naturalistic driving behaviour, and none of them studied the link between the deceleration behaviour and the intersection characteristics. Almost 4000 deceleration profiles have been extracted from previous experiments, and analysed according to the priority context. The results indicate that significant different behaviour is observed for roundabouts, give-way, and stop-signs, with stronger decelerations and higher approach speeds.

Keywords:

Braking behaviour, naturalistic data, priority traffic signs, road infrastructure.

Study objectives

This research is part of the SURCA French project funded by the Ministry of Ecological and Solidarity Transition. One of the objectives of the SURCA project is to identify the conditions that will allow autonomous vehicles (AVs) to perform as well as drivers in normal driving conditions, and above all, better than them in accident-prone situations. In this context, the literature and international experience feedback have made it possible to identify braking situations as accident-prone situations for AVs, human drivers having difficulty anticipating the behaviour of the AV in front of them (Biever et al., 2020; Favaro et al., 2017; Pokorny et al., 2021; S. Wang & Li, 2019). Indeed, AVs are designed to optimize travel according to several criteria, the search for an energy optimum (Meng & Cassandras, 2018) can lead to behaviours different from humans. There is little research on humans braking behaviour in normal driving (Deligianni et al., 2017; J. Wang et al., 2005).

The idea of this study is to seek to understand how the decelerations practiced by car drivers are influenced by certain characteristics of the road context. Indeed, we hypothesize that the deceleration profiles of light vehicles drivers preceding a stop differ according to the infrastructure that caused the stopping manoeuvre (reason for stopping): priority scheme of the intersection (traffic light, , stop sign,

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give-way) or type of road design (roundabout, pedestrian crossing; bus stop). The modelling approach consists in extracting several behaviour related indicators from identified deceleration profiles (the speed as a function of the time before the total stop). The evolution of these indicators according to the variable of interest, the *reason for stopping*, will be discussed taking into account the maximal allowed speed (*speed limit*). Finally, lessons will be learned from the perspective of AVs. The hypothesis, variable and covariate considered in the study are summarised in Table 1:

Table 1: Hypothesis, variable and covariate considered in this study.

Hypothesis :	The stopping manoeuvres carried out by light-vehicle drivers produce different deceleration profiles depending on the reason for stopping (priority regime or road design)
Variable¹ :	<i>Reason for stopping</i> : Priority scheme (traffic light, stop sign, give-way); road design (roundabout, pedestrian crossing, bus stop)
Covariate²	<i>Speed limit</i> : 30 km/h ; 50 km/h ; 70 km/h; 90 km/h

Data collection methodology

Data source

The data used in this work comes from five different experiments carried out between 2009 and 2019 by the Uni Eiffel (formerly Ifsttar) and Cerema. Although intended to study specific driving situations (eco-driving, behaviour at intersections, lateral control), these experiments have in common a protocol based on the observation of driving in a natural situation. The data thus collected represent driving behaviour not influenced by an assistance system or specific instructions that may have influenced the stopping manoeuvres of the participants. The latter have all been instructed to drive safely by being masters and responsible for their vehicle.

More than 10 thousands of kilometres have been collected through 5 different experimentations. In the majority of the experiments, the position of the vertical signage and of certain infrastructures were recorded. When this is not the case, it has been produced manually using a recording of GPS positions directly on the original site. The possible modifications of the sites have been studied but this did not lead to any legitimate modification in the initial data. The various vertical signs or infrastructures that can cause the vehicle to stop and which will be considered in the analysis are presented in Table 2.

Deceleration data

The recording of the driving parameters also benefited from a very comparable technical approach during these experiments, and in particular led to the obtaining of the following homogeneous data useful for our analysis:

¹ Variable or factors to be analysed: factors whose influence will be assessed in the selected situations.

² Covariates : Characteristics of the selected situations which may cause the results to vary and whose different modalities will be taken into account in the analysis.

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- Data from the GPS receiver: longitude, latitude, instantaneous speed and timestamp;
- Data from the CAN data bus: instantaneous speed, cumulative distance travelled and timestamp.

All of this time stamped and geo-referenced data describes not only the driving context, but also its translation into driving behaviour, particularly when performing stopping manoeuvres.

Data processing required the four following steps to build the sample used for statistical analysis:

- Search for stops of the vehicles: This involves identifying suitable deceleration sequences in the data.
- Initial step of filtering (Filtering I): A first filtering makes it possible to reduce the sample and reduce the calculation time, while avoiding aberrant data.
- Enhancement of the data with the driving context: each of the deceleration sequences were associated with a *reason for stopping* and a *speed limit*.
- Identification of the first instant of deceleration: The first instant of deceleration is identified and the sequences are truncated at this instant. Two additional filtering are then applied.

Table 2: Reason for stopping (priority schemes and road design) considered in this study.

Priority scheme	Road design
Traffic lights (TL)	Roundabouts (RA)
Stop sign (ST)	Pedestrian crossing (PC)
Give-way sign (GW)	Bus stop (BS)

Search for stops of the vehicles

A stop is defined as follows: the speed of the vehicle must remain below the threshold of 5 km/h for at least 3 seconds to constitute a stop. When a stop is detected according to the above criteria, the driving information is retrieved 20 seconds before the stop. The time series obtained constitutes a "deceleration profile", containing the dynamic parameters of the vehicle (time, position, speed, acceleration).

Initial step of data filtering

Prior to the analysis, the initial deceleration profiles obtained are filtered. This eliminates measurement errors and speeds up data processing.

- Filtering I.1: Suppression of deceleration profiles with errors
 - First, we check that the cumulative distance and the timestamp are constantly increasing and we delete the deceleration profiles that have sensor errors to avoid working on erroneous deceleration profiles.
- Filtering I.2: Suppression of deceleration profiles with speed always lower than 30 km/h.
 - Deceleration profiles for which the speed data throughout the deceleration phase are less than 30 km/s are deleted, as they are considered as irrelevant decelerations, i.e. those which are not caused by road infrastructures.
- Filtering I.3: Removal of straight curves

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- We removed the deceleration profiles with straight parts which are the result of missing data transmission by the sensors (GPS receiver and CAN data bus). These missing data were completed by connecting the end points with straight lines by the recording device, which does not represent relevant information to analyse since it is not representative of reality.

Enhancement of the data with the driving context

Each deceleration profile is then associated to the context elements which are: 1) the infrastructure that caused the stopping manoeuvres (*reason for stopping*) and 2) the maximum allowed speed (*speed limit*). Whereas the maximum allowed speeds were easy to obtain via field surveys, the identification of the infrastructure that caused the stopping manoeuvre required special treatment. Indeed, the experiments did not allow the systematic recording of videos. The process consists of identifying the type of infrastructure (priority regimes or road design) present during the last 10 meters of the final deceleration phase, and within a radius of 20 meters around this one. Using the GPS positions of the different type of infrastructures of interest present along the routes travelled during the experiments, a list of the potential infrastructures that caused the stopping manoeuvres was compiled for each deceleration profile extracted from the data. Each deceleration profile is then associated with a list of possible candidates for an infrastructure related reason to stop. The method takes into account the direction of movement of the vehicles. If the list is empty, no infrastructure related reason to stop is identified (NA); otherwise, each profile is further processed along a maximum of 5 stages. At each stage, the list of candidate infrastructures is scanned to identify whether one of them corresponds to one of reason to stops associated with this stage. If none matches, we go to the next stage and repeat the process. If a match is found, this is the infrastructure considered to have most likely generated the stopping manoeuvre. We identify and remove possible congestion situations in a further step. Thus, the heuristics for choosing the infrastructure most likely to have caused the observed stop manoeuvres is the following:

1. Stage 1 / Traffic light (TL): If the final position of a deceleration profile is observed less than 10 m from the presence of a traffic light, the traffic light is considered to be red, inducing a mandatory (at least observed) stop.
2. Stage 2 / Stop sign (ST) or give way (GW): Except in a congestion and traffic light situation, and in the presence of one of these 2 signals, the founded one will be considered as the probable cause of the stop. These two situations cannot occur at the same time.
3. Stage 3 / Roundabout (RA): Looks for roundabouts, also sometimes indicated by pedestrian crossings, but which come under a specific priority scheme which it is desirable to specifically identify.
4. Stage 4 / Pedestrian crossings (PC): In the absence of the preceding situations, the pedestrian crossing is considered as being able to be at the origin of a stop. This situation is very rare.

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5. Stage 5 / Bus stops (BS): In the absence of any other reason, if a bus stop is present, it is defined as the probable cause of the stop.

Identification of the first instant of deceleration

At this stage of data processing, all the deceleration profiles obtained have a duration of 20 seconds. However, the duration of a deceleration preceding a stop is variable, and may in particular depend on the type of road infrastructure encountered and the speed limit in force. Thus, we seek to identify the first point of deceleration of this profile, in order to be able to compare the durations according to the different variables. For this, we calculate the acceleration (a moving average type filter of order 2 seconds is applied to the raw values of the acceleration obtained by derivation of the speed signal) and look for the first moment when it passes from a positive value to a negative value. The point thus found represents the first instant of the deceleration profile. The new deceleration profiles constructed went through two additional filtering steps:

- Filtering II: Deceleration sequences lasting less than 5 seconds were excluded from the analysis.
- Filtering III: Some profiles had an initial deceleration phase, followed by a re-acceleration phase. These profiles were processed again, to remove the re-acceleration phase, only the final phase being considered as a deceleration profile.

An example of selected deceleration profiles is provided in Figure 1.

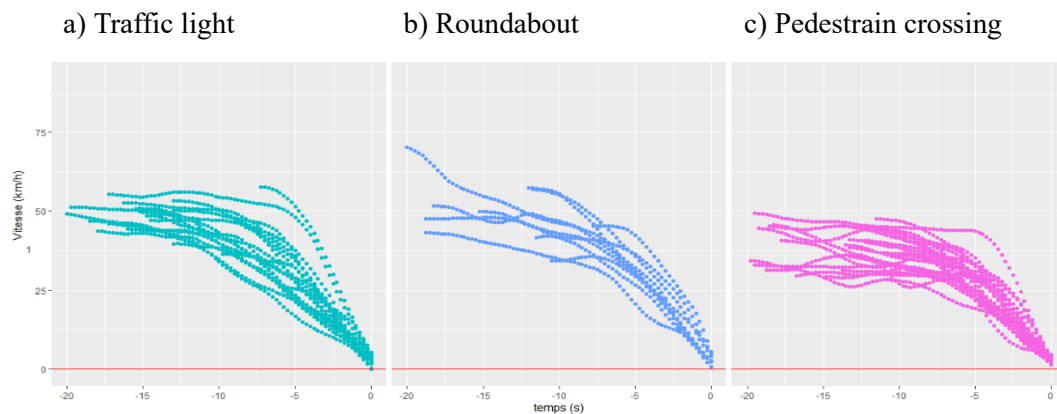


Figure 1 : Examples of selected deceleration profiles on roads with a speed limit of 50 km/h for three different reasons for stopping: a) traffic light, b) roundabout and c) pedestrian crossing.

In total, 3674 deceleration profiles were selected for analysis, which repartition across reasons for stopping and road speed limits can be seen at Table 3. Infrastructure related reasons for stopping are obviously not distributed randomly across speed limits of roads. Indeed, speed limits of roads are closely linked with the road type, being associated with different road designs' strategies. Most of the deceleration profiles are not associated with any identified cause (NA values), and most of the data are collected for roads with a speed limit of 50 km/h. It is worth noting that give-way were only observed on roads with a speed limit of 90km/h, and pedestrian crossings and traffic lights mostly on roads with a speed limit of 50 km/h. In further examination of results, the NA modality will be considered as a kind

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of reference of the stopping behaviour induced by an unpredictable source. Other modalities are providing knowledge about a specific stopping behaviour induced, or probably induced, by the priority scheme or the road design.

Table 3: Number of deceleration profiles according to the reason for stopping and the speed limit.

<i>Reason for stopping</i>	<i>Speed Limit</i>				Total
	30 km/h	50 km/h	70 km/h	90 km/h	
Bus Stop	3	40	0	0	43
Give Way	1	1	7	91	100
Traffic Light	80	505	12	0	597
NA	139	1875	177	312	2503
Pedestrian Crossing	10	235	17	1	263
Roundabout	0	16	0	0	16
Stop Sign	3	66	0	83	152
Total	236	2738	213	487	3674

Statistical analysis

The selected deceleration profiles are of various length, duration, and speed. In order to describe their characteristics, and following Wang and collaborators (2005), the information contained in the profiles was aggregated in the form of several indicators presented in Table 4.

Table 4: List of indicators calculated for each of the deceleration profiles.

<i>Indicator</i>	Description	Units
<i>Deceleration distance</i>	Total distance travelled within the deceleration (from initial deceleration to the final stop)	Meter
<i>Deceleration duration</i>	Total duration of the deceleration	Second
<i>Maximum deceleration</i>	Maximum of the observed deceleration values	m/s ²
<i>Average deceleration</i>	Mean of observed deceleration values	m/s ²
<i>Initial speed</i>	Initial speed at initial deceleration	km/h
<i>Std speed</i>	Standard deviation of speed	km/h

For each indicator, we computed both mean and standard deviation values for all speed limits merged (Table 5).

A more detailed view of the indicators repartition across the reasons for stopping is available in Figure 2. Results are showing several differences across the reasons for stopping, which significance were assessed using one-way ANOVA's for each of the 6 indicators.

The *deceleration distances* are somewhat comparable (Figure 2A), but a one-way ANOVA revealed that there was a statistically significant difference between the reasons for stopping ($F(6,3667) = 2.426$, $p = 0.0242$). Performing a Tukey's HSD Test for multiple comparisons, none of them were finally

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significant, leading to the conclusion that greater distances observed for the roundabouts is a weak evidence when taking into account the small number of such profiles (only 16).

Table 5: Computed values of the chosen behaviours related indicators according to the reason for stopping (all speed limits were merged).

<i>Reason for stopping</i>	Mean (standard deviation) of decel distance	Mean (standard deviation) of decel duration	Mean (standard deviation) of the maximum deceleration	Mean (standard deviation) of the average deceleration	Mean (standard deviation) of the std speed	Mean (standard deviation) of the initial speed
<i>Bus Stop</i>	130.45 (29.94)	16.53 (2.56)	-1.73 (0.47)	-0.53 (0.12)	9.60 (1.58)	35.90 (4.55)
<i>Give Way</i>	131.68 (48.25)	15.85 (3.50)	-2.11 (0.57)	-0.87 (0.30)	13.66 (3.41)	48.62 (9.63)
<i>Traffic Light</i>	138.32 (36.22)	17.19 (2.77)	-1.81 (0.55)	-0.54 (0.19)	10.22 (2.63)	37.16 (7.94)
<i>NA</i>	139.19 (45.45)	17.08 (3.10)	-1.85 (0.58)	-0.60 (0.23)	11.24 (3.87)	40.38 (11.73)
<i>Pedestrian Crossing</i>	139.19 (46.02)	16.86 (3.29)	-2.03 (0.71)	-0.58 (0.27)	10.39 (3.24)	37.92 (9.16)
<i>Roundabout</i>	162.67 (44.34)	17.81 (3.12)	-2.20 (0.56)	-0.74 (0.29)	13.35 (3.76)	48.90 (13.40)
<i>Stop Sign</i>	147.42 (49.83)	16.56 (3.17)	-2.11 (0.48)	-0.81 (0.28)	13.91 (4.14)	49.22 (13.58)

For the *deceleration durations* (Figure 2B), a one-way ANOVA revealed that there was a statistically significant difference in mean duration of the decelerations between at least two groups ($F(6,3667) = 3.915$, $p = 0.0006$). This is confirmed by a Tukey's HSD Test for multiple comparisons, showing significantly lower durations for give way signs than for traffic lights ($p = 0.001$, 95% C.I. = [0.36, 2.32]) and NA ($p = 0.001$, 95% C.I. = [0.3, 2.15]).

Maximum decelerations (Figure 2C), are found to be significantly different by a one way ANOVA ($F(6,3667) = 13.8$, $p = 1.4e-15$). A Tukey's HSD Test for multiple comparisons found that stop signs are associated with higher maximum decelerations than for bus stops, traffic lights, and the NA condition. Similarly, the give way signs associated max decelerations are significantly lower than the ones for traffic lights and the NA condition. Moreover, traffic lights are associated with smaller max decelerations than for pedestrian crossings ($p < 0.001$, 95% C.I. = [-0.09, -0.34]).

A one-way ANOVA to compare the *average decelerations* (Figure 2D) across reasons for stopping

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reveals significant differences ($F(6,3667) = 53.78$, $p < 2e-16$), confirmed by Tukey's HSD Test for multiple comparisons. Average decelerations associated with stop signs are significantly lower than the ones for bus stops, traffic lights and pedestrian crossings. Average decelerations associated with give way signs are significantly lower than the ones for bus stops, traffic lights, pedestrian crossing, and the NA situation.

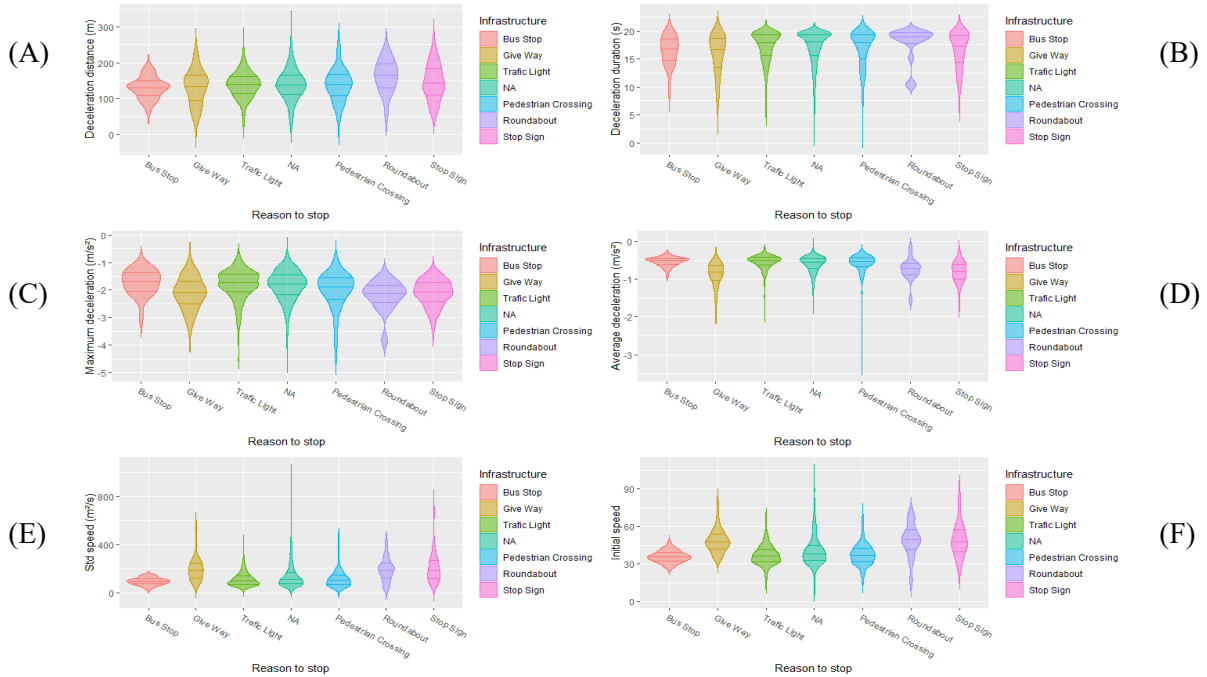


Figure 2: Violins plots of the indicators according the reason for stopping: (A) Deceleration distance, (B) Deceleration duration, (C) Maximum deceleration, (D) Average deceleration, (E) Standard deviation of speed and (F) Initial speed.

Using again ANOVA's, it is identified significant differences across the reasons for stopping for *standard deviation of speed* (Figure 2E, $F(6,3667) = 30.66$, $p < 2e-16$). A Tukey's HSD Test for multiple comparisons found that both stop signs and give way signs are associated with greater speed variations than for bus stops, traffic lights, pedestrian crossings and the NA condition. Traffic lights and pedestrian crossings values being significantly lower than for the NA condition.

Finally, a one way ANOVA confirms the existence of significant differences in the *initial speed* (Figure 2F), across the various reasons for stopping. A Tukey's HSD Test for multiple comparisons found a similar behaviour between stop signs, give way signs and roundabouts, which are all associated with higher initial speeds than the bus stops, traffic lights, pedestrian crossings, and NA condition. Moreover, traffic lights and pedestrian crossings initial speeds are significantly lower than the ones associated with the NA condition.

In order to get a clearer view of the data, Figure 3 is providing the average speed profiles obtained for each reasons for stopping according to the speed limits. Both 30 km/h and 70 km/h data were excluded from this analysis because they were not providing enough data to get interpretable confidence intervals.

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It can be seen, but not proven yet, that stop signs are associated with higher approach speeds, followed by a late but harder deceleration phase, for the both available speed limits. Although we have few data corresponding to the roundabout approach and only for 50 km/h roads (Figure 3A), they seem to follow a similar pattern than for the stop signs. In the previous statistical analysis, similarly to the stop signs, give way signs were found being associated with higher approach speeds, but a look at Figure 3 suggests that this may be a confounding effect due to the speed limit covariable, as give way signs decelerations were only observed for 90 km/h roads (Figure 3B).

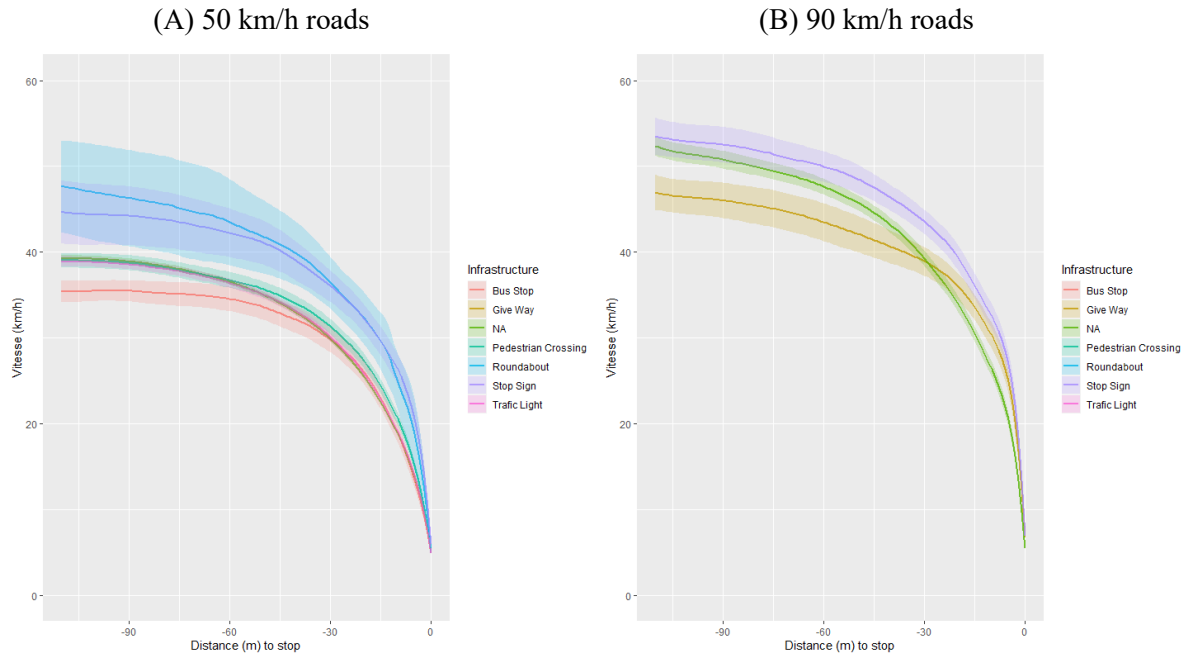


Figure 3: Average speed profiles and confidence intervals for 50 km/h (A) and 90 km/h (B) roads.

Conclusions

Results are suggesting some similarities for the deceleration behaviour at stops and give way signs. They are both associated with stronger decelerations than for the other modalities, except for the roundabouts decelerations, which also seem to share some characteristics but are not significant due to the small sample number. The same conclusions arise with the average deceleration parameter, which is significantly greater for stops and give way signs. These two conditions are also significantly associated with greater initial speed, and speed variability. These results are suggesting significant differences in driver's decelerations between predictable reasons to stop (the sign is visible, and the probability to have to stop is high), and uncertain reasons to stop (the necessity of a stop is less probable). Authors are suggesting the hypothesis that human driver's are adapting their stopping strategies according to the probability of a mandatory stopping manoeuver. If the need to stop is certain (stop signs) or almost certain (give way signs), then we observe higher approach speeds, associated with late and stronger decelerations.

The main limitation of this study is the control of the speed limit confounding covariate, which is not statistically feasible due to the sparsity of the data (give way signs are not observed for 50 km/h roads,

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roundabouts are not observed for 90 km/h roads, and only stop signs are observed for 50 km/h and 90 km/h roads). Despite this limitation, stop signs deceleration behaviour differences with the NA condition are similar across 50 and 90 km/h roads, the deceleration phase starting later for the stop signs with greater deceleration rates. Further work will differentiate stop signs between the two main speed limits 50 and 90 km/h, and will consider them as different kind of reasons for stopping.

Furthermore, results suggest that the approach speed and the deceleration characteristics are influenced by the reason for stopping. Coming back to the observed conflicts between AV's and human driver's, we believe that their interactions can be improved taking into account observed driver's deceleration characteristics. Findings from this study may also be considered in examining or evaluating the braking behaviour of AVs.

Further work is needed to estimate the effect of the speed limit, by collecting more data and by using more complex models such the generalised linear mixed models. Also, a polynomial model of the speed profiles is possible using models from the literature (Akçelik & Besley, 2001).

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