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Analyzing risky behavior of motorists during the closure cycle of railway level crossings

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Abstract

Level Crossing (LX) safety is one of the most critical issues for railways. Collisions between trains and motorized vehicles contribute most to LX accidents, while the risky behavior of motorists is the primary cause of such accidents. Therefore, motorist behavior at LXs is a safety concern that requires special attention care. The present study is a tentative to acquire a better understanding of risky motorist behavior at LXs. Namely, risk analysis of motorist behavior is performed based on field observation conducted at 11 automatic LXs (10 equipped with two half barriers (SAL2) and 1 equipped with four half barriers (SAL4)). We particularly focus on motorist behavior during the LX closure cycle when the barriers are closed down completely. Based on recorded measurements, the zigzag violation rate is analyzed with regard to the prolonged LX closure duration and LX location (railway station nearby or not), respectively. Then, some other features characterizing risky behavior are determined, such as troop phenomenon, etc. Besides, since our aim is to analyze motorist behavior at SAL2 LXs, one SAL4 LX was considered in our experiments to examine the distinction of motorist responses to SAL2 and SAL4 protection systems, so as to compare the efficiency of SAL2 and SAL4 LXs in terms of safety. In summary, the findings of our analysis offer a novel insight for interpreting significant aspects underlying motorist decision-making during the LX closure cycle and facilitate identifying technical solutions to improve LX safety.

Keywords: Railway safety; Level crossing safety; Train-vehicle collisions; Zigzag violations; Statistical analysis;

1. Context and related works

Accidents at railway level crossings (LXs), particularly collisions between trains and motorized vehicles, often give rise to serious material and human damage and seriously hamper railway safety reputation, although the majority of accidents are caused by motorist violations. Therefore, LX safety is one of the most critical issues for railways, which needs to be tackled urgently (Ghazel, 2009; Liu et al., 2016; Mekki et al., 2012). In 2012, there were more than 118,000 LXs in the 28 countries of the European Union (E.U.), and 5 LXs per 10 line-km on average in the E.U. (ERA, 2014). LX accidents account for about 30% of the total number of railway accidents in Europe and cause more than 300 deaths every year (Liu et al., 2016). In some European countries, LX accidents account for up to 50% of railway accidents (Evans, 2011a; Ghazel and El-Kourisi, 2014). The railway network in France shows more than 18,000 LXs for 30,000 km of railway lines and around 13,000 LXs show heavy road and railway traffic (SNCF Réseau, 2011). More than 16 million vehicles on average cross LXs every day and 450,000 LX closure cycles take place accordingly. Once a motorized vehicle exists at the LX intersection zone during the LX closure cycle when a train is approaching, the train cannot be stopped to avoid colliding with the vehicle, since trains can be very heavy, weighing up to 1,500 tonnes and a train running at 90 km/h generally needs 800 m to stop (Ghazel, 2017). In 2013, €32 million was spent by the State, SNCF (the French national railway operator) and local authorities, to improve safety at LXs, and about €36 million was invested in 2014. Despite numerous measures taken to improve LX safety, SNCF Réseau counted 111 collisions at LXs leading to 31 deaths and 15 severe injuries in 2016 (Plesse, 2017). This number was half the total number of collisions per year at LXs a decade ago, but still too large. In order to efficiently

19 improve LX safety, it is crucial to carry out a thorough analysis to understand motorist behavior during the closure
20 cycles of LXs. This draws the background and motivation of the current study.

21 In the existing literature, a number of works have dealt with LX safety. In early studies, motorist behavior with
22 respect to the warning time of LX control was studied by Richards and Heathington (1990). Their study indicated that
23 an increase in warning time was directly linked with an increase in risky motorist behavior. Ward and Wilde (1995a)
24 reported a field study regarding a signage warning system for passive LXs with restricted lateral visibility. The
25 proposed signage incorporates a stop sign and an advance warning to announce the restricted visibility. In this study,
26 the vehicles were tracked through a series of seven sonar units placed along the roadside at incremental distances from
27 the LX. It was reported that the approach speed of the vehicles approaching the LX did decrease after the installation
28 of the signs. Abraham et al. (1998) have studied motorist behavior at 37 LXs in Michigan and reported various
29 driver characteristics and vehicle characteristics to be important safety factors. This study showed that the motorists
30 approaching a multi-track LX from a multi-lane approach commit more violations. Cooper et al. (2007) presented
31 the research on selecting countermeasure improvements for LXs in California and suggested the use of two-long-arm
32 gates or standard two-half gates with an additional median separator for LX safety improvement according to the
33 calculated benefit/cost ratio. Khattak (2009) has made a comparison of motorist behavior at LXs in two cities of
34 Nebraska. This research has showed that motorists' unsafe behavior at LXs is location-dependent, but the magnitude
35 of reduction in unsafe motorist actions as a result of the installation of a separator along the road center at different
36 LXs is more or less similar.

37 In the recent literature, few works focus on the analysis of motorist behavior with regard to the separate phases
38 of the automated LX closure cycle. Some available studies adopted qualitative approaches for understanding motorist
39 behavior during the entire cycle of LX control, including when the LX is open to road traffic (e.g. Shappel and
40 Wiegmann, 2000; San Kim and Yoon, 2013). For example, a systems analysis framework (Read et al., 2016; Wilson,
41 2014) and a psychological schema theory (Stanton and Walker, 2011; Salmon et al., 2013) have been used to analyze
42 the contributory factors underlying LX accidents. Salmon et al. (2016) adopted the Cognitive Work Analysis (CWA),
43 which is a systems approach with theoretical underpinnings in system theory, to achieve comprehensive understanding
44 of different functions, decisions, strategies and tasks relevant to various LX stakeholders (road user, rail user and
45 authorities). This study suggested further mechanisms for collecting and analyzing actual field data, which are crucial
46 for allowing stakeholders to identify the key design requirements to improve safety at LXs. Some works (involving
47 qualitative and quantitative means) employ surveys (Wigglesworth, 2001), interviews (Read et al., 2016), focus
48 group methods (Stefanova et al., 2015) or driving simulators (Larue et al., 2015), rather than collecting real field
49 data. For example, Lenné et al. (2011) examined the effect of installing active controls, flashing lights and traffic
50 signals on vehicle driver behavior. This study was achieved through the driving simulator. Rudin-Brown et al. (2012)
51 carried out a driving simulator study that compared the efficacy and drivers' subjective perception of two active LX
52 traffic control devices: flashing lights with boom barriers and standard traffic lights. A study launched by Young
53 et al. (2015) examined where drivers direct their attention on approach to urban LXs located in busy shopping strip
54 areas in Melbourne, and whether this differs between novice and experienced drivers. Instrumented vehicles, driver
55 Verbal Protocols and post-drive Critical Decision interviews are utilized in this study. Tey et al. (2011) conducted
56 an experiment to measure vehicle driver response to LXs equipped with stop signs (passive), flashing lights and half
57 barriers with flashing lights (active), respectively. In this study, both a field survey and a driving simulator have
58 been utilized. However, we believe that the reaction of vehicle drivers in simulation context may differ from that in
59 reality, due to the different levels of feeling of danger. Davey et al. (2008) performed a study that aims to explore the
60 contributing factors toward collisions at LXs from the perception of both heavy vehicle drivers and train drivers. In
61 particular, a survey was conducted and samples of train drivers and heavy vehicle drivers were recruited as a series of
62 focus groups. In this study, the contributing factors to heavy vehicle accidents at LXs such as the heavy vehicle size,
63 the carriage length, the line of sight and the impeded acceleration were assessed using qualitative investigation.

64 Although research on human factors related to LX safety has been an area of great concern over the past decades
65 (Wilson and Norris, 2005; Wilson, 2014), the causes of collisions that occur at LXs remain insufficiently understood.
66 In general, the causes of such collisions fall into two broad classes, which are unintentional error and intentional
67 violation. As for the unintentional errors, vehicle drivers may, for instance, fail to observe the warnings or fail to
68 determine the braking distance appropriately. However, as for the intentional violations, vehicle drivers observe the
69 warnings and fully understand their meaning, but intentionally commit transgressions on their own judgment (Lenné
70 et al., 2011). In the present study, we carry out experiments that aim to quantitatively and finely analyze intentional

71 zigzag violations of motorists when LX barriers are closed. These experiments have been conducted at 11 automated
72 LXs in France, among which there are 10 LXs equipped with two half barriers and 1 equipped with four half barriers.

73 The originality of the present study is three-fold: 1) based on some experimental devices, we are able to record
74 the dynamics and category of each individual vehicle crossing the LXs during the observation period. Moreover,
75 a synchronization with the LX local control module allows for determining the LX control phase (cf. section 2.1)
76 corresponding to each individual crossing vehicle. 2) Based on the field data collected, motorist behavior during
77 “Ph4 Barriers Down” of the closure cycle (cf. section 2.1) is specifically considered. This gives a novel insight
78 compared with existing studies which analyze motorist behavior during a whole mixed LX control cycle. 3) Thorough
79 behavioral analysis has been carried out on i) the zigzag violation rate during Ph4 with regard to the prolonged LX
80 closure duration and LX location (railway station nearby or not), respectively, ii) some other features characterizing
81 risky behavior, such as troop phenomenon, etc. and iii) the distinction of motorist responses to SAL2 and SAL4 LXs
82 with regard to various phases of the closure cycle, which are rarely presented in existing works.

83 The current paper is structured as follows: the context of the conducted study and a review of existing related
84 works on LX safety analysis are given in section 1. Section 2 is dedicated to the research objective, the experimental
85 process and data collection. Analysis of zigzag violation scenarios is elaborated in section 3. Namely, the violation
86 rate, waiting queue and troop crossing phenomenon are analyzed with regard to the closure cycle duration, the LX
87 location and road traffic density. The comparison of motorist responses to SAL2 and SAL4 LXs is performed in
88 section 4. A detailed discussion about some influential factors and practical countermeasures for improving LX safety
89 is carried out in section 5. Finally, section 6 provides some concluding remarks and outlines a number of issues for
90 future work.

91 2. Method

92 2.1. Experimental objective

93 **There are four main LX types in France (SNCF, 2015), as shown in Fig. 1:**

- 94 a) SAL4: Automated LXs equipped with four half barriers and flashing lights;
- 95 b) SAL2: Automated LXs equipped with two half barriers and flashing lights;
- 96 c) SAL0: Automated LXs equipped with flashing lights but without barriers;
- 97 d) Crossbuck LXs, without automatic signaling.



(a) SAL4



(b) SAL2



(c) SAL0

(d) Crossbuck LX

Fig. 1. Four types of LXs in France.

As shown in Table 1, SAL2 (more than 10,000) is the most widely used type of LX in France according to the LX data recorded by SNCF. Moreover, more than 4,000 accidents at SAL2 contributed most to the total number of accidents at LXs from 1974 to 2014. According to the previous statistical analysis, motorized vehicle is the main transport mode causing accidents at LXs (Liang et al., 2017). Considering the train/motorized vehicle (train-MV)

Table 1. Accidents at different types of LXs in France from 1974 to 2014.

Type of LX	Number	# Accident
SAL4	> 600	> 600
SAL2	> 10,000	> 4,200
SAL0	> 60	> 50
Crossbuck LX	> 3,500	> 700

collisions, SAL2 LXs also have the most accidents from 1978 to 2013 according to the statistics shown in Fig. 2. In fact, the goal of SNCF is to perform analysis that paves the way toward significantly improving LX safety as a whole. Hence, being given the number of SAL2 LXs, dealing with this LX category consists a priority issue for SNCF. In addition, according to the SNCF statistics, the accidents at SAL2 LXs can be considered as the most representative for LX accidents in general. For all these reasons, we will focus on the analysis of train-MV collisions occurring at SAL2 LXs. It should be noted that suicide scenarios are not in the scope of our global study.

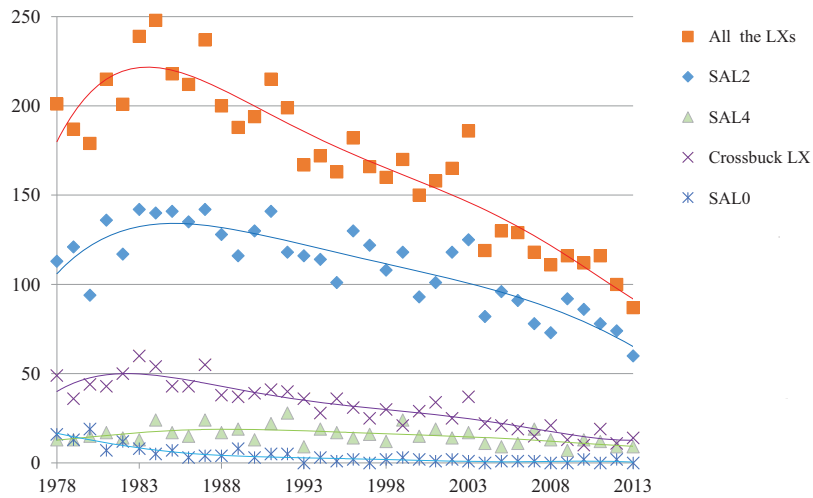


Fig. 2. The number of train-MV collisions at different types of LX in France from 1978 to 2013.

108 The control cycle of SAL2 LXs (as well as SAL4 LXs) consists of 5 phases:

109 • Ph0 “Unflash and Barriers Coming Up”: corresponds to the phase launched just after the crossing train leaves
110 the intersection zone. In this phase, the warning lights stop flashing, the sirens stop blaring and the barriers are
111 rising.

112 • Ph1 “Barriers Up”: corresponds to the phase when the LX is open for road traffic as no train is approaching. In
113 this phase, the barriers are fully opened.

114 • Ph2 “Red Flash and Siren”: corresponds to the first phase of the closure cycle right after an approaching train
115 is detected. In this phase, the warning lights flash and sirens whistle, whereas the barriers are kept raised.

116 • Ph3 “Barriers Coming Down”: is the second phase of the closure cycle. In this phase, the barriers are falling.

117 • Ph4 “Barriers Down”: is the third phase of the closure cycle. In this phase, the barriers are fully lowered and
118 the lights keep flashing.

119 When analyzing LX accident scenarios, the scenario consisting in road vehicles bypassing the half barriers to cross
120 the SAL2 LX when it is closed for the road traffic (zigzag) has been identified as a major scenario causing train-MV
121 collisions (Ghazel, 2017). Therefore, the analysis of motorist behavior at SAL2 LXs during Ph4 “Barriers Down” of
122 the LX closure cycle is important to scrutinize the major risky scenario causing LX train-MV accidents and allows
123 for a detailed assessment of various aspects related to zigzag violations of motorists. This is our consideration that the
124 present study is dedicated to discussing motorist behavior at SAL2 LXs during Ph4.

125 2.2. Selection of case study LXs

126 Ten SAL2 LXs, named according to their respective locations, i.e., LX 2 Toulouse, LX 4 Marnes-la-Coquette,
127 LX 21 Pont-Sainte-Maxence, LX 55 Ectot lès Baons, LX 58 Yvetot, LX 69 Gonfreville, LX 71 Remaucourt, LX 82
128 Neufchâteau, LX 136 Choloy, LX 356 Caussade and one SAL4 LX (LX 425 Chaniers), were selected for our field
129 measurement campaign. Since our aim is to analyze motorist behavior at SAL2 LXs, the SAL4 LX is considered in
130 our experiments for the purpose of comparing motorist responses to SAL2 and SAL4 LXs. As shown in Fig. 3, 11
131 LXs are indicated on the French map. The red circular marks represent the accurate locations of the selected LXs and
132 the railway stations in the vicinity of these LXs are also indicated by black triangle marks.

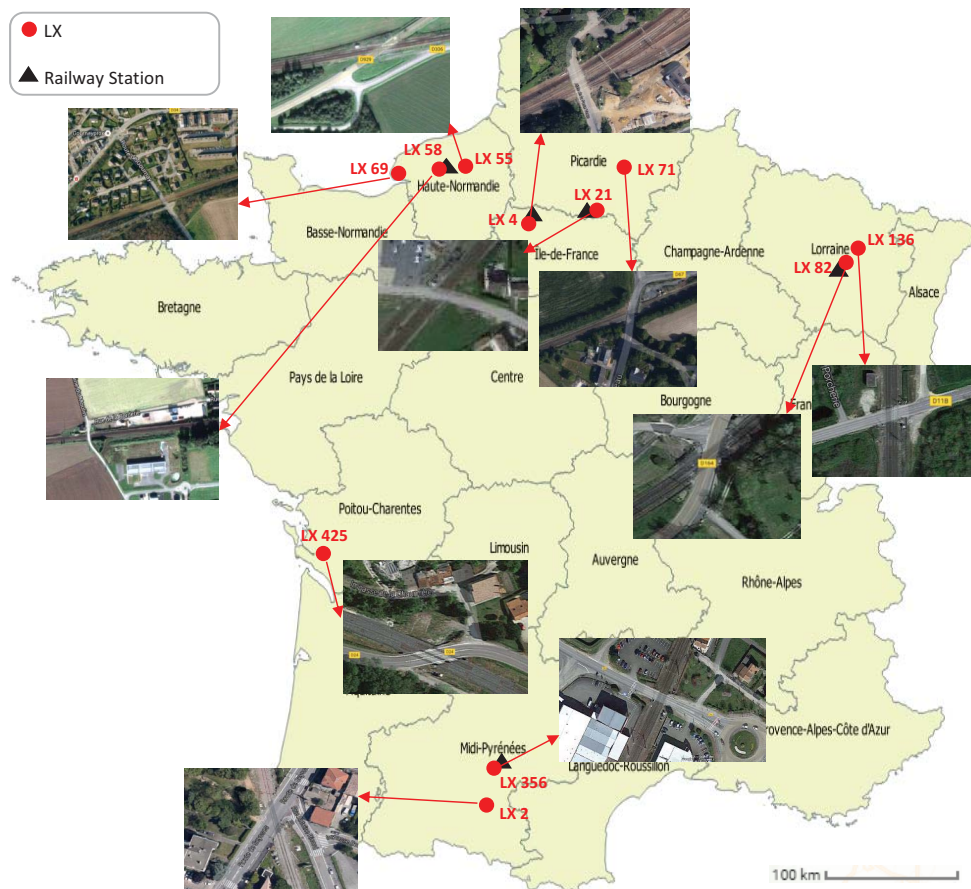


Fig. 3. Geographic information about 11 LXs.

133 The 11 LXs were selected based on various features (e.g., environment, infrastructure, equipment, railway line and
 134 road traffic involved, etc.) as well as their accident/incident statistics (cf. Table 2). **The LX selection process ensures**
 135 **that the selected 11 LXs are representative of the range across France when considering various LX features that we**
 136 **aim to analyze. Indeed, the selection of the LXs sample was based on both quantitative and qualitative assessments.**
 137 **Namely, we have analyzed the historical LX accident/incident data from 1974 to 2014, which were collected by SNCF**
 138 **and recorded in dedicated databases. Moreover railway and road traffic densities have been considered as well as the**
 139 **vicinity of the LXs.** As shown in Table 2, when considering the number of accidents, LX 2 and LX 4 take the first
 140 place among the 11 LXs considered. While considering the sum of accidents and near misses, LX 55 takes the first
 141 place.

Table 2. Collisions/near misses and road/rail traffic volumes at the LXs from 1974 to 2014.

LX	Type	# Accidents	# Near misses	# Average daily road traffic	# Average daily train traffic
LX 2	SAL2	5	7	4250	43
LX 4	SAL2	5	6	1184	124
LX 21	SAL2	0	8	570	77
LX 55	SAL2	3	114	21491	70
LX 58	SAL2	0	5	13938	89
LX 69	SAL2	0	1	10946	91
LX 71	SAL2	0	5	985	93
LX 82	SAL2	4	40	2500	94
LX 136	SAL2	3	8	3525	94
LX 356	SAL2	2	8	2892	59
LX 425	SAL4	1	4	5425	37

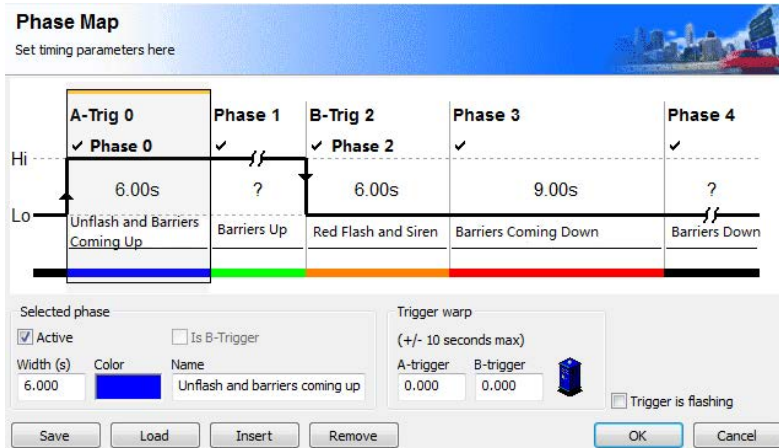
142 2.3. Road traffic measurement

143 This field observation campaign (over a period of 9 weeks) has been conducted by SNCF Réseau. The sensing
 144 equipment installed at each LX consists of two separate tubes one meter apart. As shown in Fig. 4, taking LX 58
 145 for example, these two tubes are placed perpendicularly to road traffic direction on the ground in front of the stop
 146 line, just before the LX barriers. They are connected to a counter that is a digital recording module, which, in turn, is
 147 linked to the light flashing signal to ensure synchronization with the signal cycle. The synchronization between the
 148 installed counting module and the LX control module is achieved by means of an optical sensing device installed in
 149 front of the LX flashing lights in both directions. Indeed, for safety reasons, SNCF Réseau requires that the counting
 150 module cannot interfere with the LX control module. In other words, one cannot get information about the LX status
 151 by connecting directly to the LX control module. In fact, French railways rely on a safety principle called GAMÉ
 152 (Globally at Least Equivalent) which ensures that each modification or replacement of any safety critical module must
 153 not degrade the global safety level of the system considered. Thanks to the installation set, the timestamp, vehicle
 154 direction, vehicle speed and phase, are recorded for each crossing vehicle individually.

155 The detailed traffic data collected through our installation are recorded in a specific database. As shown in Fig. 5a,
 156 a tool, called “MTExec”, is provided to visualize and handle the recorded data. Fig. 5b shows an example of road
 157 traffic data that are presented in the MTExec tool. As can be noted, the timestamp, vehicle direction, vehicle speed,
 158 vehicle type and phase information are recorded distinctly. Based on these records, the vehicle dynamics can be fully
 159 characterized.



Fig. 4. Labeled photographs of environment and devices at LX 58.



(a) The tool “MTExec” provided by MetroCount.

Reference ID	Year-Month-Day	Hour: Minute: second. Millisecond	Vehicle direction	Vehicle speed	Vehicle type
ED Ess Nb	AAAA-MM-JJ	hh:mm:ss.000	Dr	Speed	Vehicle
07 00000000	2015-02-19	18:30:23.825	BT	-----	Ph2 Red Flash and Siren
02 00000457	2015-02-19	18:30:26.018	NO	46,66	EU13-1 o o
02 0000045b	2015-02-19	18:30:26.970	S1	54,00	EU13-2 o o
02 00000460	2015-02-19	18:30:28.484	S1	57,05	EU13-1 o o

(b) Example of road traffic data recorded in the MTExec tool.

Fig. 5. The tool “MTExec” and an example of road traffic data recorded in the MTExec tool.

160 It should be noted that, in terms of ethics approval, the data collected during the experiments do not hold any
 161 personal or private aspects. Only the agreement to install the measurement devices is needed.

162 3. Behavioral analysis

163 The violation rate related to prolonged Ph4 duration, zigzag occurrence related to LX location and dispersive Ph4
 164 duration and finally, waiting queue and troop crossing phenomenon related to road traffic density and zigzag moment
 165 are discussed thoroughly. In fact, during the period of observation, the total crossings recorded at the 10 SAL2 LXs
 166 were 461596, where there were 5678 crossings happened during the closure cycle and 116 zigzags happened during
 167 Ph4. Namely, the general average violation rate is 1.230% and the general average zigzag rate is 0.025%.

168 3.1. The impact of prolonged Ph4 duration

169 The duration of Ph4 shows an important discrepancy from one closure cycle to another according to the actual
 170 speed of the train involved. In fact, the sensors responsible for announcing the train’s approach to the local LX control
 171 system are implemented in such a way as to ensure that the LX closure is triggered to ensure a minimum given delay
 172 prior to the train arrival at the intersection zone. Therefore, the location of the announcement sensors which detect the
 173 train arrival is set according to the speed limit of the track section. Thus, according to railway operation standards in
 174 France, the shortest time for train arriving at SAL2 intersection zone is 25 s following the starting of the closure cycle.
 175 Nevertheless, since different train categories, such as freight and passenger trains (with different speeds) may pass on
 176 the section where the LX is located, such a control scheme leads to inevitable long closure durations in the case of
 177 slow trains. Train-MV collisions are most likely to occur when vehicles start to cross the LX 5 s, at the earliest, before

178 trains arriving since after this delay they would not have enough time to leave the intersection zone before the train
 179 arrives. The durations of Ph2 “Red Flash and Siren” and Ph3 “Barriers Coming Down” can be considered as to be
 180 constant at each LX. Table 3 shows the duration of Ph2 and Ph3 at each LX. One can notice that the average duration
 181 of Ph2 and Ph3 altogether at these LXs is about 16 s. Therefore, we focus more particularly on the motorist violations
 182 after the first 4 s of Ph4 (25 s - 5 s = 20 s = 16 s + 4 s, where 16=length (Ph2) + length (Ph3)) in the following
 analysis.

Table 3. Duration of Ph2 and Ph3 at each LX.

LX	Ph2 duration	Ph3 duration
LX 2	8	12
LX 4	7	8
LX 21	7	8
LX 55	6	9
LX 58	8	7
LX 69	7	9
LX 71	8	9
LX 82	7	8
LX 136	9	8
LX 356	8	8
LX 425	7	9

183 In Ph4, violating vehicles skirt the half barriers to cross the LX, which represents a highly risky scenario. If one
 only considers the number of vehicle violations during Ph4, there is a possibility that, although the violation volume
 is high, the entire traffic volume is relatively high as well during the same period. Therefore, it is more appropriate to
 analyze the violation rate as expressed by Eq. (1).

$$Violation\ rate_{Ph4} = VV_M / (VD \times D_M) \quad (1)$$

184 where $Violation\ rate_{Ph4}$ represents the violation rate during Ph4, VV_M is the number of violating vehicles during a
 185 period D_M extending from Ph4 up to the violation moment, VD is the road traffic density during Ph4. It should be
 186 noted that we consider the value of the vehicle density during the one-hour time slot including the Ph4 considered to
 187 estimate the total number of vehicles waiting in front of the LX during D_M , since this number cannot be determined
 188 directly.

189 Table 4 shows the average road traffic density and the violation rate during the observation period at each LX,
 190 ranked according to the average road traffic density in descending order. Besides, the 11 LXs can be divided into
 191 3 groups, i.e., G1, G2 and G3, according to the average road traffic density. The average road traffic density of the
 192 LXs in G1, G2 and G3 is more than 0.1, from 0.01 to 0.1 and less than 0.01, respectively. We aim to determine the
 193 impact of Ph4 duration on “zigzag” motorist behavior. Generally, one would conjecture that a higher rate of “zigzag”
 194 violations would appear as the duration of Ph4 is extended. A thorough analysis is carried out to validate whether
 195 this general speculation, commonly assumed, is correct. Therefore, we adopt the average violation rate at those LXs
 196 having zigzags (cf. Table 4) to determine the overall trend of violation rate as time advances. The average violation
 197 rate is the average value of the samples of exact violation rate during each time interval involved, which can lessen the
 198 dispersion of exact violation rate values and make the trend clearer. In addition, as the number of zigzags recorded at
 199 night is very limited, we only consider those committed in the daytime (from 6:00 h to 21:00 h) exclusively.

200 Hence, by reporting the average ratio of the number of recorded zigzags during D_M , to the estimated number of
 201 vehicles during this period, and the duration of D_M , we determine the average violation rate distributed according to
 202 the time interval starting from Ph4 up to the violation moment. As shown in Fig. 6, the global trend of the average
 203 violation rate is drawn as the duration of the waiting time interval extends. The average violation rate is the average
 204 value of the samples of exact violation rate during each time interval involved, which can lessen the dispersion of
 205 exact violation rate values and make the trend clearer. **This curve attests that the violation rate during Ph4 decreases
 206 as Ph4 duration is prolonged (the longer the waiting time interval starting from Ph4 up to the violation moment, the**

Table 4. Information about average road traffic density and violation rate during the observation period at each LX.

Group	LX	Average road traffic density (/s)	Violation rate	Near to railway station
G1	LX 55	0.247	0.134	No
G1	LX 58	0.167	1.957	Yes
G1	LX 69	0.126	1.060	No
G2	LX 356	0.062	0.414	Yes
G2	LX 2	0.054	0.995	No
G2	LX 425	0.053	–	No
G2	LX 82	0.037	–	Yes
G2	LX 136	0.018	–	No
G2	LX 71	0.017	–	No
G3	LX 4	0.009	0.259	Yes
G3	LX 21	0.005	0.715	Yes

“–” means that no zigzags are observed at these LXs during the experiment period.

207 longer the Ph4 duration). This outcome demonstrates that the general speculation mentioned above that a higher rate
 208 of “zigzag” violations would appear as the duration of Ph4 is extended is not valid.

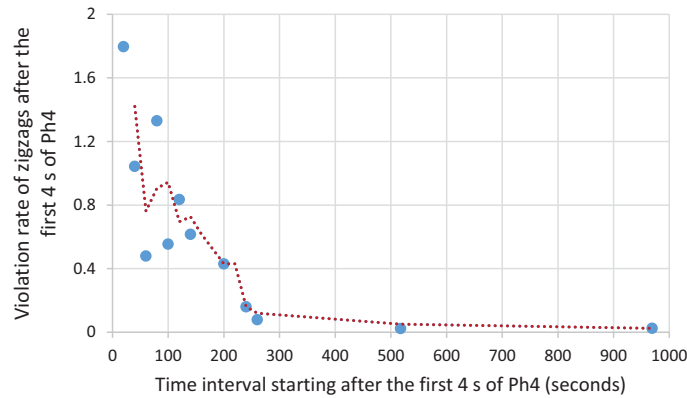
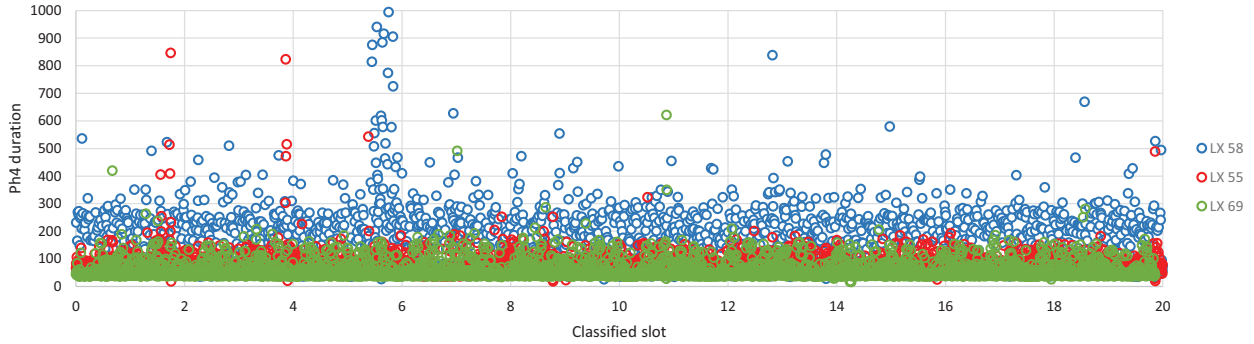


Fig. 6. The average violation rate of zigzags during Ph4 as Ph4 duration prolonged.

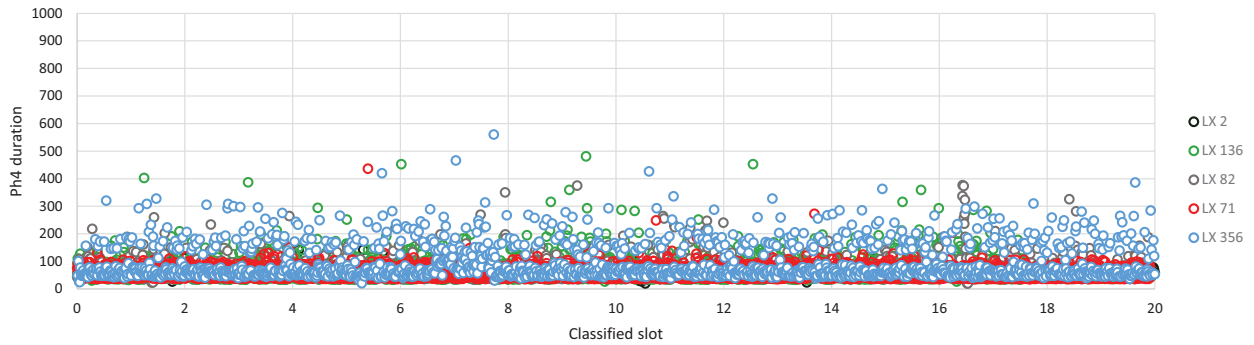
209 *3.2. The impact of LX location (near to railway station or not)*

210 In order to further analyze the factors influencing zigzag occurrence, we scrutinize the Ph4 duration at each LX
 211 during the observation period. As shown in Fig. 7, Ph4 duration distribution during the observation period is drawn
 212 with regard to 20 equal classified slots.

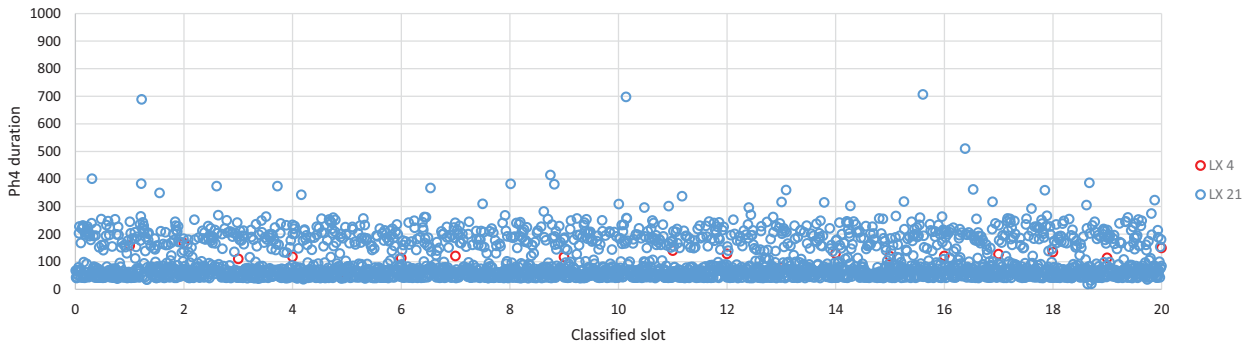
213 As for the LXs in G1 (cf. Fig. 7a), the Ph4 duration distribution at LX 58 is quite dispersive. On the contrary,
 214 the Ph4 duration distributions at LX 55 and LX 69 are more centralized. As for the LXs in G2 and G3 (cf. Fig. 7b
 215 and Fig. 7c), the Ph4 duration distributions at LX 356 and LX 21 are relatively dispersive, compared with other LXs
 216 in these two groups, respectively. Referring to Table 4, these LXs with dispersive Ph4 durations are quite close to
 217 railway stations. Thus, some trains go through slowly or just stop above the LX announcement sensors for shortly
 218 stopping in railway stations nearby. Indeed, in some cases, the sensors are installed around or in the railway stations.
 219 This fact explains the dispersive Ph4 duration distribution.



(a) Ph4 duration distribution of LXs in G1.



(b) Ph4 duration distribution of LXs in G2.



(c) Ph4 duration distribution of LXs in G3.

Fig. 7. Ph4 duration distribution with regard to classified slots.

220 These dispersion characteristics can be indicated more clearly through Fig. 8 which shows the cumulative distri-
 221 bution of Ph4 duration at the considered LXs. As shown in Fig. 8a, it is worth noticing that, for the LXs in G1, the
 222 cumulative distribution curves of Ph4 duration at LX 55 and LX 69 climb dramatically during the first 100 s of Ph4,
 223 then reach 1 after 200 s. That means Ph4 durations at LX 55 and LX 69 are quite centralized within the first 100 s of
 224 Ph4. It is because, to a large extent, no railway stations are near to these LXs. However, the cumulative distribution
 225 curve of Ph4 duration at LX 58 shows inflection points at 100 s and 280 s, which indicates that Ph4 durations at LX
 226 58 are relatively dispersive (from 100 s to 280 s). This is due to the fact that LX 58 is close to a railway station. More
 227 importantly, the violation rate at LX 58 is also the highest compared with that at LX 55 and LX 69.

228 As for the LXs in G2 and G3 (cf. Fig. 8b), LX 21 has the most dispersive Ph4 duration followed by LX 356 and
 229 LX 4 in sequence, according to their cumulative distribution curves of Ph4 duration. One can still note that these 3
 230 LXs are all close to railway stations. Moreover, LX 21 has the highest violation rate among these 3 LXs followed
 231 by LX 356 and LX 4 in sequence, accordingly. There is only one exception that LX 2 has a high violation rate but

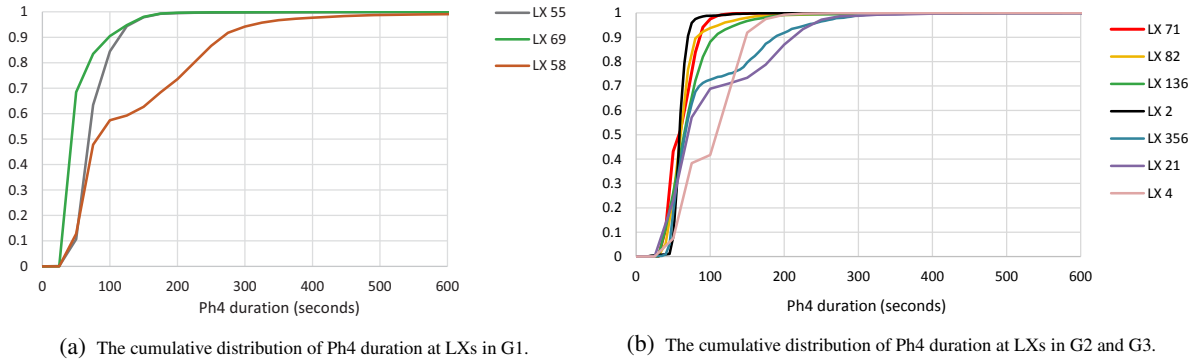


Fig. 8. The cumulative distribution of Ph4 duration.

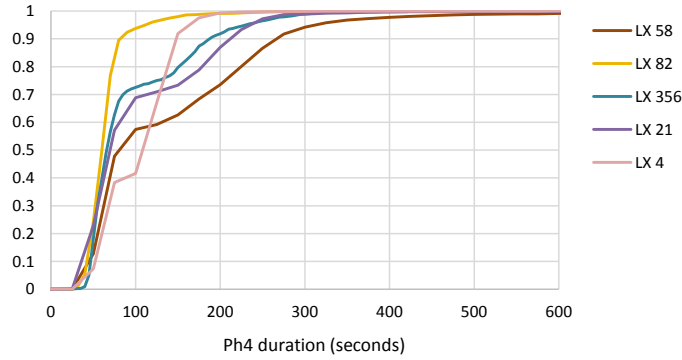


Fig. 9. The cumulative distribution of Ph4 duration at those LXs close to railway stations.

232 does not have dispersive Ph4 durations (while no railway station nearby). The surrounding of LX 2 will be further
 233 investigated in future works to explore other potential reasons for the high violation rate at this LX.

234 In order to thoroughly analyze the violation rate at each LX close to railway station, we extract the cumulative
 235 distribution (CD) curves of Ph4 duration at those LXs in Fig. 9. Moreover, the corresponding slope rates of CD
 236 between 0 s and 200 s of Ph4 are shown in table 5, which can reflect the dispersion of Ph4 duration at the five LXs.
 237 It is worth noticing that LX 58 has the most dispersive Ph4 duration (Slope rate = 0.0037) among these 5 LXs and
 238 LX 21 (Slope rate = 0.0044) takes the second place followed by LX 356 (Slope rate = 0.0046), LX 4 (Slope rate =
 239 0.0050) and LX 82 (Slope rate = 0.0050) in sequence. On the other hand, as shown in table 5, the violation rates of
 240 the 4 LXs (except LX 82) follow the same order, that is LX 58 has the highest violation rate and then LX 21 takes
 241 the second place followed by LX 356 and LX 4 in sequence. There are no zigzags or dispersive Ph4 duration found
 242 at LX 82. After checking the railway infrastructure characteristics of LX 82, we have noted that the distance between
 243 LX 82 and the railway station is about 1.3 km, however, the distance between the LX announcement sensor and the
 244 LX is only around 700 m. Therefore, as for the LX announcement sensor on the odd track, it has a distance of about 2
 245 km from the railway station; as for the LX announcement sensor on the even track, it still has a distance of about 600
 246 m from the railway station. The railway speed limit of the track section including LX 82 is 150 km/h and the railway
 247 station also has a certain length (250 – 500 m). Namely, trains would not stop above the LX announcement sensors or
 248 slow down when they pass the LX announcement sensors on both opposite directions. That is why the railway station
 249 nearby does not cause dispersive Ph4 durations at LX 82. In summary, we can infer that motorists are more likely to
 250 commit zigzag violations at the LXs located close to railway stations, i.e., with dispersive Ph4 durations. Besides, the
 251 more dispersive the Ph4 durations, the higher the violation rate of zigzags.

Table 5. The slope rates of CD between 0 s and 200 s of Ph4 at those LXs close to railway stations.

Group	LX	CD_200 s	Slope rate	Violation rate	Near to railway station
G1	LX 58	0.736	0.0037	1.957	Yes
G3	LX 21	0.870	0.0044	0.715	Yes
G2	LX 356	0.918	0.0046	0.414	Yes
G3	LX 4	0.990	0.0050	0.259	Yes
G2	LX 82	0.991	0.0050	–	Yes

“–” means that no zigzags are observed at the LX during the experiment period.

3.3. The impact of road traffic density

Waiting queues of vehicles in front of LXs can foster troop crossing phenomenon that represents a high-risk scenario. Logically, a waiting queue would be most likely to form since the beginning of Ph3 “Barriers Coming Down”². When vehicles arrive at an LX after a certain time since the beginning of Ph4, there are potentially some vehicles that have arrived earlier at the LX, which are waiting in front of the barriers. After a long time of waiting for the LX open cycle, some motorists may potentially lose their patience. Once the first vehicle in front of the LX commits zigzag crossing, the subsequent vehicles attempt to follow it closely. This scenario is called “troop crossing phenomenon”.

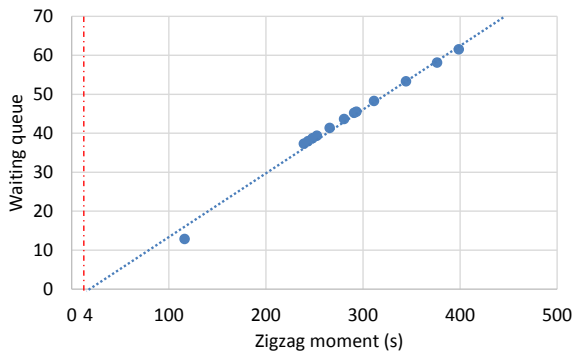
We suppose that road traffic density has an impact on the occurrence of waiting queue and troop crossing. Therefore, we chose LX 55, LX 69, LX 2, LX 4 and LX 21 which showed relatively more zigzag occurrences compared with the other LXs.

The length of a waiting queue is reflected by the number of waiting vehicles accumulated from the beginning of Ph3 up to the time moment of the zigzag occurring, which is expressed by Eq. (2).

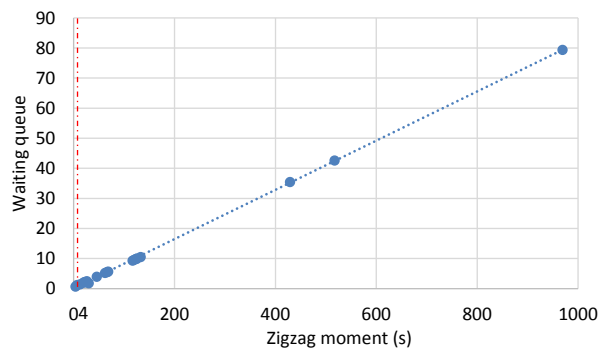
$$WQ = VD \times M \quad (2)$$

where WQ represents the length of waiting queue when the zigzag occurred; VD is the road traffic density during the closure cycle involved and M is the duration from the beginning of Ph3 up to the zigzag moment.

As shown in Fig. 10, waiting queues at these 5 LXs are drawn with regard to the time moment of zigzag occurring. The red dash line indicates the 4th second of Ph4. The blue dotted line is an auxiliary indicator to show the dispersion of the scatter points in the chart. It is worth noticing that for LX 55 (cf. Fig. 10a) and LX 69 (cf. Fig. 10b) which show quite high road traffic density, their waiting queue length is almost concentrated on the blue line and then the cluster of waiting queue length points of LX 2 (cf. Fig. 10c) is next, which shows a little bit of dispersion around the blue line. However, for LX 4 (cf. Fig. 10d) and LX 21 (cf. Fig. 10e) which show significantly low road traffic density, their waiting queue length points are extremely dispersive.

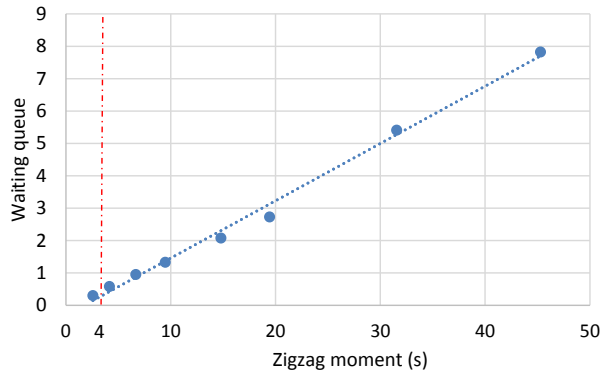


(a) The length of waiting queue at LX 55 in G1.

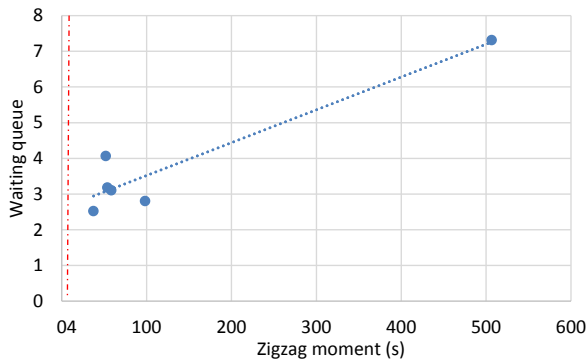


(b) The length of waiting queue at LX 69 in G1.

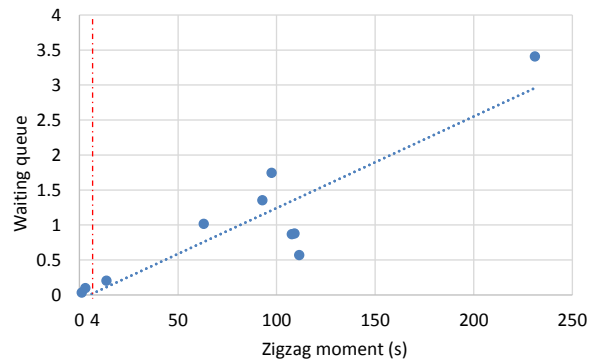
²according to statistics from SNCF Réseau



(c) The length of waiting queue at LX 2 in G2.



(d) The length of waiting queue at LX 4 in G3.



(e) The length of waiting queue at LX 21 in G3.

Fig. 10. The length of waiting queues at the 5 LXs.

272 One can point out that the troop crossing phenomenon is more noticeable at LX 55 and LX 69 than at the other
 273 LXs, due to the highest road traffic density at LX 55 and LX 69 among these LXs. Fig. 11 shows the time gap between
 274 two successive zigzagging vehicles during a same Ph4, respectively at LX 55 and LX 69. This observation is clearer in
 275 Fig. 11a, indeed, the first vehicle commits zigzag crossing after a long waiting time of 240 s, and then the successive
 276 vehicles closely follow it to cross LX 55 as well. The average time gap between these following vehicles are 14 s
 277 and the shortest time gap is only about 4 s. A similar phenomenon emerges at LX 69. There are 3 times of troop
 278 crossing just after the 1st, 6th and 10th vehicles commit zigzag crossing (cf. Fig. 11b). Moreover, the troop crossing
 279 phenomenon at LX 55 is more remarkable than that at LX 69 mainly because the road traffic density at LX 55 is
 280 higher than that at LX 69. Therefore, the aforementioned facts indicate that the higher the road traffic density at an
 281 LX, the more likely the waiting queues occur and the distribution of waiting queue length is more inclined to a linear
 282 distribution with regard to the duration from the beginning of Ph3 up to the zigzag moment. Furthermore, the troop
 283 crossing phenomenon is inclined to occur at LXs with significantly high road traffic density and the higher the road
 284 traffic density, the more distinct the troop crossing phenomenon.

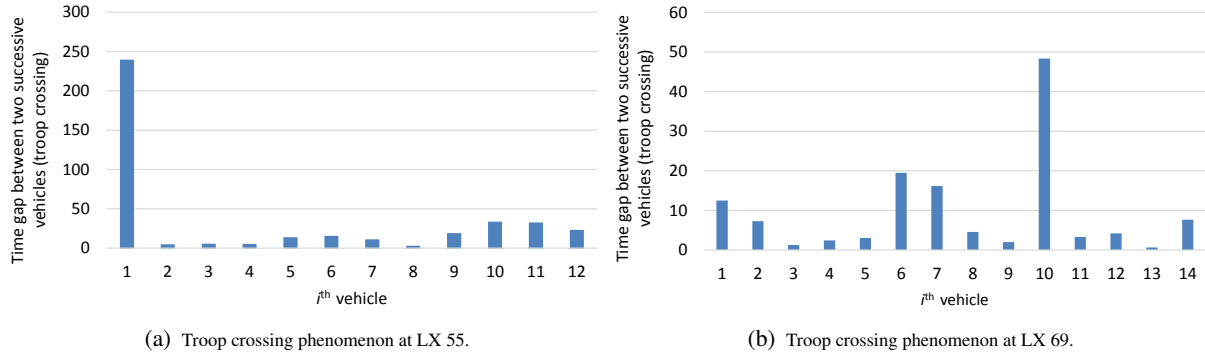


Fig. 11. Troop crossing phenomenon at LX 55 and LX 69.

4. Comparison of motorist responses to SAL2 and SAL4 LXs

LX 425, an SAL4 LX, is taken into account in our field observation in order to compare motorist responses to SAL2 and SAL4 LXs. For the purpose of making the results more trustworthy, LX 356 and LX 2, which have the approximate road traffic density to that of LX 425 (differences less than 0.01), are selected for the comparison analysis in this section. The number of crossing vehicles during the closure cycle is analyzed to explore the trend of vehicle volume during various phases of the closure cycle. Since no zigzags are observed during Ph4 at LX 425 and due to the significant discrepancy of Ph4 durations from one closure cycle to another at each LX, only crossing vehicles during Ph2 and Ph3 are considered.

Turning to the data as shown in Table 3, the duration of Ph2 and Ph3 varies among the different LXs. The first 4 s of Ph2 is a special stage. The reason is explained as follows: when motorists observe the flashing lights and hear sirens, then, if it is possible to stop before the LX, they should brake. The reaction time, namely, the operating delay of the action guided by sense organs will take almost 1 s, according to ergonomics studies (Green and Luce, 1967; Taylor et al., 1967; Welford, 1952). In addition, the longest braking coordination time of motorized vehicles does not exceed 0.8 s. Then, the braking delay itself would be 2 s on average. Therefore, a vehicle crossing during the first 4 s of Ph2 will not be regarded as a violation in our study, only a vehicle crossing subsequently to the first 4 s of Ph2 should be considered as a violation, which may correspond to either an intentional violation or the inability of the motorist to stop his vehicle safely due to a high speed.

Therefore, as for the subsequent closure period after the first 4 s of Ph2, instead of considering the successive seconds in each phase (Ph2 and Ph3), we divide Ph2 (resp. Ph3) into 2 (resp. 5) equal time intervals at each LX and then, we can make the analysis in terms of phase halves: 2nd and 3rd (resp. phase quintiles: 1st, 2nd, 3rd, 4th and 5th) in such a way as to be able to compare the road traffic volume in each time interval recorded at these LXs.

As shown in Fig. 12a, the number of vehicles crossing at the beginning of Ph2 at LX 425 is much bigger than that at LX 2 and LX 356. However, it decreases dramatically during the 2nd stage of Ph2. The number of vehicles crossing in the 3rd phase at LX 425 drops to the lowest among the 3 LXs. Moreover, one can notice that the scale of decrease at LX 425 is the biggest compared with the other SAL2 LXs.

Fig. 12b shows the normalized crossing ratio of vehicles during each phase of closure cycle at these 3 LXs. The normalized crossing ratio can eliminate the disparity of various road traffic densities at different LXs, which is expressed by Eq. (3).

$$NC = Nb_V / Nb_{VT} \quad (3)$$

where NC represents the normalized crossing ratio during a time interval of the closure cycle at an LX; Nb_V is the number of crossing vehicles during the time interval considered, and Nb_{VT} is the total number of vehicles during the whole observation period at the LX considered.

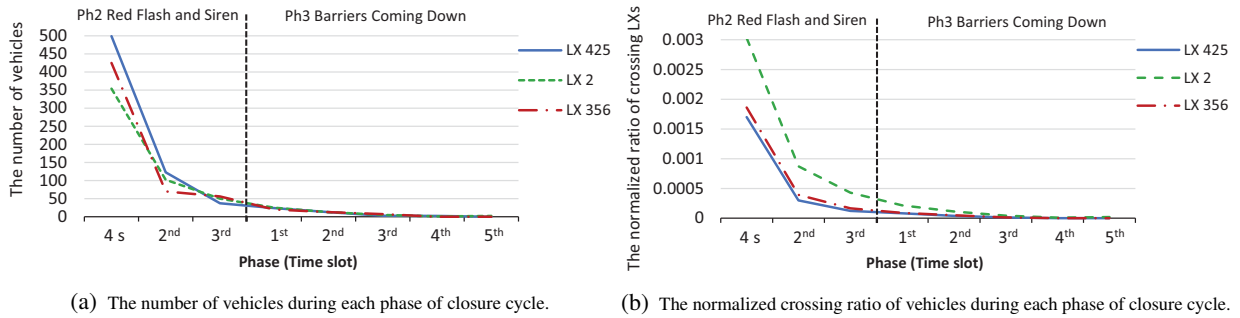


Fig. 12. Comparison of the number and normalized crossing ratio of vehicles at SAL2 and SAL4 LXs.

313 According to Fig. 12b, obviously, the normalized crossing ratio during the closure cycle at LX 425 is the lowest
 314 among the 3 LXs. This indicates that motorists are more cautious when encountering closure cycles at an SAL4 LX
 315 and they scarcely cross an SAL4 LX during closure cycles. In fact, four half barriers of an SAL4 LX act as physical
 316 separators in four quadrants to effectively prevent zigzag crossing from both opposite directions. Another reason for
 317 motorists scarcely crossing an SAL4 LX is that, motorists know clearly that if they are blocked in the intersection
 318 zone, they will not be able to escape from the closed SAL4 LX. In spite of these facts, we cannot arbitrarily state that
 319 SAL4 LXs are much safer than SAL2 LXs since the above new hazard of being blocked in the intersection zone is
 320 introduced by using SAL4 LXs. Therefore, further before/after measurements are still needed to assess the efficiency
 321 of SAL4 LXs.

322 5. Discussion

323 Based on the analysis of zigzag violations during Ph4 in section 3, we can summarize that the duration of Ph4,
 324 the existence of a nearby railway station and the road traffic density have significant impact on zigzag violations. It
 325 is recalled that during a prolonged Ph4, the longer the waiting time for vehicles, the lower the violation rate. This
 326 conclusion contradicts the general conjecture commonly assumed. Moreover, in terms of the global risk at a given
 327 LX, motorists are more likely to commit zigzag violations at the LX located close to a railway station. Indeed, the
 328 existence of a nearby railway station can foster the dispersion of Ph4 durations and, as illustrated earlier in the paper,
 329 the more dispersive the Ph4 durations at an LX, the higher the risk of zigzag violations at this LX.

330 Although the violation rate decreases as the time interval starting after the first 4 of Ph4 up to the violation moment
 331 prolongs, one cannot ignore the fact that the train-activated LX control system is susceptible to losing motorists' trust
 332 primarily due to variations in terms of Ph4 duration. Namely, it is possible for motorists to misunderstand the LX
 333 control system and commit zigzags when they have to wait for a long time without observing any train approaching,
 334 due to very slow train speed (e.g., they would think there is a failure in the LX control system, but it works well in
 335 fact). Reasonable and consistent warning time design is crucial to avoid zigzag violations during a long Ph4 (Ghazel,
 336 2017). According to a report of FHWA (1991), motorists would accept a shorter clearance time at flashing lights
 337 and attempt to skirt barriers when the warning time exceeds 40-50 s. More importantly, second train coming active
 338 warning signs could help mitigate zigzag violations when Ph4 is prolonged by successive trains approaching. A short
 339 time gap between two successive approaching trains would cause a persistent closure of the LX after the first train
 340 has passed, since there is not enough time for LX control system to finish the activity of barriers uplifting before
 341 the second train arriving. Correspondingly, the Ph4 duration is prolonged by LX keeping closed. Such a kind of
 342 warning signs can avoid motorists losing patience when confronted with long LX closure cycles caused by successive
 343 approaching trains.

344 As for the impact of road traffic density, the higher the road traffic density at an LX, the more likely the wait-
 345 ing queue formation, hence, the troop crossing phenomenon is most likely to be boosted at LXs with significantly
 346 high road traffic density. In order to reduce the collision risk fostered by long waiting queues and troop crossing
 347 phenomenon, the installation of median separators and transforming SAL2 LXs into SAL4 LXs (Four-half barrier
 348 systems) (Ghazel and El-Koursi, 2014) or two-full barrier LXs (SAL2F) are two further solutions.

349 In fact, a median separator (used with an additional “U-Turn” or “Z-Turn” prohibition sign) in front of an SAL2
 350 LX acts as a physical separator between opposing lanes of road traffic. Such a device effectively prevents zigzag
 351 violations with a visual cue intended to impede crossing to the opposing traffic lane. As shown in Table 6, the average
 352 length of waiting queue at the 4th s of Ph4 at an SAL2 LX can be a preliminary guidance for designing the minimum
 353 length of a median separator at different LXs (the length of normal-size vehicle is considered: 3.8 – 4.3 m). However,
 354 before/after measurements are still needed to assess the efficiency of such solutions.

Table 6. The length of waiting queue (the number of waiting vehicles) at the 4th s of Ph4 at each SAL2 LX.

LX	Waiting queue length at the 4 th s of Ph4
LX 55	4.942
LX 58	3.334
LX 69	2.524
LX 356	1.242
LX 2	1.080
LX 82	0.732
LX 136	0.353
LX 71	0.347
LX 4	0.188
LX 21	0.105

355 According to the analysis in section 4, the SAL4 (or SAL2F) system is a significantly effective means to avoid
 356 zigzag violations of motorists. However, it is more costly than the other aforementioned technical solutions. Moreover,
 357 as mentioned in section 4, a new hazard will be introduced while using this device, that is vehicles could be trapped
 358 on the LX intersection zone in case of traffic jam when the four half (or two full) barriers come down. One solution
 359 would be to install additional obstacle detectors in order to reopen the exit barriers and order the train to brake. Such a
 360 protection system has been tested in the U.S. (Chadwick et al., 2014). Obstacle detectors should be intelligent enough
 361 to identify the difference between a car moving slowly and one that is stationary (Silmon and Roberts, 2010). Any
 362 stationary vehicle staying for a long enough time on the LX intersection track can be assumed to be in trouble. In
 363 addition, according to the return on experience related to various LX safety strategies implemented in some countries
 364 (Anandarao and Martland, 1998; ATC, 2010; Davey et al., 2005; Taylor, 2008; Wullems, 2011), a combination of
 365 education (aimed at changing road user behavior), enforcement and engineering measures is believed to lead to high
 366 safety level at LXs.

367 6. Conclusions

368 The present study offers a new perspective on motorist behavior during the closure cycles of LXs. **The results**
 369 **obtained enable us to draw general conclusions and make recommendations for improving the whole LX safety.** Ten
 370 SAL2 LXs and one SAL4 LX were selected for field measurement and the data regarding road traffic and railway
 371 traffic at these 11 LXs were collected during 9 weeks, then analyzed to derive the main features to characterize the
 372 behavior of motorists during LX closure cycles. The experimental equipment used in this study is at the same time
 373 reliable, practical, easy to install and economical. In summary, our ad-hoc installation is more convenient for our
 374 experiment, compared with cameras, automatic video surveillance or sophisticated video recording.

375 Although many existing studies have dealt with motorist behavior at LXs, such studies have not considered the
 376 separate phases of the LX closure cycle, particularly Ph4 “Barriers Down”. Some recent studies adopted qualitative
 377 approaches for understanding motorist behavior during the entire cycle of LX control, including when the LX is open
 378 to road traffic. The main contributions of our study are that: thorough analyses on the impact of influential factors, i.e.,
 379 the duration of Ph4, the LX location (railway station nearby or not) and the road traffic density, on zigzag violations
 380 during Ph4 are carried out. Namely, the violation rate, the waiting queue and the troop crossing phenomenon during
 381 Ph4 are quantitatively and finely analyzed with regard to the above influential factors. **In fact, according to the field**
 382 **measurements we performed, the variability of Ph4 duration has a significant impact on the rate of violations. In the**
 383 **present study, such a variability is mainly due to the fact that the involved LXs are located close to a railway station.**

384 However, in general, stakeholders also need to pay attention to other operating conditions that may cause discrepancy
385 in terms of LX closure duration, such as the mixture of different train types (passenger, freight, etc.), train speeds,
386 etc. Moreover, the distinction of motorist responses to SAL2 and SAL4 LXs is scrutinized to determine the efficiency
387 of SAL4 LXs in terms of preventing zigzag violations. Thus, corresponding targeted technical suggestions can be
388 recommended according to the specific analysis results pertaining to Ph4, so as to improve LX safety. Such thorough
389 and novel analyses are rarely presented in existing works.

390 In summary, the aforementioned contributions of this study respond to the key knowledge gap of risky motorist
391 behavior at LXs with regard to separate phases during the LX closure cycle. Moreover, such analyses pave the way for
392 identifying practical design measures and improvement recommendations to prevent LX accidents. In future works,
393 we will investigate more influential factors and develop Bayesian risk models to quantify the causal relationships
394 between these influential factors and the LX safety level.

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399 works (IFSTTAR).

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