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Driver Response to Left Incurring Path Intrusions at Sign-Controlled Intersections

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Abstract

Straight intersecting path or "side" collisions account for 12% of all motor vehicle crashes and 24% of fatalities. While previous research has examined driver responses to hazards striking from the right (near side), no research has quantified driver responses to hazards striking from the left (far side) of an intersection. The purpose of this study was to measure driver response time (DRT) and response choice for two versions of this scenario. In one condition, the hazard vehicle was initially stopped at the intersection before accelerating into the path of the participant driver. In the other condition, the hazard vehicle approached and entered the intersection while moving at a constant speed of 50 km/h.

Testing was conducted using an Oktal full car driving simulator. 107 licenced drivers (N_{Female} = 57, N_{Male} = 50) completed a short familiarization drive followed by the experimental drive in which they encountered both the initially stopped and moving conditions of the straight path hazard, in a counterbalanced order. DRT was defined as the time between when the hazard vehicle crossed a trigger located two meters from the curb until the driver reacted either by touching the brake pedal or swerving.

The average DRT was 0.08 seconds in the initially moving hazard condition and 2.39 seconds in the stopped condition. In the moving condition, many participants were able to anticipate the hazard before it crossed the defined starting location. To account for the more obvious hazard precursor in the moving condition, a geographic location further from the intersection is proposed as the starting location for measuring DRT in gradually developing hazard scenarios. There was also a significant difference in DRT ($F(2) = 5.55$, $p = 0.005$) based on the avoidance action taken. Drivers who braked and steered had the longest response times and they were also more likely to get into a collision.

Introduction

Collisions at intersections represent a disproportionate number of traffic accident injuries and fatalities. Of these fatalities, about 75% occur at intersections which are not controlled by traffic lights but are instead uncontrolled or controlled using stop and yield signs [1]. Collisions at unsignalized intersections are often fatal because they are more likely to be intersecting-path or side orientations where the front of one vehicle contacts the side of another [2]. In contrast, rear-end collisions are more common at signalized intersections [2]. The risk of injury or fatality is greater during a side impact than during a frontal or rear collision of equivalent severity because there is relatively little space between the outside of the vehicle and the occupant [3]. Common safety features such as airbags and seatbelts are also less effective in side-impact collisions [3].

Failure to appropriately yield the right-of-way is often the cause of fatal collisions at unsignalized intersections. This includes scenarios where a driver runs a stop sign or fails to observe a stop or yield sign entirely. In the process of investigating such scenarios, collision reconstructionists are often asked to determine whether the collision was avoidable by the through driver or a typical driver in their position. The investigator relies on the most applicable literature to estimate a range of typical driver response times (DRTs) which is defined as the time interval between the onset of a hazard and the first measurable response to the hazard vehicle. This differs from perception-response time which is defined in SAE Standard J2944 as the time interval between when the through driver can physically sense an initiating event and the first braking response [4]. Note that there are many terms (i.e., perception-response time, brake-response time, perception-reaction time, etc.) used in the literature. In the current study, DRT is used to refer to all possible response choices including braking, swerving, or a combination of these responses.

To determine a reasonable DRT, investigators interpret and compare the research methodology to the circumstances encountered by the incident through driver. In the case of drivers responding to path intrusion hazards at unsignalized intersections, there is limited research that quantifies DRT. Moreover, while previous research has examined driver responses to hazards striking from the right (near side), few studies have quantified driver responses to hazards striking from the left (far side) of an intersection. Therefore, the purpose of this study was to examine the DRT of drivers confronted with a left-incurring hazard at an unsignalized intersection. The results of this research provide DRT values that are applicable to accident reconstructionists and collision investigators when determining the avoidance potential for a path intrusion collision. The research can also be considered by roadway designers to ensure that there is sufficient visibility for drivers to perceive potential hazards such as left-incurring vehicles.

Methods

Simulator

The experiment was conducted in the Driving in Virtual Environments (DRiVE) Laboratory at the University of Guelph using a full vehicle driving simulator. The Oktal© simulator is comprised of an instrumented Pontiac G6, six projectors, and wrap-around screens, as seen in Figure 1. The high-definition projectors and screens provide the driver with an immersive 300-degree field of view. The steering wheel was equipped with force feedback, and vibration was created in the car body through subwoofer speakers and two ButtKicker mini LFE units mounted to the vehicle frame. The simulation engine software used was SCANeRstudio v.1.6 (Oktal Sydac, Paris). The simulator collected data on the position and speed of the vehicle, as well as the driver's brake and accelerator pedal application.

Virtual Environment

The roadway was modelled after two intersections in Mississauga, Ontario: Bristol Road and Kinglet Avenue, and Matheson Boulevard and McLaughlin Road. Both are busy suburban intersections located in a mixed commercial and residential area. The total route was a combination of 15 intersections joined by stretches of road for a total distance of eight kilometres. The road included two traffic lanes, one bicycle lane in each direction, and a fifth lane in the middle that was not used for driving. Each traffic lane was 3.5 meters wide, while the bicycle lanes were 1.5 meters wide. The sidewalks were 2.3 meters wide. Roadway scenery, including trees, buildings, and sidewalks are also modelled after suburban Mississauga, however, there were no sightline obstructions between the through driver and any of the hazard vehicles. A moderate level of vehicle, cyclists and pedestrian traffic was present on the road in every scenario. There was no vehicle traffic next to or in front of the through driver. The speed limit was 60 kilometres per hour (km/h), which was indicated by signs lining the route. Lastly, road conditions were dry and skies were clear.

FIGURE 1 University of Guelph Driving Research in Virtual Environments (DRiVE) Lab full car Oktal driving simulator.

Hazard Scenarios

Two left incurring vehicle hazard scenarios were presented once to each participant during the experiment. In both hazard scenarios, the intersection was controlled by a two-way stop and the participant drivers had the right-of-way. They were instructed to travel in the curb lane and to observe the 60 km/h posted speed limit.

The hazard scenarios were differentiated by the pre-impact motion of the hazard vehicles. In one hazard scenario, the left incurring vehicle was stopped (LS) past the stop bar and two meters from the near curb of the intersection before accelerating into the path of the through driver. In the other hazard scenario, the left incurring vehicle approached at a constant speed then entered the intersection without stopping at the stop sign (LNS). The time-to-impact (the total time available for the participant driver to perceive, respond, and attempt to avoid the collision) and the eccentricity (the angle between the participant driver and the hazard vehicle) are discussed for each scenario below.

This work was part of a larger study where a total of four hazard scenarios were presented. The hazard scenarios were presented in a counterbalanced order such that every test participant experienced either the LS or LNS hazard scenario early in the study and encountered each hazard scenario only once. The results of a post hoc analysis found that the DRT values were not significantly different between the first and second ($p = 0.45$) hazard scenario presentations. The same analysis showed a significant difference between the first and third ($p = 0.022$) presentations. This indicated that participants were more attentive to the hazard scenarios after the second presentation, and accordingly only the first two presentations were included in the data analysis.

Left Incurring Hazard, Stopped (LS) In the initially stopped scenario, as the participant travelled straight in the curb lane of the main road, the hazard vehicle entered the participant's path from the left side (i.e. far-side) of the intersection. When the hazard vehicle came into view of the driver, it was stopped with its front end two meters behind the curb (Figure 2). As the participant proceeded through the intersection, the hazard vehicle accelerated into their path using a

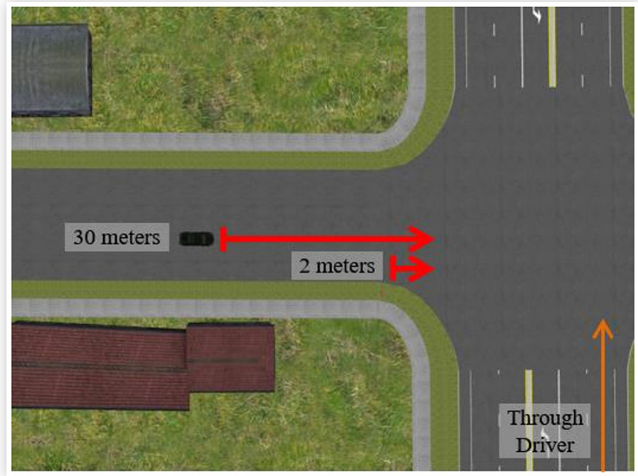
FIGURE 2 Left incurring hazard stopped two meters from the intersection.

2-phase acceleration (at a rate of 0.07 g for the first 0.9 seconds, then at a rate of 0.25 g). If the participant did not react, they collided with the right rear wheel of the hazard (Figure 3). The time-to-impact for this scenario was 4.5 seconds. Time-to-impact was measured from the moment the front of the left incurring vehicle began to accelerate and ended when the through vehicle would have struck the right rear wheel of the incurring vehicle if the through driver did not respond. The eccentricity varied between 10-13 degrees at the time the hazard vehicle began to accelerate. The variation in eccentricity is due to the slight variation in speed of the through driver as they approached the intersection.

Left Incurring Hazard, Not Stopped (LNS) In the LNS scenario, as the participant travelled straight in the curb lane of the main road, the hazard vehicle entered the participant's path from the left side (i.e. far-side) of the intersection. The hazard vehicle travelled in the curb lane at a constant speed of 50 km/h and was already travelling at that speed as it came into view of the participant driver. If the participant did not react, they would have collided with the right rear wheel of the hazard (Figure 3).

FIGURE 3 Position of the through and left incurring hazard vehicles if a collision occurred.

FIGURE 4 Left incurring, not stopped hazard vehicle at 30 meters from the intersection, with position 2 meters from the intersection identified



For the LNS hazard, DRT was analyzed using two different hazard onset times: when the through driver first had a straight line of view to the hazard vehicle (30 meters from the intersection), and when the hazard vehicle becomes an immediate hazard (2 meters from the intersection). Both positions are illustrated in Figure 4. At 30 meters from the intersection, the front of the hazard vehicle is visible to the through driver from behind a building. At this location, the time-to-impact is 3.7 seconds. At 2 meters from the intersection, the hazard vehicle is at the same location as the LS hazard when it begins to accelerate with a time-to-impact of 1.7 seconds. Time-to-impact was measured from the moment the front of the left incurring vehicle began to accelerate and ended when the through vehicle would have struck the right rear wheel of the incurring vehicle if the through driver did not respond. For both onset distances, the eccentricity was high, between 32 and 38 degrees.

Participants

107 participants, 57 female (Mean Age: 20.5 years, SD: 5.7 years) and 50 male (Mean Age: 21.3 years, SD: 6.7 years) completed the experiment. All participants held at least a G2 Ontario drivers' licence or out of province equivalent.

Measures

The response times measured in this study were defined according to the SAE International J2944 [4] standards as follows:

Driver Reaction Time (DRT) is the time interval, measured in seconds, from the onset of the hazard to the first observable response to the hazard, as outlined in Table 1.

Braking Response Time (BRT) is the time interval between hazard onset and the driver's first contact with the brake pedal.

TABLE 1 Descriptions of hazard onset and first observable response.

Hazard	Hazard Onset	First Observable Response
Left incurring, stopped (LS)	Hazard vehicle begins to accelerate into the intersection, 2 meters from the intersection.	Participant driver's first contact with the brake pedal or change in steering of at least 6 degrees.
Left incurring, not stopped (LNS)	Hazard vehicle becomes visible to the participant driver, 30 meters from the intersection	
	Hazard vehicle becomes an immediate hazard, 2 meters from the intersection	

Steering Response Time (SRT) is the time interval between hazard onset and the first movement of the steering wheel in response to the hazard. SRT was only recorded if the steering response threshold of ±6 degrees was met or exceeded.

Brake and Steer Response time (BRST) is the time interval between hazard onset and the first response by the driver in the case that they braked and swerved in response to the hazard. The first response by the driver was either first contact with the brake pedal or a steering response of at least ±6 degrees.

Statistical Analysis

Statistical analyses were conducted using R (R Foundation for Statistical Computing, Version 3.5.1, Vienna, Austria). First, the means, standard deviations, and 15th, 50th, and 85th percentile DRT scores for both scenarios were calculated. Mean DRTs were compared between LS and LNS using analysis of variance procedures ($\alpha \leq 0.05$). When appropriate, differences between means were assessed using a Tukey's HSD post hoc analysis. The effect of response type (brake, steer, or both) on DRT was similarly evaluated. Lastly, collision rates between the LS and LNS scenarios and the response types were compared using a Chi-square analysis ($\alpha \leq 0.05$).

Results

Descriptive statistics for both hazard scenarios by response type are reported in Table 2. DRTs were significantly longer in the LS scenario than in the LNS scenario at both the 2 meter ($F(1) = 221.9$, $p < 0.001$) and 30 meter ($F(1) = 4.02$, $p = 0.0479$) hazard onset locations. At 2 meters from the intersection, more than 30% of drivers responding to the LNS scenario began to respond before the hazard vehicle crossed into the intersection. These responses were reported as "negative" DRTs and are included in the results. At 30 meters from the intersection, the hazard vehicle was just visible to the through drivers from behind a building. None of the drivers anticipated the hazard from this onset location, and the average response time was 2.08 seconds.

There was a significant effect of response type (braking, steering, or both) on DRT in both the LS ($F(2) = 5.80$, $p = 0.006$) and LNS ($F(2) = 5.99$, $p = 0.005$) scenarios. Braking was the fastest response in both scenarios at 0.6 seconds faster than the average steering response. Figure 5 illustrates the DRTs for all three response types.

There was also a significant difference in the frequency of response types between the scenarios ($\chi^2(3) = 7.82$, $p = 0.05$). Specifically, more through drivers did not respond to the hazard in the LNS scenario than in the LS scenario, while more drivers braked and steered to avoid the hazard vehicle in the LS scenario. Braking was the most common response in both hazard scenarios. The response rates are displayed in Figure 6.

There was no significant difference in collision rates between the two hazard scenarios. In the LS scenario, 55% of the through drivers collided with the hazard, while 51% of the through drivers collided in the LNS scenario. There was a significant effect of response type on the collision rate ($\chi^2(3) = 25.33$, $p < 0.001$). In both the LS and LNS scenarios, the collision rate was lowest for braking responses. Collision rates for both scenarios by response type are displayed in Figure 7.

Discussion

To conduct an avoidance analysis, collision reconstructionists must apply experimentally collected DRTs from studies where

TABLE 2 Descriptive statistics for the LS and LNS scenarios, by response type. For the LNS scenario, values for 30 meters from the intersection are displayed first, followed by values for 2 meters from the intersection inside the brackets.

					Percentile (s)		
Condition	**Response**	**N**	**Mean (s)**	**SD**	**15**	**50**	**85**
Left incurring, stopped	BRT	27	2.09	0.70	1.29	2.06	2.86
	SRT	10	2.95	1.30	2.14	2.69	4.04
	BSRT	14	2.59	0.61	2.30	2.65	2.94
	All	54[1]	2.39	0.79	1.75	2.34	2.93
Left incurring, not stopped 30 meters (2 meters)	BRT	25	1.88 (-0.12)	0.57	1.29 (-0.71)	2.05 (0.05)	2.37 (0.37)
	SRT	11	2.22 (0.22)	0.83	1.81 (-0.19)	2.22 (0.22)	2.47 (0.47)
	BSRT	6	2.80 (0.8)	0.50	2.45 (0.46)	2.94 (0.95)	3.17 (1.17)
	All	53[2]	2.08 (0.08)	0.67	1.43 (-0.57)	2.22 (0.22)	2.71(0.71)

[1] There were 3 participants who did not respond to the left-incurring, stopped hazard

[2] There were 11 participants who did not respond to the left-incurring, not stopped hazard

FIGURE 5 Driver response times by response type for the left incurring stopped and not stopped scenarios.

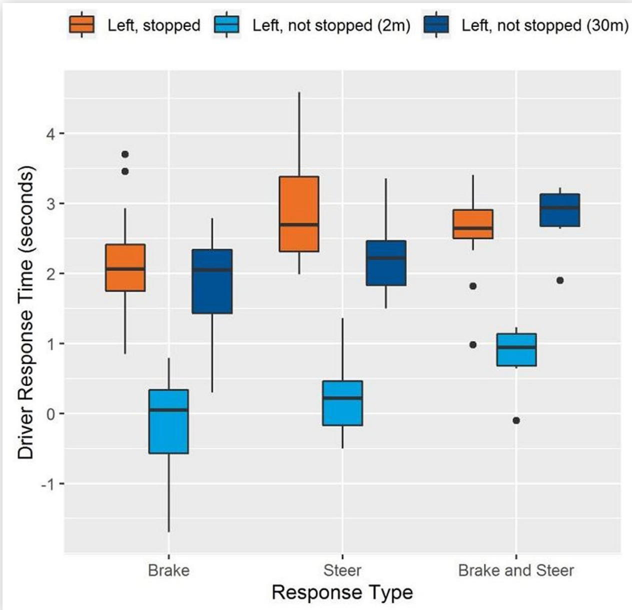
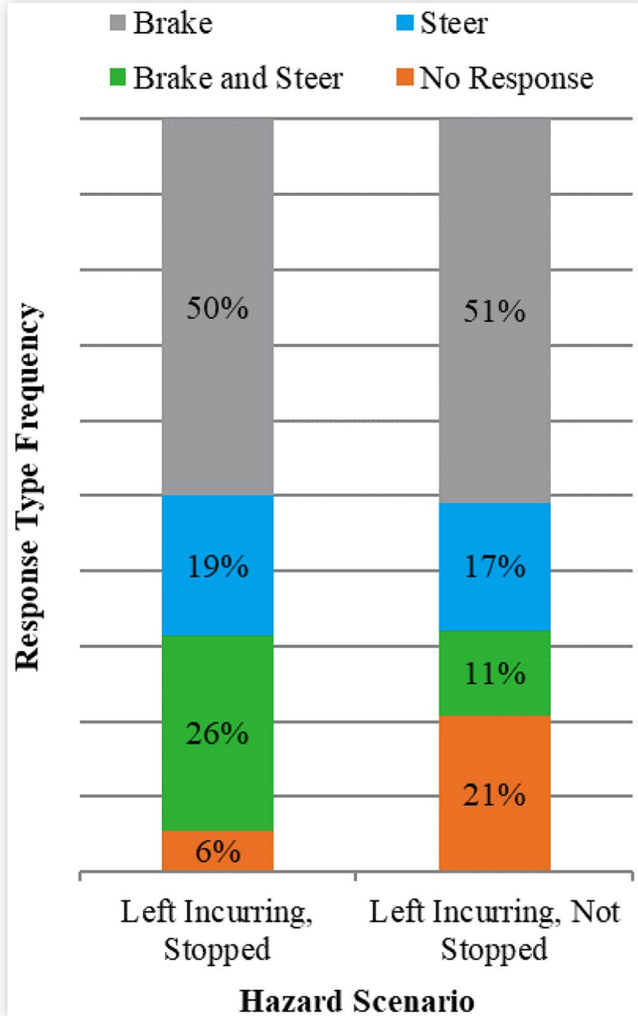


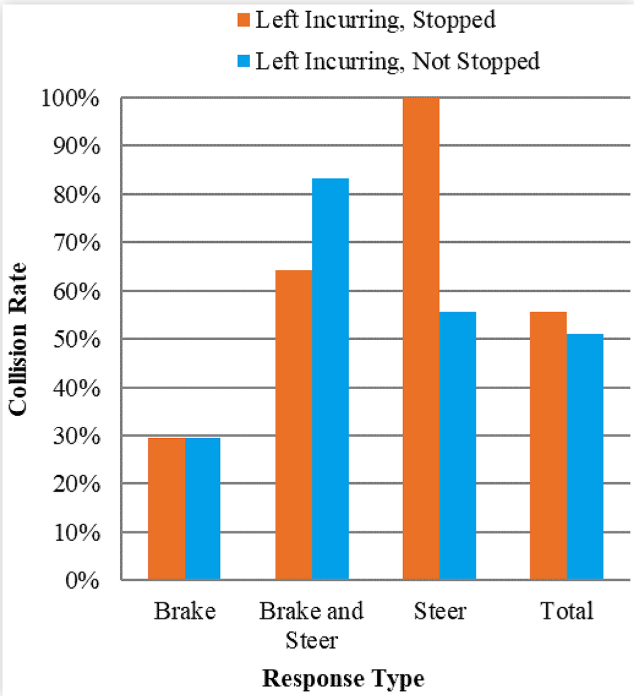
FIGURE 6 Response type rates for both left incurring hazard scenarios.



the scenario best matches the collision under investigation. For path intrusion type hazards, one way to ensure that hazard onset is the same for both the incident and the experimental hazard is to start DRT at the same geographic location. A typical hazard onset location is approximately 2 meters from the intersection [5]. In both left incursion hazard scenarios, this location is between the stop sign and intersection. At this location, the oncoming vehicle becomes an immediate hazard by entering the path of the through driver who must perceive and respond to the path intrusion to avoid a collision. In the LNS scenario, the hazard vehicle approaches the intersection at a constant speed then crosses into the intersection about 2 seconds later. Based on the hazard avoidance framework proposed by Pradhan and Crundall [6], the LNS scenario is a gradually developing hazard. As the left incurring vehicle gets closer to a collision with the through driver, there is increasing evidence of an imminent collision. Experienced drivers are better than newer drivers at recognizing this evidence as a precursor to a hazard requiring a response to successfully avoid a collision [6]. While the hazard precursor (the hazard vehicle approaching the intersection) is different than the hazard itself (the hazard vehicle in the intersection), safe drivers will detect and prepare to respond even before the precursor becomes an immediate hazard.

To discern if the through drivers were responding to the hazard precursor or responding only when the hazard had already entered the intersection, DRT in the current study was calculated from both 2 meters from the intersection and 30 meters from the intersection (the location of the through drivers first straight line of view to the hazard vehicle). The average DRT in the LNS scenario was 0.08 seconds when hazard onset was 2 meters from the intersection. The average driver responded at almost the same time that the hazard vehicle entered the intersection. Specifically, before the hazard vehicle had entered the intersection, over 30% of through drivers had already responded by braking or steering. It follows that the participant drivers were undoubtedly alerted by and responding to the hazard precursor in the LNS scenario. In contrast, when hazard onset is abrupt, a through driver cannot predict that the stopped vehicle would enter their path until it begins to accelerate from its stopped position. In the LS scenario, there was no precursor to alert the through drivers of an imminent hazard, therefore, hazard onset occurred as the left incurring vehicle began to accelerate from its stopped position. The average DRT was 2.39 seconds in the LS scenario; 0.31 seconds slower than in the LNS scenario with hazard onset at 30 meters from the intersection. This difference was consistent with a review of real-world collisions which found that DRT decreased by about 0.2 seconds when a path intrusion hazard entered the through driver's path without stopping [7]. A similar study involving through driver responses to a left turning vehicle hazard found a 0.36 seconds difference between left turning stopped and not stopped scenarios [8]. It may therefore be useful to calculate DRT for gradually developing hazards not only from the stop bar or 2 meters from the intersection, but also from the distance at which the hazard vehicle is first visible to the

FIGURE 7 Collision rates for the left incurring hazard scenarios.



through driver. Future research should investigate which characteristics of a hazardous scenario (speed, distance from the intersection, acceleration rate etc.) are most influential on the transition from precursor to hazard requiring an avoidance response.

In the current study, braking was the fastest and most common response type in both hazard scenarios. Typically, drivers will steer away from a hazard to create more space [9], however, in a left incurring vehicle hazard scenario lateral movement away from the oncoming hazard would cause the through driver to exit the roadway. The risk of a collision with the hazard vehicle was also significantly increased if the through driver steered rather than braked. In the LS scenario, 100% of the through drivers who responded by steering ended up colliding with the hazard vehicle. A comparable left incursion hazard scenario conducted by Perron et al. examined driver responses to an initially stopped vehicle with a time to collision of 3.25 seconds [10]. Responses to this left incursion hazard had a high average collision rate of 60% that was driven by steering responses to the hazard. This finding was consistent with the high collision rates for steering responses in both the LS and LNS scenarios. The data in the current study support Perron et al.'s conclusion that steering responses to left incursion hazards are ineffective. It follows that in both the LS and LNS scenarios braking was the most effective response.

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Definitions/Abbreviations

LS - Left incurring, stopped
LNS - Left incurring, not stopped
BRT - Brake response time
BSRT - Brake and steer response time
SRT - Steer response time
DRT - Driver response time

Appendix

Raw Data

Legend	
Hazard Order	First Hazard = 1; Second Hazard = 2
Hazard Type	Left incurring, stopped = LS; Left incurring, not stopped = LNS
Reaction Type	Brake = B; Steer = S; Brake and Steer = BS; None = N
Driver Response Time (DRT)	Time (s)
Collision	No collision = 0; Collision = 1

Sample #	Hazard Order	Response Type	Hazard Scenario	DRT (s)	Collision
1	1	B	LS	0.85	0
2	1	B	LS	0.95	0
3	1	B	LS	1.24	0
4	1	B	LS	1.29	0
5	1	B	LS	1.6	0
6	1	B	LS	1.72	0
7	1	B	LS	1.78	0
8	1	B	LS	1.8	0
9	1	B	LS	1.8	0
10	1	BS	LS	1.82	0
11	1	B	LS	1.9	1
12	1	B	LS	1.99	0
13	1	B	LS	2.13	0
14	1	S	LS	2.3	1
15	1	B	LS	2.31	0
16	1	BS	LS	2.33	1
17	1	B	LS	2.34	0
18	1	S	LS	2.48	1
19	1	B	LS	2.49	1
20	1	BS	LS	2.55	1
21	1	B	LS	2.61	1
22	1	B	LS	2.85	1
23	1	B	LS	2.92	1
24	1	B	LS	2.93	1
25	1	BS	LS	3.41	1
26	1	B	LS	3.46	1
27	1	S	LS	4.32	1
28	1	N	LS	-	1
29	1	B	LNS	-0.78	0
30	1	B	LNS	-0.57	0
31	1	B	LNS	-0.57	0
32	1	S	LNS	-0.5	0
33	1	S	LNS	-0.17	0
34	1	BS	LNS	-0.1	0
35	1	B	LNS	0	0
36	1	B	LNS	0.09	0
37	1	S	LNS	0.22	1
38	1	B	LNS	0.22	1
39	1	B	LNS	0.22	1

(Continued)

Sample #	Hazard Order	Response Type	Hazard Scenario	DRT (s)	Collision
40	1	B	LNS	0.28	0
41	1	B	LNS	0.34	0
42	1	B	LNS	0.36	1
43	1	B	LNS	0.72	1
44	1	B	LNS	0.79	1
45	1	BS	LNS	0.8	1
46	1	BS	LNS	1.09	1
47	1	BS	LNS	1.15	1
48	1	N	LNS	-	1
49	1	N	LNS	-	0
50	1	N	LNS	-	1
51	1	N	LNS	-	1
52	1	N	LNS	-	1
53	1	N	LNS	-	1
54	1	N	LNS	-	1
55	2	BS	LS	0.98	0
56	2	B	LS	1.11	0
57	2	S	LS	1.99	1
58	2	B	LS	2.01	0
59	2	S	LS	2.05	1
60	2	B	LS	2.06	0
61	2	B	LS	2.06	0
62	2	B	LS	2.1	0
63	2	B	LS	2.3	0
64	2	S	LS	2.35	1
65	2	BS	LS	2.49	0
66	2	BS	LS	2.52	0
67	2	BS	LS	2.53	0
68	2	BS	LS	2.74	1
69	2	BS	LS	2.82	1
70	2	BS	LS	2.89	1
71	2	BS	LS	2.91	1
72	2	S	LS	2.91	1
73	2	BS	LS	2.92	1
74	2	S	LS	2.93	1
75	2	BS	LS	3.36	1
76	2	S	LS	3.53	1
77	2	B	LS	3.7	1
78	2	S	LS	4.59	1
79	2	N	LS	-	1
80	2	N	LS	-	1
81	2	B	LNS	-1.7	0
82	2	B	LNS	-1.69	0
83	2	B	LNS	-0.75	0
84	2	B	LNS	-0.711	0
85	2	B	LNS	-0.66	0
86	2	B	LNS	-0.45	0
87	2	B	LNS	-0.35	0
88	2	S	LNS	-0.19	0
89	2	B	LNS	-0.14	0
90	2	S	LNS	-0.03	0
91	2	B	LNS	0	0

(Continued)

Sample #	Hazard Order	Response Type	Hazard Scenario	DRT (s)	Collision
92	2	B	LNS	0.05	0
93	2	B	LNS	0.29	0
94	2	B	LNS	0.33	1
95	2	B	LNS	0.34	1
96	2	S	LNS	0.37	1
97	2	S	LNS	0.46	1
98	2	S	LNS	0.47	1
99	2	B	LNS	0.47	0
100	2	B	LNS	0.53	1
101	2	BS	LNS	0.64	1
102	2	BS	LNS	1.23	1
103	2	S	LNS	1.36	1
104	2	N	LNS	-	0
105	2	N	LNS	-	1
106	2	N	LNS	-	1
107	2	N	LNS	-	1

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