Three Player Interactions in Urban Settings: Design Challenges for Autonomous Vehicles

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An observational analysis of crossing episodes between two intersecting vehicles, in which a third road user clearly affected its evolution, was conducted in an attempt to identify (i) recurring patterns of informal coordination among road users and (ii) traffic situational invariances that may inform AV prediction algorithms. The term BLOCK-EXPLOITING is introduced to describe a driver's exploitation of situational opportunities to gain priority often contrary to regulatory provisions, but favouring overall traffic efficiency. Video-data from an urban stop-controlled intersection were analysed through the lens of joint systems theory using a phenomenological framework developed in this study. Four generic types of BLOCK-EXPLOITING were identified (i.e. covering, ghost-covering, piggybacking, sneaking). Covering and ghost-covering led to minimal or no delays while piggybacking and sneaking, although abusive to other drivers, still only resulted in 1.99 to 3.33 sec delay. It is advocated that BLOCK-EXPLOITING can be socially acceptable. Proposed design challenges for AVs in mixed traffic include the ability to (i) distinguish BLOCK-EXPLOITING from errant driving, (ii) recognise to whom a 'space-offering' is addressed, and (iii) assess the appropriateness or abusiveness of a BLOCK-EXPLOITING action. Finally, this study brings to fore very short-time span joint-activity coordination requirements among diverse agents unknown to each other.

Keywords: Multiple vehicles interaction, joint-activity, observational study, informal rules

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Journal of Cognitive Engineering and Decision Making
Vol. 0, No. 0, ■■ ■, pp. 1-20
DOI:10.1177/15553434231155032
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Introduction

Integration of autonomous vehicles (AVs) in mixed traffic environment raises the need for AVs' coordination with other road users – especially, in traffic conflict situations, that is, negotiating intersections – in a safe, efficient and socially acceptable manner (Mariani et al., 2021; Vinkhuyzen and Cefkin, 2016). Although there is no consensus on whether it is socially desirable for an AV to present humanlike behaviour (Li et al., 2022; Liu et al., 2019; Mueller et al., 2020), it is widely recognized that AVs should at least be able to predict the intention of other road users in order to decide their course of action (Brown and Laurier, 2017; Markkula et al., 2020; Schieben et al., 2019; Schwarting et al., 2019).

To tackle this issue, various approaches have been proposed including (i) early prediction of a driver's manoeuvre at specific road sections (i.e. intersections, roundabouts) offering sufficient prediction-window before a potential conflict (Zyner et al., 2017; 2018), (ii) modelling of vehicles' behaviour using game theory in an attempt to build decision matrices that will enable an AV to find a solution to safely cross an intersection (Doniec et al., 2008; Fox et al., 2018), (iii) estimation of the social value orientation (SVO) of other drivers from observable trajectories enabling an AV to predict their actions and adjust their movements (Schwarting et al., 2019; Zhao et al., 2021) or even (iv) explicit communication between neighbouring vehicles enabling them to avoid an impeding conflict (e.g. crossing intersection) through argumentation (Lippi et al., 2018). Each approach raises specific issues such as ill-matching of manoeuvre-based models in various road environments (Toghi et al., 2020); hiding the essential dynamics in a real world scenario due to the way a model quantizes time and uses local information (Fox et al., 2018; Mariani et al., 2021); erroneous attribution of social intent to other drivers (Pletzer et al., 2018); mistrusting other drivers and/or disagreements resulting to time-delay of overall traffic flow (Lamas et al., 2015). Besides the above issues pertinent for each approach, other authors (Alahi et al., 2016; Toghi et al., 2021) note that a key shortcoming in all, is their common focus on dyadic interactions between road users in close proximity to each other without considering how their behaviours may be affected by other road users in their immediate surroundings.

However, there is evidence that inclusion of surrounding agents' behaviour can significantly improve prediction in proximal interactions. For instance, Alahi et al. (2016) introduced a social long short-term memory network to incorporate the subtle interactions that are taking place among pedestrians moving in dense crowds. They showed that pooling the interactions of neighbouring moving pedestrians in crowded spaces arising from social norms made possible to predict complex non-linear behaviours.

Still, the role of surrounding road users in shaping the coordination between two interacting ones in close proximity is an issue that has received little attention even in widely accepted driving behaviour models (e.g. Hollnagel et al., 2003; Michon, 1985, see also for a review Carsten, 2007; Panou et al., 2007).

As Renner and Johansson (2006) noted, applying a single-driver perspective offers only a limited understanding on how drivers coordinate their driving in a traffic situation with multiple road users. To this end, they proposed a model based on the interpredictability of participants' attitudes and actions derived from the concept of joint-activity developed by Clark (1996) and further elaborated by Klein et al. (2005).

According to Klein et al. (ibid.), the two basic requirements for effective coordination in a joint-activity are the Basic Compact and Common Ground. The Basic Compact refers to a level of commitment (often tacit) of all participants to facilitate coordination and prevent breakdowns. In cases where shorter-term individual goals may exist, the Basic Compact entails relaxing them in order to permit more global and long-term team goals to be addressed (Klein et al., 2004). The Common Ground refers to the process by which the participants try to establish and maintain mutual understanding. Common ground can be characterized in terms of three categories: (i) *initial common ground*, referring both to participants' knowledge of formal rules, conventions and practices associated with the particular joint task as well as their shared scripts about the expected behaviour of the other parties, (ii) *public events*, referring to participants' knowledge of the event history that influences available or not available options to the team and, finally, (iii) *current state of the activity*, referring to cues provided in the physical scene enabling participants to predict subsequent actions and formulate appropriate coordination.

In the domain of driving in urban settings the above concepts need to be adapted taking into account the ephemeral character of cooperation between the parties involved and their limited opportunities for negotiation. Specifically, the Basic Compact between road users with often competing individual goals, is understood as the tacit willingness to coordinate their behaviour in a way that balances their individual goals with global traffic ones. Low adherence to this Basic Compact is well manifested, for example, whenever someone blocks the traffic flow on the crossing street by placing himself in the middle of an intersection due to traffic ahead. In respect to Common Ground, it is important to stress that in road users' coordination most of the events are instantaneous with no or limited event history and limited opportunities for repairing mutual understanding through communication. Therefore, conventions and practices based on the cumulative experience of past events (i.e. initial common ground) play the major role in recognizing the situation at hand while coordination is enabled through timely exchanged cues.

An interesting example of the importance of Common Ground with respect to traffic efficiency is the so-called 'Pittsburgh left'. According to this local convention, particular to Pittsburgh Pennsylvania, a car is allowed to take a left turn at a two-lane intersection immediately after the stop light turns green (as if there were a left turn signal) provided that the driver of the oncoming car is willing to cooperate. This practice, although is technically illegal, speeds up traffic flow since the left turning car does not hinder the cars behind it from moving forward (Broz et al., 2013). As a recurring pattern, such informal conventions like the 'Pittsburgh left', reinforce both Common Ground and Basic Compact of local traffic users enhancing their willingness to cooperate and to follow common interest conventions with only minimal cues (e.g. act of creeping, flashing headlights).

Traffic coordination through such informal conventions becomes challenging in the foreseeable future with mixed traffic involving human-driven and autonomous vehicles. For example, through the use of public available videos of AVs, Brown and Laurier (2017) presented a number of traffic episodes in which failures of AVs to follow conventions led to a fundamental breakdown of Common Ground with other human parties involved. In particular, in a cross intersection episode, the edging forward of an AV at a four-way intersection, acted as a signal to other drivers of its intention to take its 'slot' to cross. However, absence of subsequent movement (e.g. creeping) was interpreted by other drivers as a signal of the AV aborting its initial intention for the moment, leaving the 'slot' to be taken by another car. Consequently the 'allowance' of the first car to take the 'slot' was interpreted by the driver of the car following the crossing one as a sign that the AV will remain standstill. But, by the moment the second car was crossing the intersection the AV also moved on, resulting to abrupt braking of both the AV and another car behind it.

The episode above vividly shows that initial common ground among human drivers may present a rich repertoire of shared conventions not only of dyadic coordination but also about more complex situations where third road users are involved. For instance, the situation created by the interaction between the two imminent road users (AV and first passing car) allows surrounding road users to detect the possibility to follow an informal convention known as 'piggybacking' and to mingle in. Typically, such mingling will be realized if judged socially acceptable (Deppermann, 2019; Laurier, 2019). In this particular episode, social acceptability of 'piggybacking' is manifested through the signs of yielding behaviour by the AV.

Until now, most studies examining human road users' decision making at intersections mainly focus on factors contributing to attention failures, such as improper lookout, age of drivers and driving inexperience (Bao and Boyle, 2009; Herslund and Jørgensen, 2003; Summala et al., 1996; Xu et al., 2014). Other studies focus on drivers' behavioural patterns at intersections, reflecting drivers' risky decision making. For instance, drivers' partial compliance with stop-sign regulation, resulting to the prevalence of a rolling stop instead of a full stop (Feest, 1968; Lebbon et al., 2007; McKelvie, 1986; 1987; Retting et al., 2003; Wen et al., 2021), or drivers' duels for priority subject to informal rules, for example, a 'first come, first served' tendency, yielding to those drivers that maintain their speed and/or come from a road with broader breadth (Björklund and Åberg, 2005; De Ceunynck et al., 2013).

As yet, the pervasive role of third road user(s) between two negotiating ones in cross intersection episodes has not been explicitly studied. However, human drivers readily recognize situational constrains/opportunities due to the presence of third road users and often exploit them to their advantage. In this study, analysis of crossing episodes between two intersecting vehicles in which a third road user clearly affected its evolution was conducted. The main objectives were first, to reveal recurring patterns where the right-of-way is altered due to the presence of a third road user and second, to identify traffic situational invariances that eventually can be used by AVs to adapt their prediction algorithms accordingly. Integration of such traffic situational invariances may be pivotal for AVs' deployment in mixed traffic.

Method

A video-based observation method was used for examining crossing order at an urban stop-controlled intersection, in an attempt to identify episodes of stop-sign running that can be attributed to the presence of a third road user affecting the vehicle that had the right-of-way. Pedestrians, due to the complexity of their behaviour, were considered only when involved in a traffic episode with at least two intersecting vehicles. The data collection method was non-intrusive as the camera was inconspicuous to passing traffic.

Site Characteristics

Video-data were collected at a right-angle intersection formed by two one-way, one-lane urban streets regulated by a stop sign. This intersection is located in central Athens, Greece, at a residential neighbourhood with narrow road structure and small neighbourhood shops that mainly serves local traffic, that is, road users who are familiar with local traffic conventions. This particular intersection was selected as it was a busy location, where the presence of low-speed vehicles including two-wheelers and pedestrians, provided opportunities for frequent three player interactions among mixed road users.

A sketch of the intersection from the camera view appears in Figure 1, showing the two intersecting one-way streets of 5.5 m width, where one street has a stop sign (hereafter named ‘stop-signed’ street) while the cross street does not, so vehicles moving on this street do not need to stop (hereafter named ‘main’ street).

The vehicles’ movement direction at the intersection is regulated by two road signs (i.e. No Right Turn and No Left Turn signs, for the ‘main’ street and the ‘stop-signed’ street, respectively) with no marked pedestrian crossing. Due to parallel parked cars (Figure 1), each street is practically composed of one traffic lane implying that crossing or turning left/right at the intersection is possible by only one car at a time; however, this spatial limitation does not apply for other types of road users (i.e. powered two-wheelers, bicyclists) making possible the simultaneous crossing of more than one road users each time.

Apparatus

The camera used was a Go pro HERO session, recording at a resolution of 1920 x 1080 and a frame rate of approximatively 30 fps. The camera was installed on the top floor of a corner building, at a height of 15 m, offering a bird’s eye view of the two intersecting streets. The positioning of the camera enabled a view of the whole intersection throughout a length of about 40 m at each street, but some of the approach to the intersection was obscured (Figure 1).

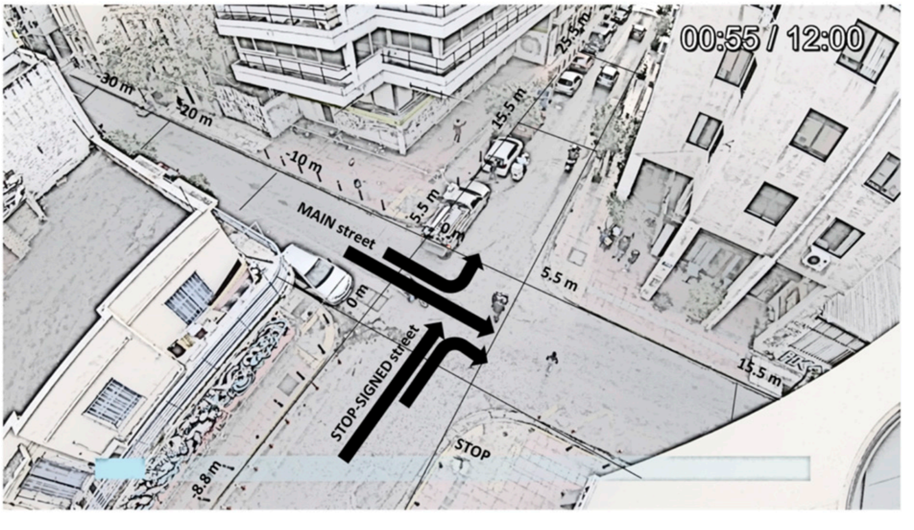

Figure 1. Observational camera view of the stop-controlled intersection studied.

Procedure

Video-recordings were made during weekday peak hours (Monday to Thursday, from 11:30 to 16:00). Weather conditions during data collection were mostly sunny ensuring good visibility of the road users' movements in the two intersecting streets. Frequent checks of camera recording and replacement of camera's memory card when necessary, were made by the researchers who were invisible to passing traffic. Allowing for changes of battery and memory card, a video footage of 986 minutes in total was collected.

Ethics

Data collection was conducted in accordance with National Technical University of Athens ethics procedures concerning observation of public behaviour. Due to the camera resolution and distance from the scene, vehicle plates as well as road users faces were non-identifiable.

Video-Observation Analysis

Data Pool of Traffic Episodes. Video-footage was first analysed by two separate analysts for identifying traffic episodes in which a vehicle crossed or turned right at the intersection before a vehicle that had the right-of-way.

For transparency purposes, (i) only episodes where a vehicle ran the stop sign while another vehicle was moving on the 'main' street at a distance less than 25 m from the intersection were included in the data pool; beyond that distance (>25 m) crossing or turning right of a vehicle moving on the stop-signed street was considered as practically non-intrusive to the vehicles moving on the 'main' street; (ii) a traffic episode was considered to start when a vehicle that had the right-of-way appeared in the 25 m zone and ended when this vehicle passed the intersection. At this stage, cascading episodes involving more than one vehicle breaching the right-of-way were also considered as one episode. Finally, (iii) as mentioned above, pedestrians were considered only when involved in a traffic episode with at least two intersecting vehicles.

Phenomenological Analysis of Traffic Episodes. Analysis of the selected traffic episodes permitted an initial filtering between two types: (i) episodes where a vehicle moving on the 'main' street was forced to yield the right-of-way only because of stop-sign running by a crossing vehicle (labelled as STOP-SIGN RUNNING episodes) and (ii) episodes where a vehicle moving on the 'main' street had already yielded for another road user, thus giving the opportunity to a vehicle moving on the 'stop-signed' street to cross or turn right at the same time slot (labelled as BLOCK-EXPLOITING episodes). From these selected episodes, 82% (126 out of 153) were BLOCK-EXPLOITING episodes and only 18% (27 out of 153) were STOP-SIGN RUNNING ones. The analysis was focused on BLOCK-EXPLOITING episodes.

More specifically, the term 'BLOCK-EXPLOITING' is introduced here to describe a driver's active search to exploit situational opportunities produced by the blocking of a vehicle that has the right-of-way, so as to easily cross an intersection before it. Usually such opportunities are presented when other road user(s) visibly affect the course of action of a vehicle that has the right-of-way, forming in turn, a temporary clearance to the vehicle(s) that have not.

From a phenomenological perspective the evolution of a BLOCK-EXPLOITING episode might be described according to the roles adopted by the road users involved in a given traffic scene, as follows: a BLOCK-EXPLOITER (i.e. vehicle moving on the 'stop-signed' street) passes the intersection before a BLOCKED vehicle (i.e. vehicle that has the right-of-way) by seizing the opportunity given from a BLOCKER (i.e. another road user) who affects the course of action of the BLOCKED.

To visually depict the aforementioned roles of the road users during a BLOCK-EXPLOITING episode, the following colour coding was used: a yellow-circled road user stands for BLOCK-EXPLOITER, a red-circled one for BLOCKER and a cyan-circled one for BLOCKED. Using this colour coding, a typical example of BLOCK-EXPLOITING behaviour is shown in Figure 2.

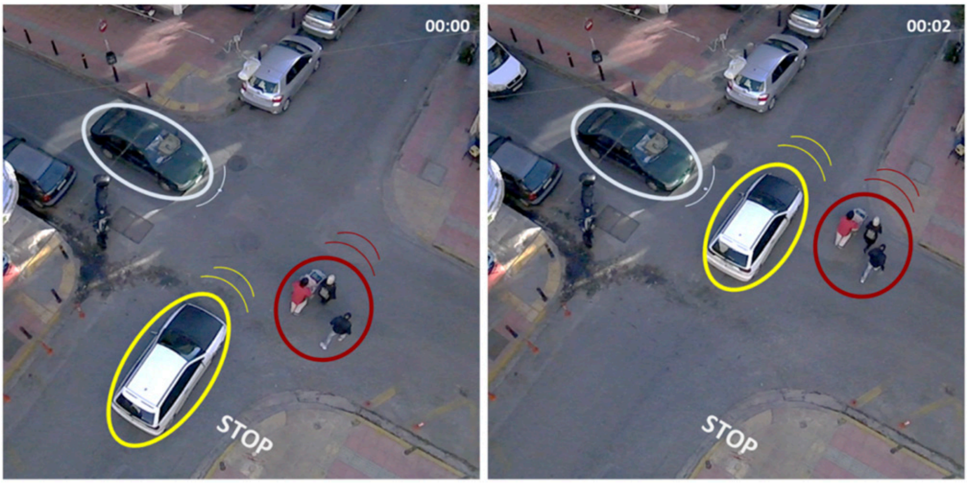

Figure 2. Coding scheme of the road users involved during a BLOCK-EXPLOITING episode. In this episode, a BLOCK-EXPLOITER (yellow-circled car) crosses before the car moving on the main street that is already BLOCKED (cyan-circled car) from the BLOKER (red-circled group of pedestrians).

At the beginning of this episode, a group of pedestrians (BLOCKER) has already initiated crossing the 'main' street, thus, forcing the vehicle that has the right-of-way (BLOCKED) to come to a full-stop before the intersection. At the same time, the driver moving on the 'stop-signed' street (BLOCK-EXPLOITER) can readily assess that the BLOCKED car will remain to a standstill by recognizing that this reaction is socially motivated, namely, making an 'offer' of a gap to the most vulnerable road users (group of pedestrians, with a stroller) without obstructing traffic on the 'stop-signed' street. That is to say, to the extent that a BLOCK-EXPLOITER is able to determine this situational inter-locking between the two other road users (i.e. connection between the movement of BLOCKER and the reaction of BLOCKED car), it is possible for them to cross before the BLOCKED car with the least effort, simply, by seizing the opportunity provided by the BLOCKER.

In reality, an external observer can never be certain about the motivation of either the driver of BLOCKED vehicle or BLOCK-EXPLOITER. Methodologically, the basic interpretation rule adopted during the analysis was that whenever the presence of a third road user visibly affected the traffic flow in the 'main' street, this was considered as the primary factor of altering the regulated road users' behaviour.

Processing of Traffic Episodes. Following the conceptual framework described above, all BLOCK-EXPLOITING episodes were analysed by two analysts sitting side-by-side to reduce observer biases. The analysis consisted of (i) writing a brief description of how an episode evolved, (ii) extracting three to four screenshots depicting the movement change of the road users involved in the episode and (iii) identifying the roles adopted by the road users involved in the given episode. Cascading episodes were further divided at this stage into partial ones involving one BLOCK-EXPLOITER per partial episode. Borderline cases, that is, disagreement between the two analysts, were excluded from further analysis. The annotated episodes were then used for identifying different types of BLOCK-EXPLOITING behaviour (see §3.2).

Additionally, the time-delay due to BLOCK-EXPLOITING was estimated by using the net time (sec) during which BLOCKED was affected by BLOCK-EXPLOITER. This was deemed appropriate since all episodes unfolded within two major time-windows. The first time-window lasted as long as the blocking condition was active (i.e. BLOCKER directly obstructed BLOCKED); the second one started from the moment that a BLOCK-EXPLOITER entered at the intersection until the moment of passing it (Figure 3). This gives rise to three possible exploitation levels: (i) the BLOCK-EXPLOITER starts and finishes crossing while the blocking condition is active (hereafter named as ‘Cautious’), (ii) the BLOCK-EXPLOITER starts crossing while the blocking condition is active and finishes crossing beyond the first time-window (hereafter named as ‘Marginal’) and finally (iii) the BLOCK-EXPLOITER starts and finishes crossing after the first time-window, that is, BLOCKER has stopped affecting BLOCKED (hereafter named as ‘Abusive’). These three exploitation levels permitted the evaluation of time-delays due to BLOCK-EXPLOITING (§3.3).

Results

In total 126 BLOCK-EXPLOITING episodes were included in the analysis while five additional ones were excluded as borderline cases (see §2.5.3). These 126 episodes consisted of 53 simple episodes and 27 cascading episodes (averaging 2.7 BLOCK-EXPLOITERs before the BLOCKED per cascading episode) resulting in total 73 partial episodes.

Descriptive Statistics

Traffic Flow Characteristics. Average traffic flow in the intersection during the observation period was as follows: 487 vehicles per hour in the ‘main’ street and 217 vehicles per hour in the ‘stop-signed’ street. This flow resulted in around 1.5 vehicle encounters per minute, within the 25m zone of the intersection. This roughly accounts to nine traffic episodes per hour.

Distribution of vehicle types included passenger cars (49% and 44%), powered two-wheelers (44% and 34%), light goods vehicles (6% and 11%), buses/trucks (1% and 9%) and pedal cyclists (0% and 1%), for the ‘main’ and ‘stop-signed’ street, respectively.

Block-Exploiting Episodes. In the 126 episodes analysed, 378 road users were identified in total, categorized into five types, as follows: cars, light goods vehicles (LGV), powered two-wheelers (PTW), pedal cyclists (PC) and pedestrians (PED). The majority of road users involved in a BLOCK-EXPLOITING episode were cars (61%) while the other road users fell into one of the four types in the following descending order: PTW (16%), PED (13%), LGV (9%) and PC (1%).

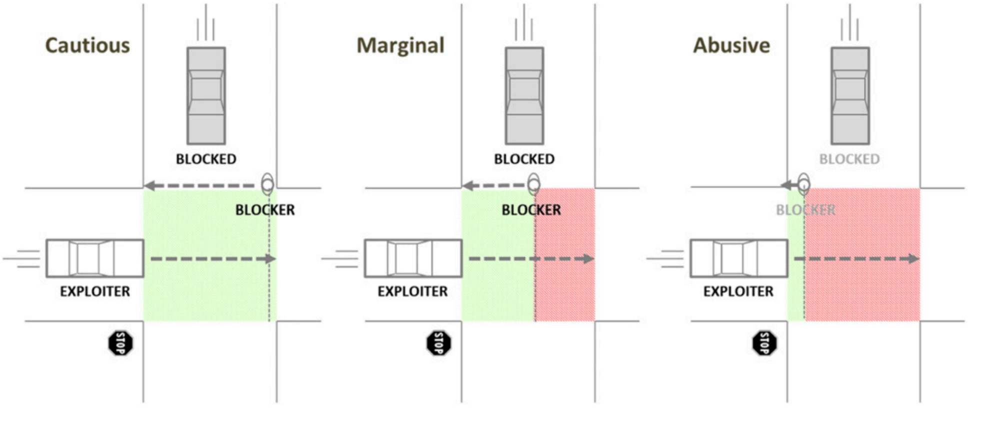

Figure 3. Three exploitation levels: (i) Cautious: a BLOCK-EXPLOITER crosses the intersection within the time-window that blocking condition is active (green-shadowed area); (ii) Marginal: a BLOCK-EXPLOITER initiates crossing while the blocking condition is active but finishes after the blocking has ceased (red-shadowed area); and (iii) Abusive: a BLOCK-EXPLOITER initiates crossing after the blocking has ceased (red-shadowed area).

The interactions among the five types of road users acting either as BLOCK-EXPLOITER or BLOCKER or BLOCKED during an episode is presented in Table 1.

As shown in Table 1, the vast majority (87%, 109 out of 126) of BLOCKED road users were automobiles (Cars, LGVs) and only 13% of them were powered two-wheelers (PTWs). Additionally, a vehicle that had the right-of-way was more frequently blocked by automobiles (Car, LGV) acting as BLOCKER (70%, 88 out of 126) followed by a pedestrian and a powered two-wheeler (PTW, PED), 20% and 10%, respectively. Finally, half of road users (52%, 66 out of 126) acting as BLOCK-EXPLOITER were automobiles (Cars, LGVs), almost a third of them (28%) were powered two-wheelers and pedal cyclists (PTWs, PC) and the rest 20% were pedestrians.

Types of Block-Exploiting

In this section, the most frequent types of BLOCK-EXPLOITING behaviour observed in this study are identified, taking the perspective of a road user moving on the 'stop-signed' street as a starting point. In total, four types were identified, named as piggybacking (11 out of 126), sneaking (18 out of 126), covering (60 out of 126) and ghost-covering (37 out of 126), described in detail below.

Piggybacking. Perhaps the most well-known type of BLOCK-EXPLOITING behaviour is the so-called 'piggybacking', in which two or more vehicles in a row cross an intersection before a vehicle that has the right-of-way (Vinkhuyzen and Cefkin, 2016). An example of piggybacking is shown in Figure 4, where a crossing vehicle (BLOCKER) that is temporarily blocking a car that has the right-of-way (BLOCKED) is seen as an opportunity for the BLOCK-EXPLOITER to form a rolling block with the BLOCKER by close following it. Evidently, the closer a BLOCK-EXPLOITER follows the lead vehicle (BLOCKER), the shorter the time-delay for the BLOCKED driver, but with a higher risk of rear-end collision.

Sneaking. A second type of BLOCK-EXPLOITING behaviour, partly related to 'piggybacking', was named 'sneaking'. The defining characteristic of 'sneaking' is that BLOCKER and BLOCKED are only loosely interlocked; so, blocking of the vehicle that has the right-of-way is co-created through proactive acts of BLOCK-EXPLOITER.

For instance, as depicted in Figure 5, a BLOCK-EXPLOITER seizes the opportunity given by the slow-turning left manoeuvre of the BLOCKER in the 'main' street by 'creeping' towards it, so as to force to a standstill the succeeding vehicle that has the right-of-way (BLOCKED). The same also holds true when

Table 1: Types of road users acting as BLOCK-EXPLOITER, BLOCKER or BLOCKED during a BLOCK-EXPLOITING episode (*note*: LGV: light goods vehicle; PTW: powered two-wheeler; PC: pedal cycle; PED: pedestrian).

		BLOCK-EXPLOITER					
BLOCKED	BLOCKER	Car	LGV	PTW	PC	PED	Total
Car	Car	21	6	14	1	16	58
	LGV	3	—	2	—	—	5
	PTW	6	—	1	1	2	10
	PED	12	2	2	—	2	18
LGV	Car	7	1	5	1	2	16
	PTW	1	—	—	—	—	1
	PC	1	—	—	—	—	1
PTW	Car	2	—	6	—	1	9
	PTW	1	—	—	—	—	1
	PED	3	—	2	—	2	7
Total		57	9	32	3	25	126

Figure 4. ‘Piggybacking’ episode. A BLOCK-EXPLOITER is close-following the lead car (BLOCKER); thus, two cars in a row are crossing the intersection before the car that has the right-of-way (BLOCKED) (*note*: cyan-circled car: BLOCKED; red-circled car: BLOCKER; yellow-circled car: BLOCK-EXPLOITER).

Figure 5. ‘Sneaking’ episode. A BLOCK-EXPLOITER waits the car that has the right-of-way to turn left; by the moment the latter (BLOCKER) turns left the BLOCK-EXPLOITER ‘creeps’ towards it, thus, forces the following car that has the right-of-way (BLOCKED) to yield (*note*: cyan-circled car: BLOCKED; red-circled car: BLOCKER; yellow-circled car: BLOCK-EXPLOITER).

a BLOCK-EXPLOITER attempts to make a right turn by ‘creeping’ towards the rear end of a vehicle crossing the intersection (semi-BLOCKER) forcing, thus, the next coming car (BLOCKED) to yield the right-of-way. Note that neither the BLOCKER nor the BLOCK-EXPLOITER alone is sufficient to fully block the next coming vehicle from the ‘main’ street. It is the BLOCK-EXPLOITER’s creeping towards to the deaccelerating BLOCKER and piggy-backing on it that eventually forces the BLOCKED car to yield. On this account, a key issue is that the creeping act may increase the risk of collision, affecting both the effectiveness

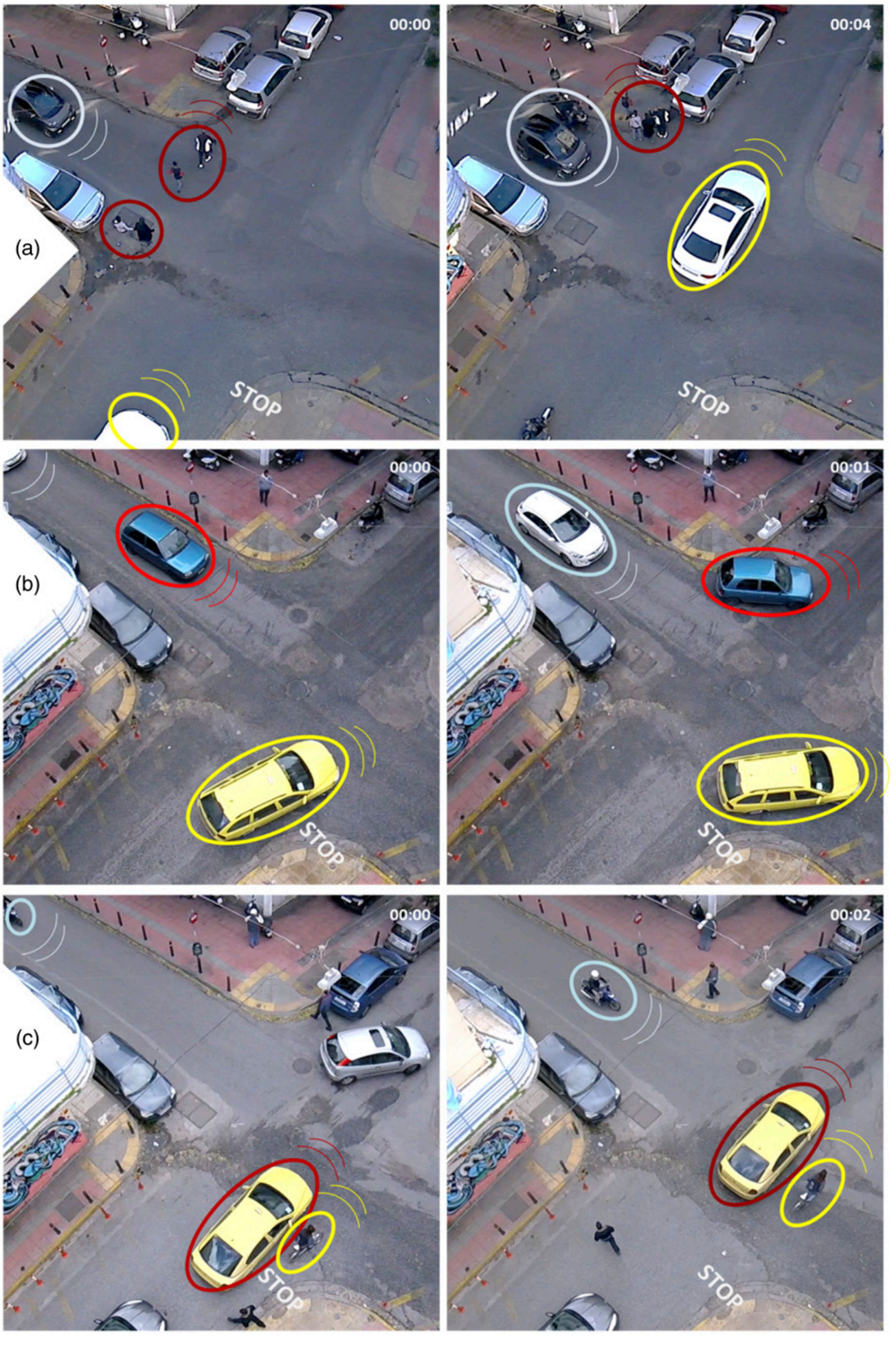

Figure 6. Variations of 'covering' episodes: (a) A BLOCK-EXPLOITER covered by crossing pedestrians (BLOCKER) crosses the intersection before the BLOCKED car; (b) A BLOCK-EXPLOITER covered by the left-turning priority car (BLOCKER) makes a right turn during the same time-slot; (c) A BLOCK-EXPLOITER covered by the crossing car (BLOCKER) crosses simultaneously before the BLOCKED vehicle (*note*: cyan-circled road user: BLOCKED; red-circled road user: BLOCKER; yellow-circled road user: BLOCK-EXPLOITER).

and social acceptability of 'sneaking' in terms of traffic efficiency.

Covering. Under the umbrella term 'covering' fall cases where a BLOCK-EXPLOITER seizes the opportunity of an already BLOCKED vehicle by another road user (BLOCKER), so that two or more road users move in parallel crossing the intersection before the BLOCKED. Some variations of 'covering' are discussed below.

A typical example of 'covering' is shown in Figure 6a, where a group of pedestrians already crossing the street in a row form a 'chain' of people (BLOCKER) in front of the BLOCKED car, thus offering an opportunity for a BLOCK-EXPLOITER to unhesitatingly cross the intersection during the same time-slot. Quite often, also, a BLOCK-EXPLOITER finds a niche to cross the intersection before a slow-moving car on the 'main street' that also acts as BLOCKER to the following vehicles behind it (BLOCKED), or to turn right at the same time with a left-turning car from the 'main' street, that also acts as BLOCKER (Figure 6b). Evidently, early recognition of the other driver's motion intention by the BLOCK-EXPLOITER as well as movement coordination are the two crucial factors for a successful parallel turning both in terms of accident risk and traffic efficiency.

Finally, another variation of 'covering' which was usually observed by two-wheelers due to the narrowness of the specific road is seen in Figure 6c. In the beginning of this episode, the BLOCK-EXPLOITER is intentionally being positioned on the side of the car waiting to cross (BLOCKER) so that, by the moment the latter one initiates crossing the BLOCK-EXPLOITER crosses simultaneously, seizing the opportunity of being covered by the BLOCKER. It seems that this practice not only increases the safety of a vulnerable road user (cyclist) but also provides an ecological solution for slow-moving road users to cross the intersection in a time-saving and relatively safe manner.

Ghost-Covering. In 'ghost-covering', the main difference is that the BLOCK-EXPLOITER is not physically covered by the BLOCKER but exploits the position of the latter to pass between BLOCKER and BLOCKED. A typical example of 'ghost-covering' has been already presented in section §2.5.2 (Figure 2). Another typical example is shown in Figure 7, where the traffic congestion after the intersection (BLOCKER) not only forces the BLOCKED car to a standstill before the intersection but also offers 'ghost-covering' to the upcoming BLOCK-EXPLOITER. Evidently, to the extent that a BLOCK-EXPLOITER is able to determine the 'ghost-covering' offered by the BLOCKER, the risk of crossing before the BLOCKED car is almost zero.

Time-delays

The frequency distribution of the episodes in terms of exploitation level (i.e. Cautious, Marginal, Abusive, see §2.5.3) as well as the time-delay (sec) of BLOCKED due to BLOCK-EXPLOITER, are summarised in Table 2. As it comes out, the dominant exploitation level was Cautious (63%, 80 out of 126), followed by Marginal (27%, 34 out of 126) and Abusive (10%, 12 out of 126).

It is worth to mention that, 97% (94 out of 97) of 'covering' and 'ghost-covering' episodes either finished while the blocking condition was active, that is, Cautious exploitation (81%) or slightly exceeding this time interval, that is, Marginal exploitation (15%). In contrast, 97% (28 out of 29) of 'piggybacking' and 'sneaking' episodes either finished after the blocking condition had ended, that is, Marginal exploitation (66%) or started after the blocking condition was over, that is, Abusive exploitation (31%).

As far as the time-delay of BLOCKED due to BLOCK-EXPLOITER, it was on average 1.3 sec lower in Marginal exploitation (1.98 sec) compared to Abusive exploitation (3.25 sec) which was evident in all types of BLOCK-EXPLOITING apart from 'sneaking'.

Analysis of communicative co-ordination between involved road users

Achieving traffic co-ordination by disobeying the traffic rules necessitates tacit knowledge and implicit communication between all road users involved. This becomes more evident when considering cascading BLOCK-EXPLOITING episodes.

Figure 7. 'Ghost-covering' episode. A BLOCK-EXPLOITER crosses the intersection before the BLOCKED car due to the traffic congestion after the intersection (BLOCKER) (*note*: cyan-circled car: BLOCKED; red-circled car: BLOCKER; yellow-circled car: BLOCK-EXPLOITER).

Table 2: Number of episodes per BLOCK-EXPLOITING type (P: piggybacking, S: sneaking, C: covering, G: ghost-covering) and level of exploitation (i.e. Cautious, Marginal and Abusive) according to time-delay (sec) of BLOCKED.

	BLOCK-EXPLOITING type											
	Frequency						Time-delay					
Exploitation level	*P*		*S*	*C*	*G*	All		*P*	*S*	*C*	*G*	All
Cautious	*f*	0	1	48	31	**80**	*M*	n/a	n/a	n/a	n/a	**n/a**
							SD					
Marginal	*f*	4	15	12	3	**34**	*M*	1.75	2.30	1.71	3.00	**1.98**
							SD	(0.50)	(0.96)	(1.23)	(1.00)	**(1.05)**
Abusive	*f*	7	2	0	3	**12**	*M*	3.14	4.00	n/a	3.00	**3.25**
							SD	(1.07)	(0.00)		(1.00)	**(0.97)**

An example of such an episode is shown in Figure 8, where (i) an initial traffic flow interruption by a PTW moving on the 'stop-signed' street gives also rise to 'piggybacking' by the following car (first BLOCK-EXPLOITER) forcing the BLOCKED car to decelerate sharply (Figures 8a-b); (ii) accordingly, the former 'piggybacker' serves as BLOCKER for two succeeding BLOCK-EXPLOITERs, that is, a next coming 'piggybacker' and a 'covering' pedestrian (Figure 8c). Finally, (iii) the traffic flow interruption in the 'main' street is partially ended by a coming PTW who manages to pass between the two remaining BLOCK-EXPLOITERs (Figure 8d). Note that, albeit increased risk, the above episode enhances traffic efficiency, that is, a total of four road users crossed before the vehicle that had the right-of-way, in less than eight seconds.

Two important observations can be derived from the above cascading episode.

First, the BLOCK-EXPLOITERs' involvement is based on their projection of how the traffic scene will evolve in the near future taking into account both the future position of the BLOCKER and the apparent movement constraints of the BLOCKED vehicle. Neither of these two projections is purely kinematic but also grounded on (i) '*the fact that the other road*

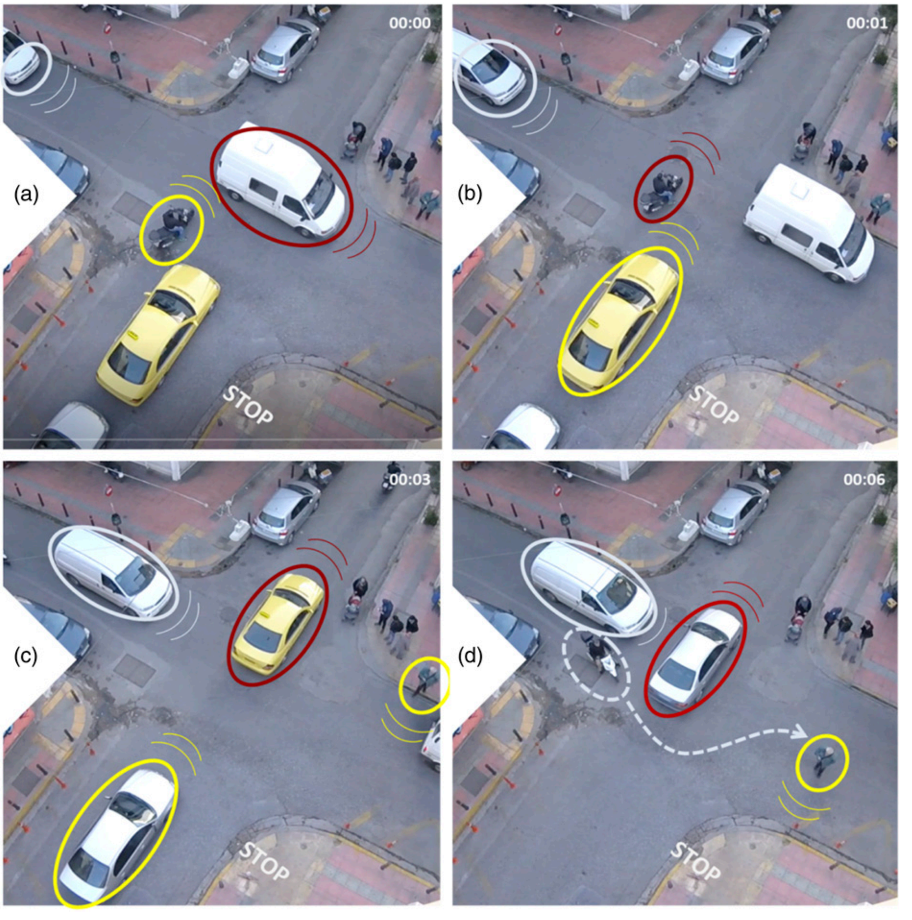

Figure 8. Cascading block-exploiting episode: (a–b) A BLOCK-EXPLOITER follows closely the lead scooter (BLOCKER) so as two vehicles in a row cross the intersection before the BLOCKED car; (c) the former 'piggybacker' serves as BLOCKER for two succeeding BLOCK-EXPLOITERs, that is, next coming 'piggybacker' and 'covering' pedestrian; (d) end of blocking by the priority rider who passes through the two BLOCK-EXPLOITERs (*note*: cyan-circled road user: BLOCKED; red-circled road user: BLOCKER; yellow-circled road user: BLOCK-EXPLOITER).

users will respond to self-actions and (ii) *the knowledge of how other road users might react to self-actions*' (Zhao et al., 2021, p. 454). This can be easily understood at the beginning of the episode above, where the first two BLOCK-EXPLOITERs seem to force the driver of the BLOCKED car to slow down against traffic rules. Such a forcing action is situationally legitimatized based on the shared knowledge that in dense urban traffic the delay of a vehicle that has the right-of-way is socially preferable for balancing the traffic delay on road users moving on the 'stop-signed' street. Conversely, non-conforming to the socially expected action plan will not only lead to the decay of traffic efficiency but also to increased traffic risk, as is the case with drivers who are unfamiliar to the social conventions of a particular setting. Although being precautious and compliant to traffic rules, unfamiliar drivers may nevertheless jeopardize the traffic choreography or even cause traffic accident due to not socially conforming behaviour.

A final broader issue is related to the tolerance of BLOCKED road users against breaching the right-of-way. For instance, during the course of the episode above, both second and third BLOCK-EXPLOITERs seize the opportunity given by a previously acting BLOCK-EXPLOITER forcing the BLOCKED car to an even longer standstill. Video observations in this particular traffic setting suggest that a cascading episode is accepted for as long as the BLOCKED vehicle is physically constrained by the initial BLOCK-EXPLOITER whereas, arrival of each additional BLOCK-EXPLOITER is typically followed by an ‘edging’ of BLOCKED towards the intersection signifying an attempt to interrupt a subsequent block-exploiting to take place. This edging of the BLOCKED vehicle is interpreted as a complaint of Abusive exploitation suggesting that there is a limit of ego-delay acceptance.

Discussion

In this study, a phenomenological analysis of crossing order violations at an urban stop-controlled intersection was conducted, in an attempt to identify recurring patterns where the right-of-way was altered due to the presence of a third road user, against traffic rules. Such types of traffic situations, although critical for the deployment of AVs in mixed traffic environment, especially in dense urban traffic (e.g. Boggs et al., 2020; Reed et al., 2021), have not received much attention in driving behaviour models and related studies.

Co-ordination of vehicles’ crossing order involving more than two road users, can be more properly described as a joint-activity (Klein et al., 2005) rather than as a ‘Chicken’ game (Fox et al., 2018), provided that the two basic requirements for effective coordination (i.e. Basic Compact and Common Ground) are met. As mentioned in the introduction, in the case of driving, the Basic Compact between road users unknown to each-other is a tacit willingness to relax their often competing individual goals, in favour of overall traffic efficiency. This Basic Compact may promote traffic efficiency over compliance to traffic code. Likewise, the Common Ground, in traffic encounters with very limited time horizon and communication opportunities, is established and maintained predominantly through shared conventions and practices, while coordination is enabled through timely exchanged cues.

To examine in detail the road users’ tacit knowledge on how and when rule-breaking of crossing order at a stop-controlled intersection is appropriate and socially acceptable, the term ‘BLOCK-EXPLOITING’ was introduced. In this study, the term BLOCK-EXPLOITING designates a driver’s deliberate intention to cross before a vehicle that has the right-of-way exploiting the latter being temporarily constrained by another road user.

Noteworthy that BLOCK-EXPLOITING is neither necessarily limited to the vehicle(s) moving on the ‘stop-signed’ street nor to one road user each time; depending on the traffic situation and its dynamics, any given set of road users could potentially act as BLOCK-EXPLOITERs. However, for reasons of clarity and methodological consistency, in this study only those BLOCK-EXPLOITING episodes in which the presence of a single third road user visibly affected the traffic flow in the ‘main’ street were considered for further analysis, in order to avoid possible interpretation biases about road users’ motivational factors for altering the regulated crossing order.

Following the above selection criterion, in total, 126 BLOCK-EXPLOITING episodes were analysed and described in the section §2.5.2. Four major types of BLOCK-EXPLOITING behaviour were identified, named as piggybacking, sneaking, covering and ghost-covering.

A main distinction among these four types lies on the role of BLOCK-EXPLOITER during an episode. In both piggybacking and sneaking, the BLOCK-EXPLOITER by definition has an active involvement into forcing the BLOCKED to yield, while in covering and ghost-covering, the BLOCK-EXPLOITER is passive in the sense that yielding of BLOCKED is effected exclusively by a third road user (BLOCKER). Correspondingly, in the first two types of BLOCK-EXPLOITING (i.e. piggybacking, sneaking), hereafter named as active types, crossing of BLOCK-EXPLOITER is feasible only after the BLOCKER has stopped to affect BLOCKED; while in the latter two types (i.e. covering, ghost-covering), hereafter named as passive types, crossing of BLOCK-EXPLOITER is feasible while the blocking condition is still active.

A key issue arising from the recognition of the various types of BLOCK-EXPLOITING behaviour is the social acceptability of the different types based on values of traffic efficiency and levels of risk. To the authors' opinion, this issue is pivotal to the challenge of enabling an AV to act as BLOCKER or BLOCK-EXPLOITER in the future mixed traffic environments.

Social acceptability of Block-Exploiting

Results of this study show that of the total 153 stop-sign running episodes, the great majority (82%, 126 out of 153) involved BLOCK-EXPLOITING with only 18% being simple one to one encounters (i.e. not involving situational opportunities offered by a third road user).

In fact, the readiness of human road users to immediately discern and exploit such situational opportunities offered by a third road user was ubiquitous in all types of BLOCK-EXPLOITING. However, most (77%, 97 out of 126) of the episodes analysed in this study were passive types of BLOCK-EXPLOITING [covering (48%); ghost-covering (29%)] with only about one fourth (23%, 29 out of 126) being active types [piggybacking (9%); sneaking (14%)]. This finding clearly suggests that human road users are more inclined to act as BLOCK-EXPLOITERs in traffic situations where the stage is already prepared by others. In addition, in passive types of BLOCK-EXPLOITING there is no need to intentionally hinder others' movements along with the negative social connotations that this entails. This seems to result in the widespread acceptability of the two passive types of BLOCK-EXPLOITING while the social acceptance of the two active types of BLOCK-EXPLOITING seems to be context-dependent.

Secondly, the majority (81%, 79 out of 97) of passive types of BLOCK-EXPLOITING did not result in any delay of BLOCKED (i.e. Cautious exploitation) while in the vast majority of active types (97%, 28 out of 29) the mean delay of BLOCKED ranged from 1.99 to 3.33 sec, in Marginal and Abusive exploitation, respectively.

It is important to note that the delays induced from BLOCK-EXPLOITING might be judged either as positive or neutral from the perspective of overall traffic flow. Indeed, Cautious exploitation leads to clear gains for overall traffic efficiency, compared to traffic adhering to traffic code, since the BLOCKED would anyway remain standstill during BLOCK-EXPLOITER crossing. Marginal exploitation leads to relative gains taking into account the time that BLOCKED would anyway remain standstill. Finally, in Abusive exploitation, notwithstanding increased risk, there is stochastically neither gain nor loss in efficiency, in the sense that the crossing time of BLOCK-EXPLOITER is theoretically equal to that of BLOCKED, assuming that they both start crossing from a standstill position.

From the BLOCKED's point of view, on the other hand, Cautious exploitation leads to no additional time delay; Marginal exploitation exerts some additional time delay depending on the traffic situation, while Abusive exploitation is the most time-consuming scenario since the BLOCK-EXPLOITER clearly acts antagonistically to BLOCKED. Thus, from the BLOCKED's perspective, Abusive exploitation and occasionally Marginal exploitation may be perceived as anti-social behaviours (Faghisolouk et al., 2021; Nordfjærn and Şimşekoğlu, 2014). According to the above, the two passive types of BLOCK-EXPLOITING are judged as the most effective and socially acceptable both in terms of delay and risk-taking. In contrast, in active types, effective coordination of road users largely depends on the driving skills and timely actions of BLOCK-EXPLOITER, so, in addition to prolonging the delay of BLOCKED they raise questions in terms of traffic safety.

Finally, less than half (41%, 53 out of 126) of the episodes analysed in this study were simple BLOCK-EXPLOITING episodes while the rest were parts of cascading episodes, averaging 2.7 BLOCK-EXPLOITERs per cascading episode. In essence, the escalation of a BLOCK-EXPLOITING episode exacerbates the dilemma of tolerating or not traffic rules violation in dense urban traffic. On the one side there is the socially recognized need for balancing the delay of all road users while on the other, there is the realistic need for maintaining the regulatory structure of traffic priority rules. The rather blurry line separating adaptive from malformed traffic seems to depend on local conventions which demarcate certain types of BLOCK-EXPLOITING and tolerance limits as socially acceptable. Video observations in this particular traffic setting showed that a cascading episode was socially acceptable for as long as the BLOCKED was physically constrained by the initial BLOCK-EXPLOITER. Indeed, when this condition applies as in covering and ghost-covering, a cascading episode can improve traffic efficiency by bringing about a controlled deviation from the regulatory structure. This trade-off does not seem to apply in active types of BLOCK-EXPLOITING.

Putting these findings in terms of joint-activity, in the two passive types of BLOCK-EXPLOITING (covering, ghost-covering), the Basic Compact is evidently manifested by the willingness of BLOCKED driver to yield the right-of-way as long as he remains constrained in his progress, while the Common Ground (i.e. facilitation of a driver moving on the ‘stop-signed’ street) is established upon the shared knowledge that a particular third user acts as BLOCKER as well as the shared convention that yielding the right-of way occurs within the time-window of BLOCKER’s crossing. To the extent that these two requirements are met, effective coordination can be easily achieved using only motion cues (e.g. crossing rate of a BLOCKER). In contrast, in the two active types of BLOCK-EXPLOITING (piggybacking, sneaking), the Basic Compact is maintained as long as the BLOCK-EXPLOITING serves global traffic efficiency goals. Practically, this means that Basic Compact is maintained only during the time window that the driver that has the right-of-way is blocked by a third user (BLOCKER). Further to it, the Common Ground is established upon shared conventions about the appropriate manner and timing that a driver manifests the intended BLOCK-EXPLOITING behaviour (e.g. creeping, edging). In any case, the more familiar the road users are with a particular traffic environment, the less their Basic Compact depends on the traffic code and more to their tacit willingness to maintain overall traffic efficiency. In addition, the developed conventions that form their initial Common Ground enhance coordination, resulting in a traffic flow far more efficient than that expected by a strict adherence to the traffic code.

Description of informal traffic coordination among multiple road users as a joint-activity has also important implications for effective coordination among human-driven and autonomous vehicles in future mixed traffic environments. In general, contemporary decision making modules of AVs are organized with the following priority: i) safety, ii) legality and iii) efficiency. The findings of this study suggest that apart from the fundamental priority of safety, the Basic Compact would be maintained if decision making of an AV put more emphasis on global traffic efficiency even to the detriment of fully complying traffic rules. In addition, the findings stress the need for maintaining Common Ground with human road users either through integrating common conventions in the intention-prediction algorithms of AVs or through dynamic coordination based on connectivity technologies. With no doubt, maintaining Common Ground with human road users will turn to be a key issue towards avoiding coordination failures among human-driven and autonomous vehicles or even new forms of automation failures obscure to human road users thus, more difficult to be handled (Bainbridge, 1983; Woods, 1996).

Could an AV act as BLOCKER or BLOCK-EXPLOITER?

From an AV perspective, the ability to establish and maintain Common Ground with human road users, namely, to infer an intended BLOCK-EXPLOITING by human road users and, even more, to coordinate its course of action as BLOCK-EXPLOITER with them (e.g. pedestrians, cyclists, conventional vehicles) can be quite challenging. Although the present analysis is based on road users' interactions in conventional traffic environment, it is possible to put forward a set of design challenges arising for AVs by examining some exemplar cases of road users' coordination observed in this study.

Will the Other Road User Run Into Me?. Consider, for example, the frequent practice of 'covering' by two-wheelers at intersections (Figure 6c). A human driver waiting to cross can easily understand a two-wheeler's 'covering' intent. An AV, however, should first determine whether the two-wheeler's movement signifies an intended 'covering' action or errant driving behaviour. Then, it should be technically possible for an AV to share a limited road opening with another vehicle moving in close lateral proximity. The same also holds true in the case of 'piggybacking'. Inability of an AV to infer an intended 'piggybacking' action may lead the AV into a hurried avoidance movement resulting in confusion and disorganization to all road users involved. *Therefore, a design challenge for effective deployment of AVs in mixed traffic environment is their ability to determine whether the movement course of another vehicle signifies a BLOCK-EXPLOITING action or errant driving behaviour.*

Is this 'Space-Offering' for me?. A second design issue arises from the need of an AV to identify the origin of situational blocking between two other road users of interest. In general, this information could be extracted by projecting the trajectories of all road users that may affect an AV's course of action in the near future (Schwarting et al., 2019; Zhao et al., 2021; Zyner et al., 2018); however, this may not be sufficient in the case of 'ghost-covering'. For example, the presence of a stationary car that has the right-of-way before the intersection (i.e. cyan-circled car in Figure 7) provides an ambiguous signal regarding its movement intention. (Does the driver intend to turn left and needs extra time? … to pass behind the crossing pedestrians? …to facilitate vulnerable road users?). A human driver can clarify this as a provisional sign of 'space-offering' based on their tacit knowledge about the actions suggesting an 'offer' (Laurier, 2019; Kendrick and Drew, 2016), as well as its connotation, that is, decongesting the intersection for as long as necessary for the pedestrians to cross. An AV, however, should first be able to determine whether 'space-offering' is primarily destined to another road user or the AV itself. Then, it should be possible for an AV to infer the socially acceptable range of actions to follow within a time-window based on the needs of another road user rather than those of itself. *Therefore, a second design challenge for effective deployment of AVs in mixed traffic environment is their ability to determine whether 'space-offering' is addressed to the AV itself or to another road user, and to recognise the time limits of this offer for non-trespassing upon the others' generosity.*

Is there room for Another Block-Exploiter?. Finally, a challenging issue arises from the road users' pressure for maximizing their gains as a cascading BLOCK-EXPLOITING episode unfolds, without jeopardizing the general traffic. Consider, for example, an AV acting either as BLOCK-EXPLOITER or BLOCKED in the cascading episode shown in Figure 8. In both scenarios, an AV focused only on the current position of the other road users would run the risk of either causing an aggressive reaction from the other road users due to Abusive exploitation by the AV (Lee et al., 2021; Li, 2022) or falling into a long-time standstill due to Abusive exploitation by the other road users (Liu et al., 2020; Zhao et al., 2021). *Therefore, a third design challenge for effective deployment of AVs in mixed traffic environment is their ability to track the local history among the road users involved in a developing episode for assessing the appropriateness or abusiveness of their future action possibilities.*

The above projections of future design challenges for AVs are tentative and should be read with caution given the ongoing debate on whether it is socially desirable for an AV to present humanlike behaviour (Li et al., 2022; Liu et al., 2019; Mueller et al., 2020). In any case, the proposed phenomenological framework seems promising to extent our understanding on how human drivers will adapt their behaviour in the future mixed traffic, yielding fruitful feedback for designing coordination among multiple road users including various autonomous vehicles.

Limitations and Future Research

A few limitations of this study are worth noting. Specifically, the types of BLOCK-EXPLOITING identified in this study were extracted from a one-way, stop-controlled intersection where only one car could cross each time. This resulted in the absence of more complex interactions as might be expected, for example, at two-way stop-controlled intersections (Early et al., 2016). Therefore, the four types of BLOCK-EXPLOITING identified should not be construed as an exhaustive list but rather as generative types of BLOCK-EXPLOITING behaviour that need to be further elaborated in future studies. Second, although these types of behaviour can be observed in many different cultures, their frequency and social acceptability are deeply intertwined with prevailing cultural norms. Therefore, these findings need to be enriched with cross-cultural studies. Finally, methodologically wise, the interpretation of social acceptability of the four types of BLOCK-EXPLOITING was interpretative in nature, based on observable vehicle reactions and knowledge of local socio-cultural norms shared by both by observed road users and analysts rather than on declared statements of the road users observed.

Conclusions

The term BLOCK-EXPLOITING was introduced in this study to describe a common practice observed in urban intersections where a road user exploits traffic situational opportunities to gain priority in violation of the traffic code. Such practices are embedded in local socio-cultural norms and, depending on the situation, may present advantages in terms of traffic efficiency.

Four generic types of BLOCK-EXPLOITING were identified (i.e. piggybacking, sneaking, covering, ghost-covering) and it is advocated that they can be socially acceptable provided that BLOCK-EXPLOITERs' actions are timely, inter-predictable and, not endangering to others.

In this sense, covering and ghost-covering are the two predominant types of BLOCK-EXPLOITING behaviour that seem beneficial to remain in use in future mixed traffic environments and should definitively be addressed and possibly also adopted by AVs. On the other hand, piggybacking and sneaking raise questions in terms of traffic safety. However, the need for AVs to be able to recognize a human road user's intention of both piggybacking and sneaking will not cease to exist.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work is a part of the Hi-Drive project. Hi-Drive has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no 101006664. Content reflects only the authors' view and European Commission is not responsible for any use that may be made of the information it contains.

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