Supplementary material to the paper "A model of dyadic merging interactions explains human drivers' behavior from input signals to decisions"

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February 2024

This document contains additional information on the results presented in the paper "A model of dyadic merging interactions explains human drivers' behavior from input signals to decisions". It is divided into additional results and details on the statistics. The model collided 29 times in 990 trials, and the human participants collided 28 times in 990 trials.

1 Additional Results

1.1 Collisions

A limited number of trials ended in a collision. Figure 1 shows the high-level outcome of all trials for the model and human behavior, including these collisions. Collisions happened infrequently and in all conditions in both the human and the model trials.

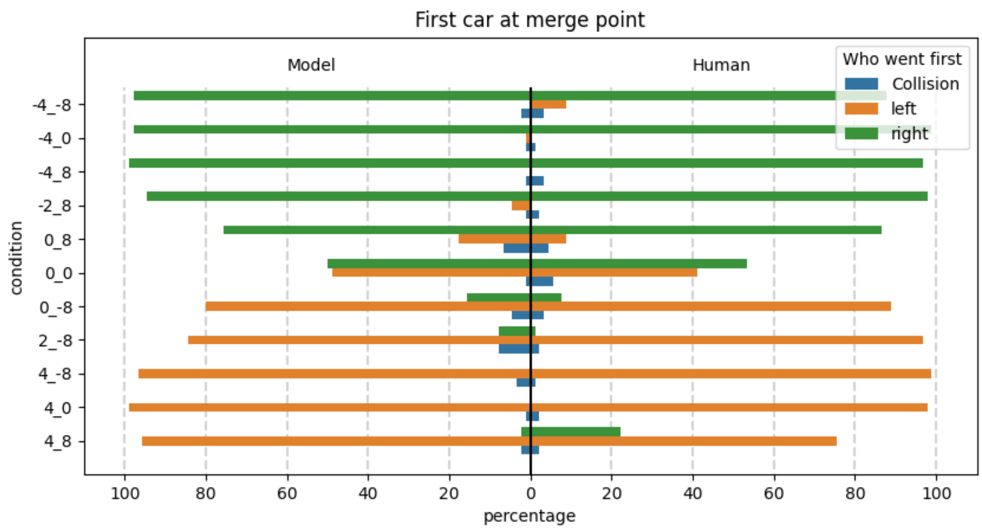

Figure 1: Which vehicle went first in which condition including collisions

Table 1: Linear mixed-effects regression models describing the effect of projected headway, relative velocity, and the interaction all from the perspective of the vehicle that merged first on the CRT for the human (H) and model (M) (number of observations H/M: 962/961,log-likelihood H/M: -1038.5/-1319.9. Collisions were excluded.)

(a) Fixed effects

	Estimate	SE	Z	P-value	CI 0.025	CI 0.975
Intercept - H	1.61	0.11	15.18	4.9×10^{-10}	1.4	1.8
Intercept - M	1.84	0.10	17.65	9.5×10^{-70}	1.64	2.05
projected headway - H	-0.24	0.02	-15.3	2.1×10^{-47}	-0.28	-0.21
projected headway - M	-0.19	0.02	-10.7	1.3×10^{-26}	-0.22	-0.15
relative velocity - H	0.40	0.08	5.0	6.1×10^{-7}	0.25	0.56
relative velocity - M	0.23	0.206	0.09	6.8×10^{-3}	0.06	0.40
headway : relative velocity - H	-0.13	0.02	-6.08	1.7×10^{-9}	-0.18	-0.09
headway : relative velocity - M	-0.19	0.03	-6.96	3.5×10^{-12}	-0.24	-0.13

(b) Random effects

Pair	1	2	3	4	5	6	7	8	9
Random Intercept - H	-0.04	-0.35	-0.34	-0.037	-0.02	0.09	0.47	0.28	-0.04
Random Intercept - M	0.23	-0.32	-0.38	0.12	-0.09	0.06	0.31	0.21	-0.13

1.2 Conflict Resolution Time

To investigate the time it takes drivers to resolve this conflict, we use the Conflict Resolution Time (CRT) [1]. This metric describes the time between the start of the interaction (i.e., the tunnel exit) and the moment the drivers are no longer on a collision course. For details on how to calculate the CRT, and for an extended analysis of human behavior, see [2].

In human merging, the CRT depends not only on the kinematic conditions but also on the high-level outcome of a trial [2]. This can also be seen in Figure 2-A, where the CRTs for pair three show outliers in some conditions. These outliers represent the conditions where the other vehicle went first.

To account for this, we view the relationship between the kinematic conditions and CRT from the (kinematic) perspective of the vehicle that merged first (Figure 2-B). A positive number for projected headway or relative velocity indicates an advantage for the vehicle that merged first. The effects of kinematics are small but significant and similar for the model and human data (Table 3). The largest difference is the velocity effect, which is twice as large in human behavior than in the model simulations. Overall, the model shows higher values for CRT than the human participants (Figure 2-C). There is a correlation between the model CRTs and the human CRTs.

Figure 2-A reveals that, particularly in conditions 4_8 and -4_-8, the model can not reproduce the CRTs for all pairs accurately. This could be related to the fact that in human behavior, these conditions show a substantial number of trials where the vehicle with the disadvantage emerges first, while the model does not replicate this phenomenon (Figure 1. This could indicate that humans use a proxy to estimate the relative velocities and projected headways. However, the precise underlying mechanisms are unknown.

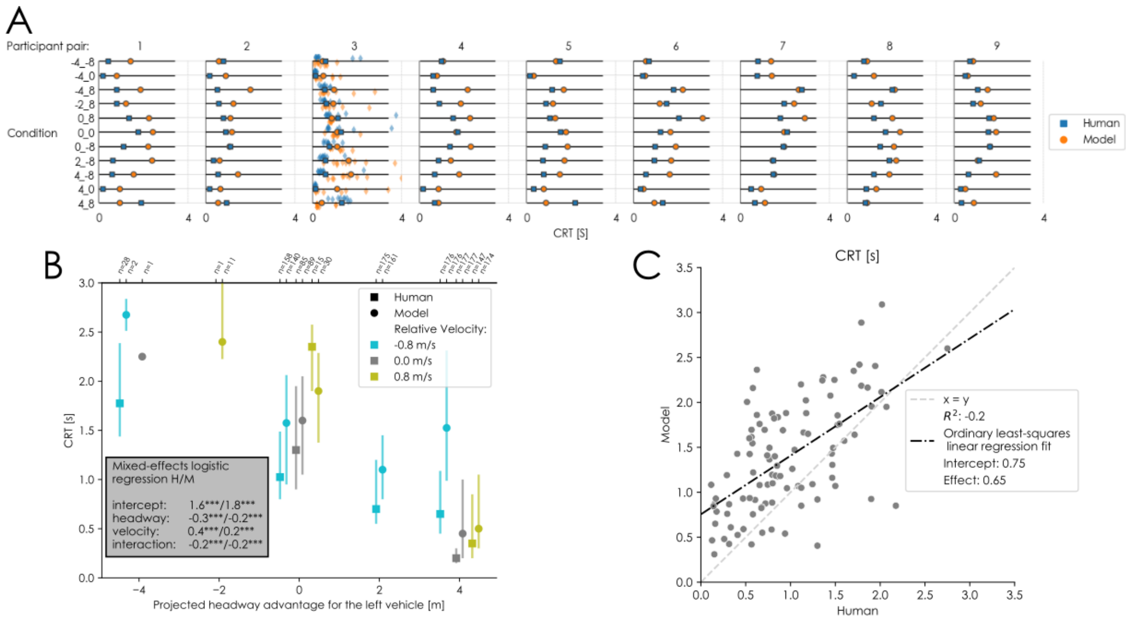

Figure 2: An overview of the behavior in terms of Conflict Resolution Time (CRT). **A**: the mean CRT values per pair, per condition. All underlying data of pair 3 is shown. **B**: the effects of projected headway and relative velocity on the CRT. The projected headway and relative velocity in this plot are seen from the perspective of the first merging vehicle. A positive number indicates an advantage for the vehicle that merged first. Markers show the mean values, lines indicate the interquartile ranges. **C**: the correlation between the model and human CRTs

2 Details on Statistics

We used multiple statistical models (mixed-effects regression models and linear regression models) to compare the model's behavior to human behavior in the results section of the paper. The details of all statistical models are presented here per level of behavior (i.e., figure in the paper).

2.1 High-level decisions

To investigate the effects of the kinematic conditions on the high-level outcome of the experiment, we fitted a logistic regression model (Table 3) to the proportion of the trials where the left vehicle merges first: $p \sim \Delta v + \Delta a$, where p is the probability of left merging first and Δv and Δx are the

Table 2: Ordinary least squares linear regression on the model behavior as a function of human behavior in terms of CRT. Number of observations: 99, degrees of freedom residuals: 97, R-squared: 0.357, adjusted R-squared: 0.351

	Estimate	SE	t	P-value	Confidence interval 0.025	0.975
Intercept	0.75	0.099	7.60	1.8×10^{-11}	0.56	0.95
Human input	0.65	0.09	7.35	6.4×10^{-11}	0.48	0.82

Table 3: Mixed-effects logistic regression models describing the effect of projected headway and relative velocity on which driver merged first for the human (H) and model (M) (number of observations H/M: 962/961,log-likelihood H/M: -191.0/-190.4. The parameters for the human data were previously published [2]. Collisions were excluded, the left vehicle going first was labeled as 1, right first as 0.

(a) Fixed effects

	Estimate	SE	Z	P-value	Confidence interval 0.025	0.975
Intercept - H	-0.32	0.212	-1.50	1.3×10^{-1}	-0.73	0.10
Intercept - M	-0.03	0.345	-0.07	9.4×10^{-1}	-0.70	0.65
Projected headway - H	1.15	0.080	14.4	7.0×10^{-47}	0.99	1.31
Projected headway - M	1.35	0.104	12.9	6.2×10^{-38}	1.14	1.55
Relative velocity - H	-3.413	0.321	-10.6	2.9×10^{-26}	-4.04	-2.78
Relative velocity - M	-1.752	0.226	-7.77	7.9×10^{-15}	-2.19	-1.31

(b) Random effects

Pair	1	2	3	4	5	6	7	8	9
Random Intercept - H	-0.54	-0.42	-1.17	0.06	-0.13	-0.51	0.16	-0.22	-0.13
Random Intercept - M	-0.41	1.06	-0.94	-0.52	-0.99	0.19	1.77	-0.53	0.13

Table 4: Ordinary least squares linear regression on the model behavior as a function of human behavior in terms of individual contribution per high-level outcome. Number of observations: 36, degrees of freedom residuals: 34, R-squared: 0.903, adjusted R-squared: 0.900

	Estimate	SE	t	P-value	Confidence interval 0.025	0.975
Intercept	-0.09	0.08	-1.09	2.8×10^{-1}	-0.254	0.08
Human input	1.04	0.06	17.76	8.9×10^{-19}	0.924	1.16

relative velocity and projected headway respectively. A random intercept per pair was included in the model. Collisions were excluded from this analysis.

To investigate the correlation between the model's output and human behavior, we fitted an ordinary least-squares linear regression to the mean deviation from the initial velocity per participant per high-level outcome (e.g., the left driver's behavior in all trials where the right driver merged first). The details of this regression can be found in Table 4.

2.2 Safety margins

To investigate the effects of the kinematic conditions on the gap drivers keep at the merge point, we fitted a linear mixed-effects regression model (Table 5) to the gap: $g \sim |\Delta v| + |\Delta x| + \Delta v * \Delta x$, where g is the gap and Δv and Δx are the relative velocity and projected headway respectively. A random intercept per pair was included in the model.

To investigate the correlation between the model's output and human behavior, we fitted an ordinary least-squares linear regression to the mean gap per pair per condition. The details of this regression can be found in Table 6.

Table 5: Linear mixed-effects regression models describing the effect of absolute headway, absolute relative velocity, and the interaction of signed headway and relative velocity on the gap that drivers keep between the vehicles at the merge point for the human (H) and model (M) (number of observations H/M: 962/961,log-likelihood H/M: -1990.9/-2167.1. Collisions were excluded.)

(a) Fixed effects

	Estimate	SE	Z	P-value	CI 0.025	CI 0.975
Intercept - H	4.13	0.45	9.14	6.1×10^{-20}	3.24	5.01
Intercept - M	5.21	0.28	18.43	7.7×10^{-76}	4.66	5.77
Absolute projected headway - H	0.15	0.04	4.23	2.4×10^{-5}	0.08	0.22
Absolute projected headway - M	-0.21	0.043	-4.95	7.5×10^{-7}	-0.30	-0.13
Absolute relative velocity - H	-0.18	0.17	-1.1	0.28	-0.52	0.15
Absolute relative velocity - M	0.065	0.206	0.32	0.75	-0.34	0.47
Headway : relative velocity - H	0.18	0.03	6.04	1.5×10^{-9}	0.12	0.24
Headway : relative velocity - M	0.21	0.036	5.89	4.0×10^{-9}	0.14	0.29

(b) Random effects

Pair	1	2	3	4	5	6	7	8	9
Random Intercept - H	-0.49	1.21	1.94	-0.01	-0.35	1.07	-1.61	-1.86	0.09
Random Intercept - M	-0.15	0.91	0.89	0.25	0.08	-0.27	-0.97	-0.16	-0.57

Table 6: Ordinary least squares linear regression on the model's gap-keeping behavior as a function of human gap-keeping behavior. Number of observations: 99, degrees of freedom residuals: 97, R-squared: 0.178, adjusted R-squared: 0.169

	Estimate	SE	t	P-value	Confidence interval 0.025	Confidence interval 0.975
Intercept	3.2	0.34	9.5	1.7×10^{-15}	2.53	3.87
Human gap	0.34	0.07	4.58	1.4×10^{-5}	0.190	0.48

Table 7: Linear mixed-effects regression models describing the effect of project headway, relative velocity, and the interaction of projected headway and relative velocity on the absolute maximum deviation from the initial velocity that drivers use for the human (H) and model (M) (number of observations H/M: 1980/1980,log-likelihood H/M: -2482/-3850)

(a) Fixed effects

	Estimate	SE	Z	P-value	CI 0.025	CI 0.975
Intercept - H	1.93	0.16	12.2	2.1×10^{-34}	1.62	2.24
Intercept - M	2.14	0.19	110.09	1.4×10^{-28}	1.76	2.51
Projected headway - H	-0.23	0.02	-12.35	4.8×10^{-35}	-0.27	-0.19
Projected headway - M	-0.23	0.038	-6.14	8.4×10^{-10}	-0.31	-0.16
Relative velocity - H	-0.55	0.09	-5.99	2.2×10^{-9}	-0.73	-0.37
Relative velocity - M	0.55	0.18	2.98	2.9×10^{-3}	0.18	0.91
Headway : relative velocity - H	0.22	0.03	7.56	8.7×10^{-14}	0.16	0.27
Headway : relative velocity - M	-0.07	0.058	1.25	0.21	-0.19	0.04

(b) Random effects

Pair	1		2		3		4		5	
Driver	left	right	left	right	left	right	left	right	left	right
Random intercept - H	0.11	-0.29	-0.53	0.89	1.41	-0.82	-0.27	0.25	0.63	-0.39
Random intercept - M	0.50	-0.20	-1.13	0.84	0.82	-1.09	0.23	0.14	0.50	-0.73
Pair	6		7		8		9			
Driver	left	right	left	right	left	right	left	right		
Random intercept - H	0.53	-0.15	-0.98	0.21	0.18	-0.65	0.10	-0.23		
Random intercept - M	0.05	0.40	-0.75	0.32	0.57	-0.27	-0.00	-0.19		

2.3 Control inputs

To investigate the effects of the kinematic conditions on the absolute maximum deviation from the initial velocity, we fitted a linear mixed-effects regression model (Table 7) to the absolute deviation of the initial velocity: $a \sim \Delta v + \Delta x + \Delta v * \Delta x$, where a is the maximum absolute deviation from the initial velocity and Δv and Δx are the relative velocity and projected headway respectively. Collisions were excluded from this analysis and a random intercept per driver was included in the model.

To investigate the correlation between the model and human input behavior, we fitted an ordinary least-squares linear regression to the mean maximum absolute deviation from the initial velocity per driver per condition. The details of this regression can be found in Table 8.

Table 8: Ordinary least squares linear regression on the model's absolute maximum deviation from the initial velocity as a function of human maximum deviations. Number of observations: 297, degrees of freedom residuals: 295, R-squared: 0.505, adjusted R-squared: 0.504

					Confidence interval	
	Estimate	SE	t	P-value	0.025	0.975
Intercept	0.61	0.10	5.9	1.0×10^{-8}	0.406	0.812
Human velocity deviation	0.90	0.05	17.4	5.1×10^{-47}	0.796	0.999

References

[1] Olger Siebinga, Arkady Zgonnikov, and David Abbink. Interactive merging behavior in a coupled driving simulator: Experimental framework and case study. *Human Factors in Transportation*, 60:516–525, 2022.

[2] Olger Siebinga, Arkady Zgonnikov, and David A. Abbink. Human Merging Behaviour in a Coupled Driving Simulator: How Do We Resolve Conflicts? *IEEE Open Journal of Intelligent Transportation Systems [IN PRESS]*, PP:1–1, 2024.