High- and Low-Order Overtaking-Ability Affordances: Drivers Rely on the Maximum Velocity and Acceleration of Their Cars to Perform Overtaking Maneuvers

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Objective: The aim of this study was to answer the question, Do drivers take into account the action boundaries of their car when overtaking?

Background: The Morice et al. affordance-based approach to visually guided overtaking suggests that the "overtake-ability" affordance can be formalized as the ratio of the "minimum satisfying velocity" (MSV) of the maneuver to the maximum velocity (V_{max}) of the driven car. In this definition, however, the maximum acceleration (A_{max}) of the vehicle is ignored. We hypothesize that drivers may be sensitive to an affordance redefined with the ratio of the "minimum satisfying acceleration" (MSA) to the A_{max} of the car.

Method: Two groups of nine drivers drove cars differing in their A_{max}. They were instructed to attempt overtaking maneuvers in 25 situations resulting from the combination of five MSA and five MSV values.

Results: When overtaking frequency was expressed as a function of MSV and MSA, maneuvers were found to be initiated differently for the two groups. However, when expressed as a function of MSV/V_{max} and MSA/A_{max}, overtaking frequency was quite similar for both groups. Finally, a multiple regression coefficient analysis demonstrated that overtaking decisions are fully explained by a composite variable comprising MSA/A_{max} and the time required to reach MSV.

Conclusion: Drivers reliably decide whether overtaking is safe (or not) by using low- and high-order variables taking into account their car's maximum velocity and acceleration, respectively, as predicted by "affordance-based control" theory.

Application: Potential applications include the design of overtaking assistance, which should exploit the MSA/A_{max} variables in order to suggest perceptually relevant overtaking solutions.

Keywords: driving, overtaking, affordance, acceleration, virtual reality

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INTRODUCTION

In France, failed overtaking maneuvers are responsible for 21.5% of fatal accidents (National Interministerial Observatory for Road Safety, 2011). Similar, alarming observations have been made in other countries (DEKRA, 2013; Duivenvoorden, 2010). The large number of fatalities has motivated the launch of prevention plans (Royal Society for the Prevention of Accidents, 2009), modifications to legislation (Williams & Preusser, 1997), or development of Advanced Driver Assistance Systems (Hegeman, Brookhuis, & Hoogendoorn, 2005; Hegeman, van der Horst, Brookhuis, & Hoogendoorn, 2007; Jamson, Chorlton, & Carsten, 2012; Milanes et al., 2012). However, for maximum efficiency, such preventive measures must be accompanied by a better understanding of the underlying human factors and the perceptual processes used by drivers to identify safe overtaking conditions. To this aim, we investigate whether drivers are sensitive to their vehicle's maximum velocity and acceleration while overtaking.

Affordance-based models (Fajen, 2005, 2007a) provide a framework that makes drivers' sensitivity to the kinematic limits of their car crucial for the perception of overtaking situations. For example, the "shrinking gap" problem (Fajen & Matthis, 2011) shows that subjects attempting to pass safely through a moving gap rely on a variable that specifies (in intrinsic units) their minimum locomotor speed. This study led us to formalize the minimum speed necessary to safely overtake a lead car while avoiding oncoming traffic (Morice, Diaz, Fajen, Basilio, & Montagne, 2015). In virtual reality, we manipulated independently the "minimum satisfying velocity" (MSV) allowing to safely overtake the lead car and the maximum velocity (V_{max}) of the driver's car. When MSV/$V_{max} \leq 1$, it was physically possible to overtake the lead car because the MSV was

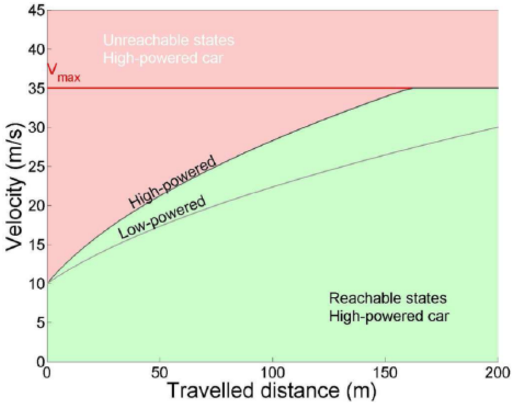

Figure 1. Numerical simulations of the performance state space for two accelerating cars as a function of maximum acceleration (A_{max}; 2 and 3.5 m/s² for low-powered and high-powered cars, respectively) and maximum velocity (V_{max}; 35 m/s). The colored spaces partition the state space in terms of reachable and unreachable states for the high-powered car.

lower than or equal to the of V_{max} of the driver's car; otherwise, overtaking was not possible. We found that overtaking frequency decreased when the MSV/V_{max} ratio approached 1 and that overtaking frequency was not significantly affected by V_{max} provided that drivers' behavior was expressed as a function of the MSV/V_{max} ratio. Therefore, the MSV/V_{max} variable allows for perception of the safeness of overtaking maneuvers depending on the V_{max} of the driven car. However, real-life cars are bounded not only by a V_{max} but also by a maximum acceleration (A_{max}) that also constrains the performance envelope of a car, as illustrated in Figure 1. Indeed, in combination to the V_{max}, the A_{max} determines the driver's field of possibilities (the "reachable states"). Such an action limit is, for instance, essential in the perception of crossing possibility while approaching an intersection (Marti, Morice, & Montagne, 2015; McKenna, 2004).

Both V_{max} and A_{max} would therefore limit drivers' overtaking possibilities. Indeed, as demonstrated by Morice et al. (2015), a larger V_{max} would offer drivers more opportunities to perform a safe overtaking maneuver. This last comment is illustrated in the upper row of Figure 2, showing numerical simulations of two cars constrained by different V_{max} (i.e., slow and fast cars), attempting to overtake a lead car moving at a constant velocity while avoiding to collide a stationary obstacle standing on the opposite lane. The upper right panel shows that slow and fast cars accelerate similarly from an initial velocity of 10 m/s to reach a higher MSV. When reaching its V_{max}, the slow car stops accelerating and moves at a constant velocity, preventing it to catch MSV. This moment corresponds in the upper left panel to the point from which slow and fast cars' trajectories diverge. From this moment onward, the slow car's trajectory is no more able to pass the lead car before reaching the stationary obstacle position. Conversely, the fast car benefits from more time to continue accelerating and reach MSV before exceeding V_{max}, which allows it to safely overtake the lead car. We hypothesize that, in parallel, the driver of a high-powered car would also benefit from a larger A_{max} as illustrated in the lower row of Figure 2. Indeed, if one considers the same initial velocity of 10 m/s, the larger the A_{max} (i.e., high-powered vs. low-powered car), the safer overtaking would be, regardless of V_{max}, as MSV will be reached quicker (Figure 2, lower right panel). Hence, the car's A_{max}, in addition to the car's V_{max}, determines drivers' overtaking opportunities.

Drivers would take advantage from relying on A_{max} in addition to V_{max} to improve their perception of overtaking possibility. We therefore hypothesize that the definition of the *overtake-ability* affordance should be extended by scaling the MSA required to accelerate from the current velocity to the MSV before it exceeds the V_{max} of the car by the A_{max} of the vehicle being driven. The MSA/A_{max} ratio would thus be an enriched property with regard to MSV/V_{max}, reflecting better the car's action possibility.

Experiment

In this experiment, we investigated overtaking in an affordance-based framework. Using a virtual reality scenario, we tested the hypothesis that drivers perceive overtaking affordances by perceiving the MSA/A_{max} ratio.

If drivers are sensitive to V_{max} only, they are expected to overtake in any situation when MSV/$V_{max} \leq 1$, whatever the MSA/A_{max} ratio. If drivers are sensitive to A_{max}, they will decide to overtake only in situations when MSA/$A_{max} \leq 1$ (including conditions when MSV/$V_{max} \leq 1$).

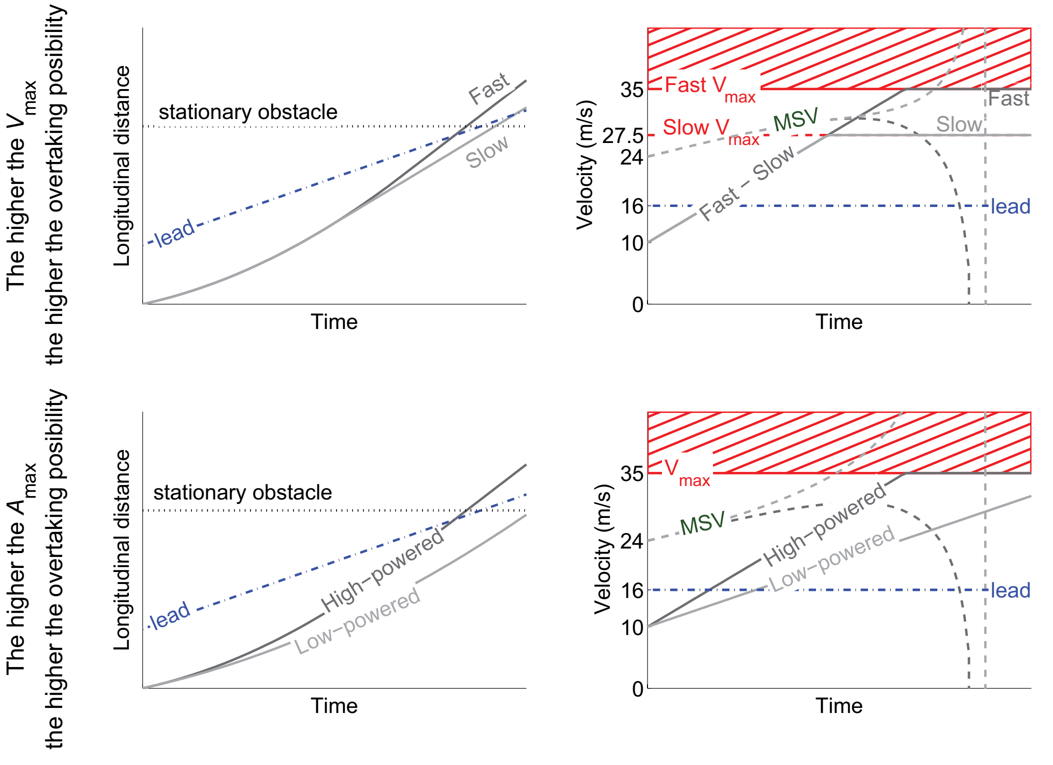

Figure 2. Position (left panels) and velocity (right panels) time series for cars limited by different maximum velocity (V_{max}; 27.5 and 35 m/s for slow and fast cars, respectively; upper row) and acceleration (A_{max}; 2 and 3.5 m/s² for low-powered and high-powered cars, respectively; lower row). Fast and high-powered cars offer safer overtaking possibilities than slow and low-powered vehicles.

METHOD

Participants

Eighteen volunteers (13 men and five women) were divided into two mixed-gender groups. Their average age was 22.84 years (*SD* = 2.63 years), and all had normal or corrected-to-normal vision. All participants held a valid driving license and had an average of 3.58 years of driving experience (*SD* = 2.24 years). The experimental protocol was approved by the local ethics committee. Participants were not told the purpose of the study.

Task

Drivers were asked to perform overtaking maneuvers, if deemed possible. They were free to accelerate or brake by using appropriate pedals. They controlled the initiation of lateral excursions between lanes (an overtaking maneuver) by turning the steering wheel over ±30°: A counterclockwise turn moved the car from the right to the left lane, whereas a clockwise turn moved the car in the opposite direction. Feedback about the speed of the vehicle was provided by optic flow and engine noise; speedometer was not displayed.

Apparatus

Figure 3 illustrates the fixed-base driving simulator. Participants sat in a Playseat (Mobsim); they manipulated two pedals (Trackstar 6000 GTS) with their right foot and used their hands to turn a steering wheel (ECCI, Trackstar 6000 GTS). The data from the pedals and steering wheel were sent to a computer, and OpenGL-based software controlled the motion of the virtual car online. From the

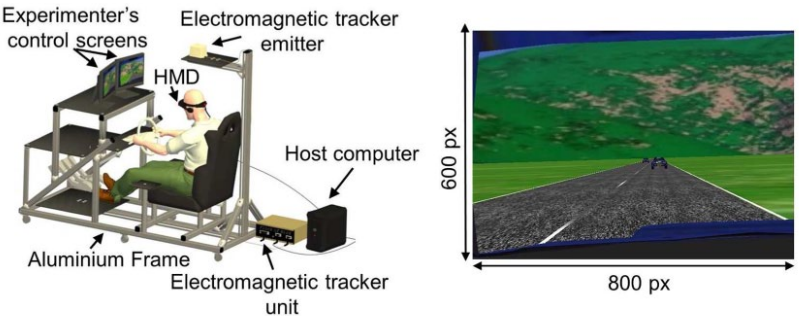

Figure 3. Left: Overview of the virtual reality setup. Participants wearing a head-mounted display sat on a Playseat. Right: Typical screenshot of the virtual scene prior to an overtaking maneuver, including two lanes 3.5 m wide; two cars 4.415 m long × 1.740 m wide × 1.475 m high, respectively acting as an obstacle and a lead car; and the landscape. At the trial start, obstacle and lead cars' optical diagonal sizes were equal to 0.57° and 1.77°, respectively.

driver's viewpoint, the virtual scene was rendered as two 800 × 600 pixels stereoscopic images refreshed at 75 Hz in a head-mounted display (Hi-res 900 stereo, Cybermind Corp.). An electromagnetic tracking system (Flock of Birds, Ascension Technology Corp.) was used to tether the virtual scene to driver's head rotations from a fixed observation point (0.975 m above ground level, at the center of the driver's Playseat). The driver could display side and/or center rearview mirrors in the virtual scene by holding dedicated buttons. Mirrors were sized and located realistically relative to the virtual car so as to allow drivers, if deemed comfortable, to fixate the visual content of mirrors while controlling the surrounding driving environment in peripheral vision.

Procedure

Participants initially performed 20 practice trials to familiarize themselves with the task. Each trial began with an initial phase during which the virtual car was moved by the computer at a velocity V_s (see next subsection and Table 1) and a 0-m/s² acceleration until it crossed the starting line. From this point, a lead and a stationary obstacle vehicle appeared in the right and left lane, respectively, and drivers were free to control their acceleration and position using the pedals and steering wheel. The experiment lasted approximately 2 hr.

Independent Variables/Design

We manipulated the A_{max} of the virtual car as a between-group variable. Participants were assigned to either a low-powered (A_{max} = 2 m/s²) or a high-powered (A_{max} = 3.5 m/s²) virtual car. These values were respectively based on the maximum acceleration in second gear of a Fiat Cinquecinto 0.9 and a Subaru Impreza WRX 2009 (Glenn, 2013). The V_{max} was constant between groups (35 m/s). The appearance and size of the driver's car was constant between groups (4.415 m long × 1.740 m wide × 1.475 m high).

We manipulated the MSV as a within-participant variable with five values ranging from 21 to 38.5 m/s in 4.375-m/s increments for both the low-powered and high-powered groups. The five MSV conditions were set by maintaining the lead car's velocity (V_L) at a constant value equal to MSV/1.5, where 1.5 is the ratio of the distance between the driver's car and the obstacle car to that between the lead and the obstacle car (see Table 1). The initial positions of the lead (75 m) and obstacle (224.5 m) cars relative to the participant's car on the road longitudinal axis were constant between trials, and so were their visual appearance and size.

MSV was calculated as the quotient of the length of the trajectory required by the driver's car to safely overtake (d_s) and the time until the lead car jeopardized the overtaking maneuver ($t_{overtaking}$) and was formalized as

TABLE 1: Overview of Experimental Conditions and Dependent Variables According to Independent Variables Manipulated

All Groups (V_{max} = 35 m/s)				Low Powered (A_{max} = 2 m/s²)			High Powered (A_{max} = 3.5 m/s²)		
V_L (m/s)	MSV (m/s)	MSV/ V_{max} (%)	MSA/ A_{max} (%)	V_S (m/s)	T_s (s)	MSA (m/s²)	V_S (m/s)	T_s (s)	MSA (m/s²)
14	21	60	25	18.32	10.69	0.50	16.31	10.69	0.87
			50	15.64	10.69	1.00	11.63	10.69	1.75
			75	12.96	10.69	1.50	6.94	10.69	2.62
			100	10.34	10.69	2.00	2.68	9.26	3.50
			110[a]	7.61	10.69	2.50	1.02	8.28	4.37
16.92	25.375	72.5	25	23.16	8.85	0.50	21.50	8.85	0.87
			50	20.94	8.85	1.00	17.62	8.85	1.75
			75	18.73	8.85	1.50	13.83	8.06	2.62
			100	16.55	8.85	2.00	10.68	6.98	3.50
			125	14.34	8.26	2.50	7.67	6.25	4.37
19.83	29.75	85	25	27.86	7.54	0.50	26.44	7.54	0.87
			50	25.97	7.54	1.00	23.21	6.74	1.75
			75	24.09	7.28	1.50	20.56	5.50	2.62
			100	22.43	6.30	2.00	18.37	4.76	3.50
			125	20.91	5.64	2.50	16.36	4.26	4.37
22.75	34.125	97.5	25	32.60	4.80	0.50	31.82	3.63	0.87
			50	31.60	3.40	1.00	30.51	2.57	1.75
			75	30.84	2.77	1.50	29.50	2.10	2.62
			100	30.20	2.40	2.00	28.65	1.82	3.50
			125	29.63	2.15	2.50	27.90	1.62	4.37
25.67	38.5	110	+Inf[b]	35.00	–Inf	0.50	35.00	–Inf	0.87
			+Inf[b]	35.00	–Inf	1.00	35.00	–Inf	1.75
			+Inf[b]	35.00	–Inf	1.50	35.00	–Inf	2.62
			+Inf[b]	35.00	–Inf	2.00	35.00	–Inf	3.50
			+Inf[b]	35.00	–Inf	2.5	35.00	–Inf	4.37

Note. Shaded cells indicate that overtaking was not possible. V_{max} = maximum velocity; A_{max} = maximum acceleration; V_L = lead car's velocity; MSV = minimum satisfying velocity; MSA = minimum satisfying acceleration; V_S = initial velocity; T_S = time required to reach the MSV when adopting the MSA; Inf = infinite value.
[a]Such a configuration required the initial velocity of the participant's car to be −1.22 m/s to get a MSA/A_{max} ratio of 125%. As a negative velocity makes no sense in an overtaking situation, we decided to set the initial velocity to 1.02 m/s to reach the maximum theoretical MSA/A_{max} ratio (110%) while still making overtaking impossible.
[b]The MSA/A_{max} cannot be computed as the driver is bounded by V_{max}.

$$\text{MSV} = d_s / t_{\text{overtaking}}. \quad (1)$$

We also manipulated the MSA at the start of each trial as a within-participant variable with five values ranging from 0.5 to 2.5 m/s² in 0.5-m/s² increments (for the low-powered group) and from 0.875 to 4.375 m/s² in 0.875-m/s² increments (for the high-powered group). MSA was computed as the minimum acceleration required to reach MSV (before reaching V_{max}). MSA was adjusted by manipulating the initial velocity (V_S, in meters per second) of the participant's car (from 18.32 to 35 m/s and from 16.31 to 35 m/s

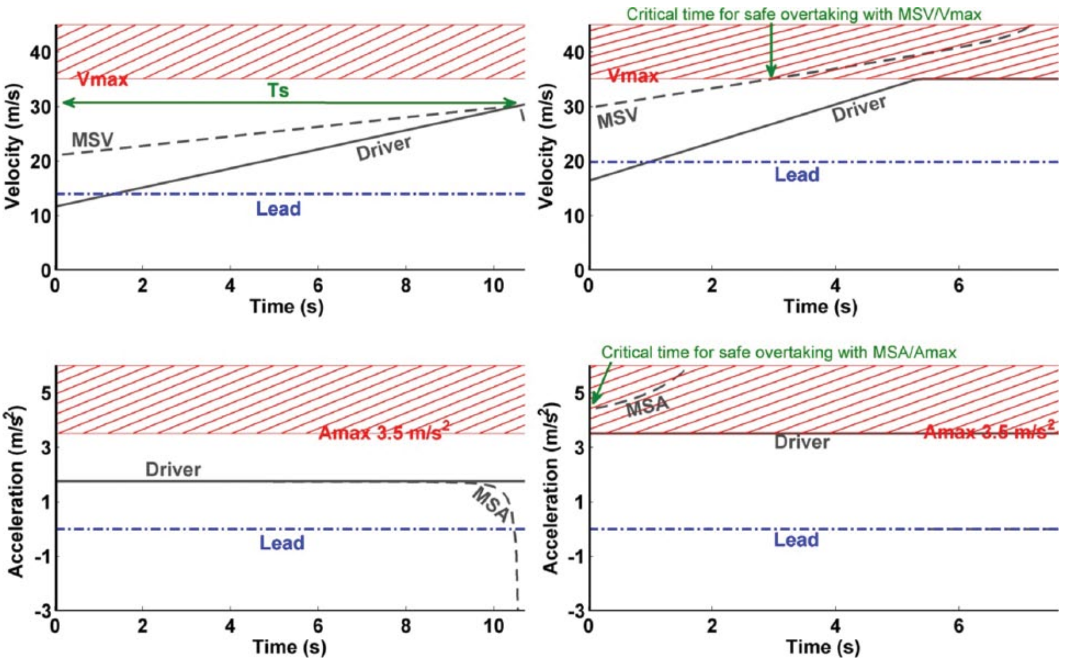

Figure 4. Time course of velocities (upper panels) and acceleration (lower panels) for two overtaking conditions (60% MSV/V_{max} and 50% MSA/A_{max}, left panels, and 85% MSV/V_{max} and 125% MSA/A_{max}, right panels). Overtaking is affordable in both conditions based on MSV/V_{max} but only in the first condition based on MSA/A_{max}. MSA/A_{max} would therefore be a higher-order property than MSV/V_{max}, allowing earlier perception of critical time for safe overtaking. MSV = minimum satisfying velocity; V_{max} = maximum velocity; MSA = minimum satisfying acceleration; A_{max} = maximum acceleration.

for the low-powered and high-powered groups, respectively) and the lead car's velocity (V_L, in meters per second). This manipulation changed the time required to reach the MSV when adopting the MSA (T_s, in seconds; see Table 1 and Figure 4). MSA was calculated as follows:

$$\text{MSA} = \frac{-\left(V_{max} - V_s\right)^2}{\left[2\cdot\left(d_s - V_{max}\cdot\frac{d_L}{V_L}\right)\right]} \quad (2)$$

Since MSA already included the V_{max} and the MSV variables, MSA/A_{max} can thus be considered as a "higher-order" property and MSV/V_{max} as a "lower-order" one. Such a label is inspired from the higher-order/lower-order appellation of perceptual variables found in the direct perception theory literature. First, MSA/A_{max} would allow drivers to better identify overtaking opportunities since MSV/V_{max} < 1 becomes a necessary but insufficient condition to guarantee safe overtaking. Second, MSA/A_{max} would allow identifying more rapidly overtaking opportunity. Numerical simulations based on 75% of V_S revealed that in all of our experimental conditions, MSA exceeded A_{max} earlier (3.11 and 2.23 s on average for A_{max}, corresponding to the low- and high-powered vehicle, respectively) than MSV exceeded V_{max}. Perceiving the MSA/A_{max} ratio would thus allow drivers to save time, at least for short-range overtaking and small V_S (Figure 4).

Note that MSV and MSA values were selected in order to make overtaking opportunities identical for both groups. MSV/V_{max} and MSA/A_{max} ratios were identical for the two groups, namely, 25%, 50%, 75%, 100%, and 125% for MSA/A_{max} and 60%, 72.5%, 85%, 97.5%, and 110% for MSV/V_{max} (see Table 1). These conditions were repeated five times in random order for each participant, resulting in 125 experimental trials (5 MSV conditions × 5 MSA conditions × 5 repetitions). Conditions in which the MSV/V_{max} and MSA/A_{max} ratio equaled 100% corresponded to the theoretical maximum overtaking opportunity. Hence, 80 of the 125 trials (64%) could result in successful overtaking maneuvers.

For each participant, two lure trials during which another car overtook the participant's car were randomly included. This design discouraged the driver from systematically initiating an overtaking maneuver at the start of the trial without checking the rearview mirror.

Dependent Variables

For each trial, we recorded collisions between the participant's car and either the lead or obstacle cars and also identified the maneuver selected by each participant: overtaking, bailing out, and following. Collisions were then categorized depending on the maneuver in progress at the moment of their occurrence. Collisions during overtaking maneuver were defined as collisions occurring after the driven car has passed the lead car, namely, when cutting in the trajectory of the lead car or colliding the obstacle car. Collision during bailing-out (namely, during a lateral excursion from the left to the right lane) and following maneuvers resulted exclusively in a crash into the lead. The collision frequency and overtaking frequency (both successful maneuvers and maneuvers that resulted in collision) were calculated for each participant and each condition. A frequency of 100% indicates that the overtaking maneuver succeeded in each of the five trials for a given condition.

Statistics

In our initial analyses, we aimed to find whether collisions were caused by a reliance on any of the experimental factors. Therefore, a three-way mixed-design ANOVA was performed on collision frequency induced by overtaking maneuvers using A_{max} as the independent variable (two modalities: low powered and high powered) and repeated measures on MSV/V_{max} (four modalities, ranging from 60% to 97.5% in 12.5% increments) and MSA/A_{max} (five modalities, ranging from 25% to 125% in 25% increments). Data from trials in which MSV/V_{max} was equal to 110% were excluded from the analyses since the corresponding MSA/A_{max} values were always positively infinite. Individual percentages of collision frequency in conditions that showed no within-participants variance (i.e., conditions for which no participant was found to collide with surrounding vehicles) were replaced by random values ranging from 0 to 1 (whereas frequency ranged from 0% to 100% in other conditions). This procedure occurred during one condition (MSV/V_{max} = 60% × MSA/A_{max} = 25%) for the analysis of collision frequency.

Second, we analyzed whether drivers in the low-powered and high-powered groups initiated similar overtaking maneuvers as a function of the MSA/A_{max} ratio. Individual overtaking frequencies were fitted (using factorial regression) by adjusting the coefficients *a* through *d* in the function defined by Equation (3):

$$f(x,y) = a \cdot x + b \cdot y + c \cdot x \cdot y + d, \quad (3)$$

in which $f(x,y)$ corresponds to the probability of observing an overtaking maneuver, x is either MSV or MSV/V_{max}, and y is either MSA or MSA/A_{max}. In this equation, the coefficients *a* and *b* express a proportional influence of x and y on overtaking frequency, *c* reflects the $x \times y$ interaction, and *d* is a constant that acts as a vertical offset modulating the average frequency of overtaking maneuvers. These adjustments were used to determine which of the coefficients *a* through *d* varied as a function of A_{max}. Separate one-way independent group ANOVAs (A_{max}) were then performed on individual *a*-through-*d* coefficients (expressed as a function of MSV and MSA) in order to quantify between-group differences in the selection of overtaking maneuvers. In addition, separate one-way ANOVAs (A_{max}) were performed on individual *a*-through-*d* coefficients expressed as a function of MSV/V_{max} and MSA/A_{max} to test the hypothesis that behavior was similar across groups when MSV and MSA were expressed as a ratio of V_{max} and A_{max}, respectively.

Finally, a three-way mixed-design ANOVA was performed on overtaking frequency, using A_{max} as the independent variable and repeated measures on MSV/V_{max} and MSA/A_{max}. Moreover, multiple regressions were carried out on various combinations of variables based on their assumed influence on the success of an overtaking maneuver. For all statistical analyses, p was .05. Data from lure trials in which another car overtook the participant's car at the beginning of the trial were excluded from all analyses. Individual percentages of overtaking frequency in conditions that showed no within-participants variance (i.e., conditions for which no driver was shown to perform an overtaking maneuver) were replaced by random values ranging from 0 to 1. This procedure occurred during three conditions (MSV/V_{max} = 60%, 72.5%, and 85% × MSA/A_{max} = 125%) for the analysis of overtaking frequency. For all tests, partial effect sizes were computed (η^2_p) and post hoc comparisons were conducted using Newman-Keuls a posteriori tests.

RESULTS

Collisions

Our first hypothesis predicted that if drivers do perceive an overtaking affordance, they would initiate the maneuver only when overtaking is possible. Drivers in the low-powered and high-powered groups collided with surrounding cars in 15.8% and 14.4% of trials, respectively. Among them, the small percentage of collisions resulting from overtaking attempts (2.84% and 3.56% of trials for the low-powered and high-powered groups, respectively) tended to confirm that participants could accurately distinguish whether the situation allowed safe overtaking or not. Collisions most frequently occurred during bailing-out maneuvers (11.20% and 10.04% for the low-powered and high-powered groups, respectively), when drivers hastened their return to the right-hand lane while colliding the left side of the lead car. Collisions infrequently occurred during following maneuvers (1.78% and 0.8% for the low-powered and high-powered groups, respectively), when driver crashed into the lead car's rear bumper.

Our second hypothesis was that the exclusive use of MSV/V_{max} without care of MSA/A_{max} would lead drivers to initiate unsafe overtaking maneuvers. Specifically, they would decide to overtake when MSV/V_{max} indicated a safe overtaking opportunity (e.g., MSV/V_{max} equal to 97.5%), while at the same time MSA/A_{max} (e.g., MSA/A_{max} equal to 125%) indicated that overtaking was unsafe. A three-way ANOVA (A_{max} × MSV/V_{max} × MSA/A_{max}) with repeated measures on MSV/V_{max} and MSA/A_{max} was performed on the frequency of collisions resulting from overtaking maneuvers. This ANOVA revealed a significant MSV/V_{max} × MSA/A_{max} interaction, $F(12, 192) = 1.98$, $p < .05$, $\eta^2_p = .11$. Newman-Keuls post hoc analyses showed that collisions occurred significantly more frequently in a small, specific set of conditions in which MSA/A_{max} was equal to 50% or 100% and MSV/V_{max} was equal to 97.5% (collision frequency equal to 13.33% and 20% for the low- and high-powered groups, respectively; $p < .05$). No significant differences were found in other MSV/V_{max} conditions for which MSA/A_{max} was superior to 100% (collision frequency equal to 1.67% and 1.67%; $p > .05$). Whereas a large number of collisions—especially in conditions in which MSA/A_{max} > 1—would indicate that drivers randomly attempted to perform overtaking maneuvers, our results led us to conclude that participants avoid collisions by perceiving overtaking opportunities on the basis of the MSA/A_{max} ratio.

Overtaking Frequency

Our third hypothesis was that if drivers rely on MSA/A_{max}, overtaking frequency would vary as a function of MSA and A_{max}.

Figure 5A shows average overtaking frequencies plotted as a function of MSA and MSV manipulations for the low-powered (black surface) and high-powered groups (gray surface), respectively. As expected, overtaking frequency decreased with increases in MSA for both groups of drivers but also unexpectedly with increase of MSV. In addition, overtaking frequency seemed to overlap for both groups on the MSV but not the MSA axis. The absence of overlap on the MSA axis is indicated by the double-headed arrow. This finding not only confirms that drivers changed the way they initiated overtaking maneuvers as a function of MSV/V_{max}, as already evidenced, but most importantly suggests that they were also sensitive to MSA and A_{max}.

We then fitted overtaking frequency with Equation (3) using MSV and MSA as predictors.

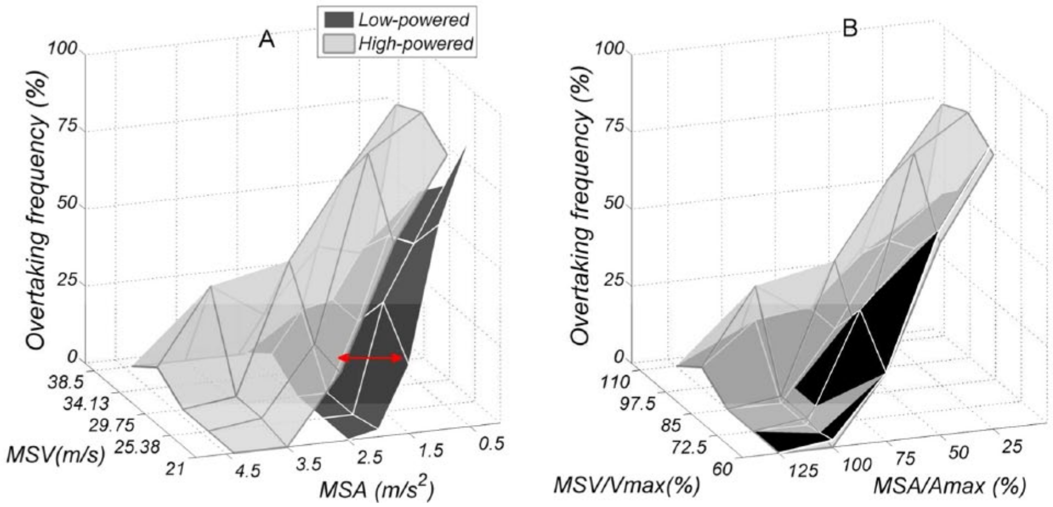

Figure 5. Average frequency of overtaking maneuvers plotted as a function of (Panel A) minimum satisfying velocity (MSV) and minimum satisfying acceleration (MSA) and (Panel B) MSV/V_{max} and MSA/A_{max} for the low-powered (black) and high-powered (gray) groups. V_{max} = maximum velocity; A_{max} = maximum acceleration.

Individual adjustments led to average R^2 values equal to .76 and .71 for the low-powered and high-powered groups, respectively.

One-way ANOVAs (A_{max}) were performed separately on each of the coefficients to highlight the respective contribution of MSA, MSV, and MSV × MSA in overtaking frequency as a function of group (cf. Table 2). These ANOVAs revealed no significant main effect of A_{max} on the coefficient *a,* $F(1, 16) = 0.99$, $p > .05$. The absence of between-group differences on *a* confirms that both groups, with the same V_{max}, responded in the same way to the manipulation of MSV. However, the ANOVA revealed a significant main effect of A_{max} on the coefficient *b,* $F(1, 16) = 14.87$, $p < .05$, $\eta^2_p = .48$. The negative value of *b* for the high-powered group is lower than for the low-powered group. This finding underlines that an identical increase in MSA resulted in a bigger decrease in overtaking frequency for the low-powered than for the high-powered group. The higher positive value of *c* for the low-powered compared to the high-powered group also suggests that overtaking frequency was influenced by the MSA × MSV interaction as a function of group, $F(1, 16) = 7.58$, $p < .05$, $\eta^2_p = .32$. Hence, for a given MSV condition, the change in overtaking frequency as a function of MSA is more pronounced for the low-powered than for the high-powered group. These results show that, when expressed as a function of MSV and MSA, overtaking maneuvers are initiated differently as function of group (A_{max}).

Figure 5B shows a transformation of Figure 5A, in which each MSA and MSV condition was divided by A_{max} (2 m/s² and 3.5 m/s² for the low-powered and high-powered groups, respectively) and V_{max} (35 m/s). It is important to note that overtaking frequency dropped to 0% for both groups when MSV/V_{max} and MSA/A_{max} exceeded 100% (i.e., when MSV and MSA required for successful overtaking were greater than the car's V_{max} and A_{max}). This finding suggests that drivers in both groups reliably perceived situations in which overtaking requirements exceeded their car's capabilities. Moreover, the two overtaking frequencies surfaces overlap, suggesting that the groups behaved similarly for a given MSA/A_{max} ratio.

We then fitted individual overtaking frequencies with Equation (3); in this case, variance in overtaking frequency results from the influence of MSV/V_{max} and MSA/A_{max}. This analysis determined whether the between-group differences in overtaking frequency (due to the manipulation

TABLE 2: Average Interindividual Values of the Best *a*-to-*d* Coefficients Used to Fit Individual Overtaking Frequency as a Function of MSA and MSV and MSA/A_{max} and MSV/V_{max}

Predictor/Coefficient	Low Powered	High Powered	*F* Value
MSV and MSA			
a (MSV)	19.10	–4.27	0.99
b (MSA)	–100.71	–62.57	14.87*
c (MSV × MSA)	2.38	1.41	7.58*
d (vertical offset)	58.21	67.02	0.09
MSV/V_{max} and MSV/A_{max}			
a (MSV/V_{max})	–1.57	–1.49	0.04
b (MSA/A_{max})	–2.01	–2.19	0.45
c [(MSV/V_{max}) × (MSA/A_{max})]	0.02	0.02	0.04
d (vertical offset)	58.21	67.02	0.09

Note. MSA = minimum satisfying acceleration; MSV = minimum satisfying velocity; A_{max} = maximum acceleration; V_{max} = maximum velocity. Significant between-group differences are indicated by asterisks.
*$p < .05$.

of MSA) found in earlier analyses vanished when MSA/A_{max} was taken into account.

One-way ANOVAs (A_{max}) were separately performed on *b* and *c* coefficients. These analyses highlighted the identical contribution of MSA/A_{max} and MSV/V_{max} × MSA/A_{max} interactions in overtaking frequency for both groups (cf. Table 2). ANOVAs revealed no significant effect of A_{max} on *b* and *c*, $F(1, 16) < 0.45$, *ns*. These results confirm that between-group differences in overtaking frequency that are due to the manipulation of MSA, vanish when MSA is expressed as a scale that integrates A_{max}. Hence, the decision to overtake appears to be similar among groups when the overtaking affordance is expressed through MSA/A_{max} and MSV/V_{max} ratios.

Although we predicted that between-group differences in overtaking frequency expressed as a function of MSA would vanish when expressed as a function of MSA/A_{max}, we did not expect between-group differences in coefficient that fit overtaking frequency due to the MSA/A_{max} × MSV/V_{max} × A_{max} interaction. This effect can be seen in Figure 5 and was revealed by a three-way mixed-design ANOVA performed on individual values of overtaking frequency, $F(12, 192) = 2.52$, $p < .05$, $\eta^2_p = .14$. Post hoc analyses showed that the high-powered group overtook significantly more frequently in a small and specific set of conditions that combined MSA/A_{max} equal to 50% or 25% and MSV/V_{max} equal to 72.5% or 85% ($p < .05$), respectively.

We suspected that other, underlying variables were the reason for these differences as MSV/V_{max} and MSA/A_{max} were identical for all groups. Separate multiple regression were performed for overtaking frequency, MSA/A_{max}, and candidate variables (MSV/V_{max}, T_s, V_s, MSV – V_s, and [MSV – V_s]/T_s). Each of these variables relies on the driver's speed, and the combination of multiple variables allowed us to isolate those that were most relevant. The results of these analyses are summarized in Table 3.

The analyses revealed that overtaking frequencies were significantly correlated with two pairs of variables: MSA/A_{max} + MSV/V_{max} and MSA/A_{max} + T_s, that is, the time required to reach MSV starting from the current velocity by accelerating at MSA (see between-group changes in T_s in Table 1). As T_s was the only candidate variable that had a significant influence in the regression ($p < .05$), had an adjusted R^2 that was as high as the initial variable MSV/V_{max} (0.57), and varied between group, we concluded that drivers seemed to combine MSA/A_{max} and T_s to accurately perceive overtaking opportunities. The

TABLE 3: Results of Multiple Regressions Between Overtaking Frequency, MSA/A_{max} (Predictor 1), and T_s, V_s, MSV – V_s, and (MSV – V_s)/T_s (Predictor 2)

Predictor 1	*F* Value	Predictor 2	*F* Value	Adjusted R^2
MSA/A_{max}	473.17*	MSV/V_{max}	8.42*	0.57
MSA/A_{max}	420.33*	T_s	5.96*	0.57
MSA/A_{max}	425.98*	V_s	3.18	0.57
MSA/A_{max}	251.15*	MSV – V_s	0.01	0.56
MSA/A_{max}	214.79*	(MSV – V_s)/T_s	1.96	0.56

Note. MSA = minimum satisfying acceleration; MSV = minimum satisfying velocity; A_{max} = maximum acceleration; T_S = time required to reach the MSV when adopting the MSA; V_S = initial velocity.
*$p < .05$.

combined influence of MSA/A_{max} and T_s on overtaking frequency could be the cause of the significant between-group differences in overtaking frequency observed in Figure 5, and such an explanation was confirmed by three-way mixed-design ANOVAs (MSV/V_{max} × MSA/A_{max} × A_{max}) performed on overtaking frequency.

DISCUSSION

We investigated the reliability of a driver's decision to overtake (or not) in an effort to clarify the causes of overtaking accidents. In line with Morice et al. (2015), we hypothesized that drivers would safely overtake (or not) based on their perception of an overtake-ability affordance. However, rather than using the V_{max} of the driver's car as a scale for perceiving the MSV needed to overtake the lead car, we extended the study of Morice et al. by hypothesizing that drivers would also rely on a more relevant capability: the A_{max} of their car. We predicted that drivers would use A_{max} to assess the MSA required to accelerate from their current velocity to the MSV before reaching their car's V_{max}. We showed that a driver's decision not only varies with MSA/A_{max} but also (and unexpectedly) as a function of T_s. We discuss these results in the following sections.

Driver's Sensitivity to MSA/A_{max}

We hypothesized that the perception of MSV/V_{max} < 1 was a necessary but insufficient condition to guarantee safe overtaking. We thus predicted that relying solely on MSV/V_{max} would lead drivers to make mistakes in estimating overtaking maneuvers. In particular, they would initiate overtaking maneuvers in situations in which MSV/V_{max} < 1, but there would be collisions with other vehicles in situations that combined MSV/V_{max} < 1 and MSA/A_{max} > 1. On the other hand, we anticipated that the perception of MSA/A_{max} ≤ 1 was a necessary and sufficient condition to guarantee safe overtaking.

Our analyses of collisions revealed results that are consistent with the use of MSA/A_{max} as an affordance to initiate overtaking maneuvers. Collisions were infrequent and occurred in a few sets of "risky" conditions (e.g., MSV/V_{max} = 97.5 and MSA/A_{max} = 100%). This finding suggested that drivers reliably distinguished safe from unsafe overtaking situations. The overall frequency of collisions in our study was similar to the frequency of collisions reported in real-world overtaking accident reports (Wilson & Best, 1982) and laboratory studies (Gordon & Mast, 1970; Gray & Regan, 2005).

Moreover, our analyses of overtaking frequencies confirm the use of MSA/A_{max}. Indeed, the frequency of overtaking consistently dropped to 0% when MSV and MSA exceeded V_{max} and A_{max}, respectively. Furthermore, both low-powered and high-powered groups behaved quite similarly when overtaking frequencies were plotted as a function of MSV/V_{max} and MSA/A_{max}. Similar results were reported by Warren (1984) and Warren and Whang (1987) in the perception of aperture-crossing and stair-climbing possibilities. These studies showed that similarities in approach behavior (despite variation in shoulder width and leg length) were due to the scaling of the aperture and stairs by the body property in question. Here, similarities in overtaking behavior are due to the scaling of overtaking requirements to the actions capabilities V_{max} and A_{max}.

Why Did Drivers Not Rely Entirely on MSA/A_{max}?

In our experiment, reaching MSV before it exceeded V_{max} was a necessary but not sufficient condition for a successful overtaking maneuver, whereas reaching MSA before it exceeded A_{max} was a sufficient condition. In other words, MSA/A_{max} was a high-order affordance, making MSV/V_{max} useless. Identical MSA/A_{max} ratios should thus lead expert drivers to perceive overtaking opportunities as identical, independently of MSV/V_{max}. However, we found an unexpected sensitivity to the time required for the car to reach MSV from its initial velocity (T_s). Drivers in the high-powered group seemed more likely to overtake than drivers in the low-powered group, although overtaking opportunities were theoretically identical for both groups. Moreover, the three-way mixed-design ANOVA of overtaking frequencies revealed that they varied as a function of the MSV/V_{max} × MSA/A_{max} × A_{max} interaction. Finally, MSA/A_{max} and T_s were both found to be significant and to best predict overtaking frequencies among candidate variables. Since T_s is a property close to MSV/V_{max}, the results are consistent with the ones previously reported by Morice et al. (2015), maybe due to the tiny improvement of accuracy of MSA/A_{max} as compared to MSV/V_{max} for usual drivers.

The "higher-order" label of MSA/A_{max} was given in reference to perceptual variables that perfectly specify some physical properties (see Jacobs, Michaels, & Runeson, 2000, and Michaels & de Vries, 1998, for smart demonstrations) because it perfectly informs drivers about their driving possibility. It was hypothesized to be opposed to the "lower-order" property MSV/V_{max}, whose correlation with overtaking possibility decreases as overtaking distance and time decrease and when the necessity to accelerate increases. In theory, the affordance-based control framework (Fajen, 2007a) allows an infinite range of behaviors and chances of success provided that the "ideal" state remains below the action capability boundary. However, as the ideal state (MSV in our case) moves closer to the boundary (V_{max}), the number of possible behaviors decreases and temporal constraints increase. Therefore, if drivers do not have to perform large acceleration because they drive at a velocity close to MSV (as in Morice et al., 2015), MSV/V_{max} covaries with the number of possible behaviors and informs quite accurately drivers about their overtaking possibility.

However, the present study required larger acceleration than in Morice et al. (2015) to perform safe overtaking. Therefore, drivers may have relied on T_s as a lower-order estimation of the temporal constraints of the overtaking situation. In other words, drivers may have used T_s to perceive their degree of freedom to follow MSA and to determine their safety margin. In line with the affordance-based control framework, T_s thus enables drivers to quantify the "safe region" (Fajen, 2005) in order to select and regulate the most appropriate action mode (e.g., overtaking, following, etc.) given the temporal constraints of the overtaking situation. Therefore, drivers may be in an intermediate step of perceptual learning in which they mix between higher-order and lower-order variables. Previous results indeed revealed that the dynamics of perceptual learning is quite fast but not instantaneous (Bastin, Fajen, & Montagne, 2010; Fajen, 2007b; Flach, Jagacinski, Smith, & McKenna, 2011; McKenna, 2004). The introduction of an unbeknownst increase or decrease of V_{max} and A_{max} would thus be required. Such a methodology, in line with experimental evidence of rapid recalibration of agent to their maximum deceleration when braking (Fajen, 2007b) or V_{max} when intercepting target (Bastin et al., 2010), would serve as an ultimate demonstration of participant level of calibration.

LIMITATIONS AND FUTURE RESEARCH

The present study refines the portrayal of the variables implied in the perception of the overtaking possibility with regard to the Morice et al. (2015) study. Nevertheless, the conclusions drawn need to be nuanced with regard to the following limits. We believe that some poor performances of the devices used (e.g., limited field of view and low resolution of the head-mounted display) do not jeopardize the validity of this study, since it kept invariant the essence of the real-life visual world. On the contrary, some features of the virtual simulation used (e.g., unconventional operation of the steering wheel, stationary vehicle in the left-hand lane) may limit the generalizability to real passing behavior by generating, for instance, more collisions during bailing-out maneuvers than in real driving or more "risky" overtaking attempts than with speed fluctuations of the oncoming traffic, respectively. Finally, and maybe more importantly, the use of a fixed-base driving simulator may have weakened the possible bridge between the perceptual process evidenced in the present experiment and those used in natural environments. Indeed, it is noteworthy that visual and nonvisual contributions may contribute to the perception of action-scaled affordances as the minimum required velocity to pass through a shrinking aperture (Fajen & Matthis, 2011). For instance, in real-life overtaking, vestibular information may help drivers to retrieve from visual relative displacements of objects components due to their self-motion (stimulating the vestibular system) from those due to the movement of surrounding (e.g., lead) cars. Such a limitation should lead the researcher interested in practical issues associated with training and design, as well as keen on the understanding of decision-making process, to be cautious with our results (Flach et al., 2011).

Demonstrating that, depending on expertise, drivers rely on the MSV/V_{max} and/or the MSA/A_{max} ratios when deciding to overtake or not is the first prerequisite to showing evidence that drivers perceive an overtaking-ability affordance. A second step in the experimental affordance-based approach of overtaking would consist in identifying the source of information that supports the overtake-ability affordance. This method would be in line with the agenda followed by previous researchers on body-scaled affordances (Warren & Whang, 1987) and action-scaled affordances (Fajen, 2005; Fajen & Matthis, 2011). We believe that perceiving the overtake ability cannot result from a separate perception of MSA and A_{max} followed by a comparison between them. Indeed, such a process would first imply for the agent to be sensitive to an acceleration (i.e., the MSA) or a differential between velocities, but the poor ability of the human perceptual system to reliably detect acceleration (Watamaniuk & Heinen, 2003; Werkhoven, Snippe, & Toet, 1992) discredits such strategy. Second, perceiving the overtake ability through comparison between separate perception of MSA and A_{max} values would disavow the main affordance hypothesis assuming that action boundaries provide critical references for perceiving directly possibility for action.

We thus suggest that MSA is perceived directly in units of A_{max}. When properly calibrated, sources of information about MSA should indicate to drivers the percentage of A_{max} necessary to safely overtake. Our definition of the overtaking-ability affordance (MSA required to accelerate from the current velocity to the MSV before it exceeds V_{max} scaled by A_{max}) is expected to provide a starting point and landmarks for identifying candidate perceptual information that drivers could use to perceive MSA/A_{max}. Indeed, perceptual support of properties analog to MSV for successful interception (Bastin et al., 2010) and passing through aperture (Fajen & Matthis, 2011) exist, based on optical specifications of passing distance, time to passage, and current speed. The optical specification of MSA, however, remains to be identified.

To be fully consistent with real-life overtaking behavior, authors of future research should investigate drivers' ability to exploit changes in their action limits when changing gear. Are drivers able to be aware that the current gear, unlike the lower gear, is unable to provide enough A_{max} to reach MSA and decide to activate a lower gear in order to successfully perform a safer overtaking maneuver? In the same vein, it would be interesting to investigate drivers' ability to calibrate changes in their A_{max} not only with gear changes but also with the velocity changes for a given gear.

PRACTICAL IMPLICATIONS

Conceiving an advanced driver assistance system (ADAS) dedicated to overtaking maneuvers is a concern nowadays. Its common principle consists in helping the driver to judge whether a gap will be safe enough for overtaking. However, few devices exist and most studies are limited to task analysis and numerical simulation of controller behavior (Arvind Raj, Dinesh, Manish Patil, & Sasikala, 2013; Barańska, 2010; Hegeman, Tapani, & Hoogendoorn, 2009). To our knowledge, the few completed prototypes rely on road features (e.g., road curvature, legal overtaking restrictions, speed limits) and actions limits (e.g., driver's car V_{max} and sometimes a maximum "comfortable" acceleration) but ignore the obstacle traffic (Loewenau et al., 2006; Milanes et al., 2012; Naranjo, Gonzalez, Garcia, & de Pedro, 2008). Oppositely, when taking into account the oncoming traffic, they use a behavioral database and preprogrammed threshold (Barańska, 2010; Hegeman et al., 2009) to compute the spatio-temporal constraints and remain at the step of simulations (Ruiz, Gil, Naranjo, Suárez, & Vinagre, 2007; Yang & Zhou, 2008).

We believe that the effectiveness of ADAS for overtaking relies on the coherence of the solution with human perception. Individuals must agree with the recommendations of the device (Wiener, 1981) rather than trying to get round it (Stanton & Pinto, 2001). Therefore, if future devices are to be fully efficient, they must rely on the same perceptual variables as those used by humans, albeit with more sensitive sensors. Our work has shown that in theory MSA/A_{max} is sufficient to discriminate between safe and unsafe situations. However, if it is to be consistent with the decisions taken by humans, any overtaking assistance device should include a safety margin based on T_s.

CONCLUSIONS

In conclusion, this study extends the study of Morice et al. (2015) by revealing that drivers are sensitive not only to their car's V_{max} by also to its A_{max} for perceiving overtaking possibility, consistent with the affordance-based framework. From a practical point of view, overtaking assistance devices should include the variable MSA/A_{max}—which uses these underlying actions limits for determining the driver's overtake possibility—to be fully accepted by drivers.

KEY POINTS

- We formalize an overtake-ability affordance based on the minimum acceleration required for safe overtaking.
- Drivers take the maximum acceleration and velocity of their vehicle into account in overtaking maneuvers.
- The affordance-based framework offers a new perspective for safe overtaking maneuvers.

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