Theoretical Issues in Ergonomics Science

ISSN: 1463-922X (Print) 1464-536X (Online) Journal homepage: https://www.tandfonline.com/loi/ttie20

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https://doi.org/10.1080/1463922X.2020.1736686

Defining interactions: a conceptual framework for understanding interactive behaviour in human and automated road traffic

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ABSTRACT
Rapid advances in technology for highly automated vehicles (HAVs) have raised concerns about coexistence of HAVs and human road users. Although there is a long tradition of research into human road user interactions, there is a lack of shared models and terminology to support cross-disciplinary research and development towards safe and acceptable interaction-capable HAVs. Here, we review the main themes and findings in previous theoretical and empirical interaction research, and find large variability in perspectives and terminologies. We unify these perspectives in a structured, cross-theoretical conceptual framework, describing what road traffic interactions are, how they arise, and how they get resolved. Two key contributions are: (1) a stringent definition of "interaction", as "a situation where the behaviour of at least two road users can be interpreted as being influenced by the possibility that they are both intending to occupy the same region of space at the same time in the near future", and (2) a taxonomy of the types of behaviours that road users exhibit in interactions. We hope that this conceptual framework will be useful in the development of improved empirical methodology, theoretical models, and technical requirements on vehicle automation.

ARTICLE HISTORY
Received 8 January 2020
Accepted 26 February 2020

KEYWORDS
Road vehicles; human behaviour; human-automation interaction; conflicts; communication

Relevance to human factors/Relevance to ergonomics theory

Smooth interactions with other road users—human or automated—is central to human safety, efficiency and satisfaction in road traffic. This paper ties together previously disparate theoretical and empirical work on road traffic interactions into a single conceptual theoretical framework.

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Introduction

The general study of how humans interact and communicate with each other is a large and multifaceted intellectual endeavour, dating back millennia and spanning a wide range of academic disciplines, including philosophy, sociology, and anthropology (Bowles and Gintis 2003; Eco 1986; Gatewood 1985; Goffman 1961), linguistics (Austin 1962; Searle 1975), psychology and human factors (Zalesny, Salas, and Prince 1995; Klein, Wiggins, and Dominguez 2010), cognitive neuroscience and biology (Bshary and Bergmüller 2008; Pezzulo, Donnarumma, and Dindo 2013), as well as artificial intelligence and robotics (Mavridis 2015; Hill, Ford, and Farreras 2015), and more. An interesting subdomain of this enterprise concerns interactions in road traffic, between drivers, riders, cyclists, pedestrians and so on. These road traffic interactions retain many of the features of human interaction in general, such as coordination, collaboration, competition, and negotiation (Elvik 2014; e.g., Choudhury et al. 2007; Risser 1985) as well as communication both in the form of language-like signs (e.g., turn indicators) and the "body language" of how one moves on or near the road (Sucha, Dostal, and Risser 2017; Domeyer et al. 2019; Portouli, Nathanael, and Marmaras 2014). Interactive behaviour in traffic also has clear applied societal relevance through the connection to road safety. For example, interaction failures where one driver assumes that another driver will be yielding have been identified as a key contributory factor behind fatal intersection crashes (Ljung Aust, Fagerlind, and Sagberg 2012), and similar misunderstandings, such as a failure to clearly communicate one's own intended future behaviour, have been observed in safety-critical car-pedestrian incidents (Habibovic et al. 2013). Therefore, traffic interactions have been investigated both for their applied importance and their general relevance to human interaction, in a number of different fields, including road safety engineering (Tarko 2012; Svensson 1998; Hydén 1987), traffic psychology (Elvik 2014; Risser 1985; Renner and Johansson 2006), as well as anthropology and sociology (Merlino and Mondada 2019; Goffman 1971; Haddington and Rauniomaa 2014; Portouli, Nathanael, and Marmaras 2014), but using different tools, theoretical perspectives, and terminologies, to address slightly different aspects of the phenomenon of road traffic interactions. At present, there is no unifying conceptual framework bringing these different perspectives together, to support effective cross-fertilisation of theories and methods.

Over the last few years, road traffic interaction research has come increasingly into the spotlight, with the deployment of capable driver assistance and automation systems, and the prospect of fully self-driving vehicles at some point in the future (e.g., SAE levels 4 and 5; Society of Automotive Engineers 2018). There are large hoped-for societal and economic benefits of such highly automated vehicles (HAVs) (Fagnant and Kockelman 2015; Dia and Javanshour 2017; Piao et al. 2016), but it is increasingly acknowledged that interactions with human road users constitute a key challenge for the HAV development (Brown and Laurie 2017; Schieben et al. 2019; Millard-Ball 2016; Brooks 2017; Rasouli and Tsotsos 2019). Failure of a HAV to successfully interact with human road users may lead to congestion and human frustration, as a result of overly cautious behaviour on the part of the HAV (Millard-Ball 2016; Brown and Laurie 2017), or may even lead to crashes, if HAVs behave in ways that are unexpected by human road users (Alambeigi, McDonald, and Tankasala 2020). Improved understanding and models—both qualitative and quantitative—of how humans interact in traffic is a key prerequisite for vehicle manufacturers and software developers to program HAVs to successfully interact with humans (Camara et al. 2019; Markkula et al. 2018; Sadigh et al. 2018; Schwarting et al. 2019). This adds urgency to previously existing interaction-related research questions, and also introduces new research questions specific to human-machine interaction, for example whether and how eye contact or other human communicative gestures ought to be replaced with external human-machine interfaces (Merat et al. 2018; Clamann 2015; Cefkin et al. 2019). In this context, when user interface designers, vehicle engineers, and machine learning scientists are joining the already cross-disciplinary mix of anthropologists, traffic psychologists, and human factors researchers studying interactions, the importance of a shared conceptual understanding, and an agreed set of terms and definitions, is even stronger.

Therefore, our key objective in this paper is the provision of a high-level, conceptual framework for defining, describing and discussing road traffic interactions, using a cross-disciplinary approach. We see a number of key advantages of developing this conceptual framework. Firstly, clear definitions of terms can help make communication between researchers more effective. Secondly, empirical methodology for observation of interactions will benefit from being based on precise definitions of not least (1) what an interaction is, and (2) a taxonomy of different types of interactive behaviours to be studied; the present paper provides both of these. Thirdly. setting of technical requirements on HAVs, will benefit from being based on a comprehensive and structured overview of how road traffic interactions work, and what interaction capabilities HAVs are therefore likely to need. Fourthly and finally, the framework can also form the basis for further development of more complete quantitative models of interaction behaviour, which in turn can be used to develop, test and further optimise HAVs (Camara et al. 2019; Markkula et al. 2018; Sadigh et al. 2018; Schwarting et al. 2019).

We begin the paper by providing a literature review, summarising the diverse range of existing theories and terminologies around interactions, as well as the types of behaviours that have been identified in empirical examinations of road traffic interactions. Then, we introduce the concept of a "space-sharing conflict", and derive from it stringent definitions for the terms "interactive behaviour" and "interaction". Then, we propose a taxonomy of the types of road user behaviours that tend to arise during space-sharing conflicts and interactions. Before concluding, we discuss how the proposed conceptual framework relates to and connects the previously existing theoretical perspectives, and how it can be applied in future work.

Background

Existing theoretical perspectives on road traffic interactions

The existing theoretical literature on interactions can roughly be partitioned into four complementary perspectives, each briefly summarised in its own subsection below. For the most important theoretical concepts, many of which have multiple conflicting definitions, the exact wordings of the original authors are quoted in a table in the Appendix.

Traffic conflict and safety perspectives

Some researchers have approached the topic of interactions primarily from a traffic safety perspective, focusing on collisions and their avoidance, using the presence of a collision course itself to define the pivotal concept of the *traffic conflict*: "An observable situation in which two or more road users approach each other in space and time to such an extent that a collision is imminent if their movements remain unchanged" (Amundsen and Hydén 1977). This approach has been operationalised in the Traffic Conflict Technique (TCT), as a methodology for quantitatively classifying observed traffic situations with a collision course along a severity continuum (Svensson 1998; Tarko 2012; Hydén 1987), ranging from *undisturbed passages* to *accidents*, with the intermediate term *potential conflict* acknowledging that sometimes drivers can be said to interact even in the absence of an objective collision course. While the term "interaction" has been used in this body of work, precisely what is meant by it has not been a main concern. An exception is Svensson (1998), who nevertheless kept to the strict focus on traffic safety by defining an interaction as "a traffic event with a collision course where interactive behaviour is a precondition to avoid an accident", essentially equating it with a "conflict" as defined above. This literature has also used the term *encounter*, to refer to a meeting between road users that is not immediately safety-critical in nature (Svensson 1998; Várhelyi 1998).

Game-theoretic perspectives

Other researchers have taken an interest in road traffic interactions from a perspective of game theory, i.e., "the study of mathematical models of conflict and cooperation between intelligent rational decision makers" (Myerson 1991, 1). In this type of work on road traffic, reviewed by Elvik (2014), the risk of a collision is often also a crucial element, but only as one of several potential outcomes of an interaction, carrying a large cost to both involved parties. The other outcomes of a given interaction are typically formulated as providing a higher "payoff" to one or the other of the road users, very often in terms of *order of access*, i.e., who gets to pass a contested location first. From this type of perspective, an interaction can be understood as a situation where multiple road users simultaneously pursue their own goals, and reciprocally need to adapt their behaviour to the assumed goals and behaviour of the others. Game theory provides the mathematical tools for analysing how rational decision makers should be expected to behave in such situations, as a function of the assumed payoffs and costs involved. The result is coordinated interactive behaviour, which may be both of a cooperative or competitive nature. Recently, this type of perspective has been increasingly applied to also model human-HAV interactions (Fox et al. 2018; Millard-Ball 2016; Sadigh et al. 2018; Schwarting et al. 2019).

Sociological perspectives

The two types of perspectives listed above are both rather quantitative in nature. Other, more qualitatively oriented researchers have been more interested in the sociological aspects of road traffic interactions, as a special case of human social interaction in general. The sociologist Goffman developed a theory of everyday interactions (Goffman 1963; Goffman 1971; Hviid Jacobsen and Kristiansen 2015), that has been influential in the interpretation of ethnographical observations of road traffic (Merlino and Mondada 2019; Haddington and Rauniomaa 2014). Hviid Jacobsen and Kristiansen (2015) provide a useful overview, introducing Goffman's distinction between *unfocused interactions*, where people are copresent without being directly engaged in a shared activity, and *focused interaction*s, where people sustain a shared focus of attention (Goffman 1963). When road users interact, they can be regarded as sustaining a shared focus of attention, even if this often happens in a very fleeting and elusive manner (Haddington and Rauniomaa 2014). This relates strongly to the perspective on road traffic actions as brief episodes of *joint action* (Clark 1996; Renner and Johansson 2006).

Furthermore, Goffman suggests a number of key motivations behind human behaviour in interactions. These can be *strategic* in nature, aligning with the game-theoretic type of analysis introduced above. However, Goffman also proposes that behaviour in interactions can arise in less calculated manners, as *interaction rituals* where stereotyped behaviours or rules for behaviour have become established norms for extending courtesy and respect to others, where the appropriate behaviour depends on how the involved parties interpret and define the situation at hand, the "frame" (Hviid Jacobsen and Kristiansen 2015). In traffic, this interpretation is influenced by elements such as infrastructure, traffic rules, cultural expectations, and so on (Renner and Johansson 2006).

Communication and linguistics perspectives

The abovementioned type of shared reference frame, or *common ground* (Clark and Brennan 1991) between interacting road users, has also been an important concept for researchers describing interactions as a form of language that road users engage in together to coordinate (Klein 2001) and agree on a mutually compatible future motion plan. In their analyses of road traffic interactions, Portouli, Nathanael, and Marmaras (2014) argue that, in cases of uncertainty, road users deliberately seek reciprocal interaction to communicate their motion intent and coordinate towards an agreed order of access to the shared traffic space. They describe such communicative interactions via a linguistic model, making use of Austin's (1962) speech act theory. In this theory, communication is not just about the *locutionary act* of producing a spoken utterance (in verbal communication), or blinking one's headlights or positioning oneself in some way on the road (in road traffic communication). Instead, often in speech and virtually always in traffic, the communicative behaviour can at the same time be regarded as an *illocutionary act* which conveys a certain force upon another road user or otherwise aims to achieve some impact on the traffic situation. This could include, for example, requesting something from someone else (e.g., to speed up), or promising to do something oneself (e.g., to let someone else pass first).

Domeyer et al. (2019) take an information-theoretic perspective on communication (Shannon 1948) in their evaluation of driver-pedestrian interactions, emphasising that road users are reciprocally encoding and decoding communication, not least by how they move and place themselves in traffic. Many authors, including recent literature addressing human-HAV interactions, have discussed such kinematic behaviours as forms of *implicit communication,* in contrast with *explicit communication* behaviours such as speech, hand gestures, headlight flashes, and so on. However, the exact definitions of these terms have varied (Fuest, Sorokin, et al. 2018; Powelleit, Winkler, and Vollrath 2018; Rasouli and Tsotsos 2019).

Summary

Overall, it is clear that the differing research objectives pursued by the various authors reviewed above have engendered a wide range of approaches and theoretical perspectives, with considerable variability in terminology and definitions (this is particularly clear from

Table A1). However, it should be noted that these perspectives are not necessarily in theoretical conflict with each other, but rather emphasise different aspects of road traffic interaction. Taken together, the review above provides a first rough outline of how interactions can be understood in a more general, cross-theoretical sense, across a range of aspects such as collision avoidance, order of access, coordination, reciprocity, and communication. The rest of the paper will aim to fill in this outline with a more complete and structured picture of interactions. The next section takes a first step in this direction, by moving from abstract theory to concrete empirics.

Empirical observations of behaviour in road traffic interactions

The previous section outlined the main theoretical perspectives on interactions. To make it clearer what these abstract concepts are actually referring to, it is helpful to also review the range of specific types of behaviour these theories are trying to describe. Table 1 provides a, by no means exhaustive, listing of behaviours that have been empirically observed in interactions, and that have been interpreted as having an impact on the interaction process.

Overall, it is clear from Table 1 that human road users exhibit interactive behaviours for a wide range of putative purposes beyond mere movement in space. These include acknowledging awareness of others, conveying appreciation, indicating desire to access a certain traffic location, indicating intentions of passing a location before someone else, yielding and letting others pass first, or requesting specific behaviours from others. In a later section of this paper ("Taxonomy of road user behaviour in space-sharing conflicts"), we map these behaviours to our proposed behaviour taxonomy, and Table 1 incorporates this mapping in the M-A – A-S columns.

Table 1 also reflects the recent rapid increase in the number of studies investigating interactions between HAVs and human road users, particularly pedestrians. Overall, the results of the human-HAV interaction studies can be taken to suggest that the processes by which pedestrians interpret the intentions and anticipated behaviours of HAVs will not be vastly different from conventional vehicles. However, new external human-machine interfaces (eHMIs) may aid in increasing positive affect and increased understanding in situations where negotiation of some sort is required, as evidenced by the number of studies showing that participants express subjective liking for this type of external communication channels (Clamann 2015; Fridman et al. 2017; Habibovic et al. 2018)

It should be noted that even though some of the behaviours in Table 1 are listed as reported only for human drivers or only for HAVs, this distinction is not the key message here. It would seem that, at least in theory, any purpose achieved by a behaviour of a human vehicle driver could be achieved by a HAV exhibiting a similar or suitably adapted behaviour (e.g., replacing eye contact with eHMI), and vice versa (e.g., a human driver could in theory also fit their vehicle with eHMI displays for manually triggered, externally projected "pedestrian advice").

Conceptual framework for road traffic interactions

In this section, we describe our proposed conceptual framework. We begin by highlighting how all road traffic interactions can fundamentally be said to constitute a form of collision avoidance, but in an observer-dependent, less rigid sense than in traffic conflict theory.

Table 1. Examples of human behaviours observed in empirical research on road traffic interactions, organised by the purpose of each behaviour. For behaviours exhibited by a human, this purpose is an interpretation by the referenced authors. For behaviours exhibited by a HAV, the purpose is a design goal that was intended by the authors. The M-A – A-S columns refer to the behavioural taxonomy defined in the section "Taxonomy of road user behaviour in space-sharing conflicts" of this paper (cf. Figures 2 and 3), with "X" indicating primary impacts of the behaviour, and "/" indicating secondary impacts, or that the impact might vary according to the context.

Interpreted/intended purpose of behaviour	Empirically observed behaviour	M-A	M-S	M-R	P-A	P-S	P-R	A-S	References
Accepting offered access to conflict space	Pedestrian leaning forward and beginning to move	X	/						(Haddington and Rauniomaa 2014)
Adapting trajectory to avoid conflict space	Pedestrian changing trajectory to accommodate HAV	X	X						(Madigan et al. 2019)
	Pedestrian walking around HAV	X	X						(Rothenbucher et al. 2016)
Conveying awareness of others	Making eye-contact				X	X	/		(Haddington and Rauniomaa 2014)
	eHMI indicating that the HAV has perceived a pedestrian					X			(Mahadevan, Somanath, and Sharlin 2018)
Conveying thanks	Raising hand							X	(Haddington and Rauniomaa 2014; Brown and Laurie 2017)
	Driver activating hazard lights							X	(Haddington and Rauniomaa 2014)
	HAV projecting lights/symbols to convey gratitude to other vehicles							X	(Powelleit, Winkler, and Vollrath 2018)
Indicating desire that someone move in a certain way	Close following of a slower lead vehicle	/	/	X					(Portouli, Nathanael, and Marmaras 2014)
	Flashing headlights at slower lead vehicle		/	X					(Portouli, Nathanael, and Marmaras 2014)
	HAV projecting Pedestrian Advice, Walk / Don't Walk symbols, or similar		/	X					(Ackermann et al. 2019; Clamann 2015; Mahadevan, Somanath, and Sharlin 2018)
Indicating desire to access a conflict space	Changes in pedestrian walking speed	X	X	/					(Beggiato et al. 2018)
	Subtle pedestrian movement in the direction of the road	/	X	/					(Merlino and Mondada 2019; Rasouli, Kotseruba, and Tsotsos 2017)
	Pedestrian placing a foot on the street	/	X	X					(Beggiato et al. 2018)
	Pedestrian hand wave towards driver		X	X					(Sucha, Dostal, and Risser 2017)
	Pedestrian allocating gaze to car		X	/	X	/			(Rasouli, Kotseruba, and Tsotsos 2017)
	Pedestrian eye contact with driver		X	/	X	/	/		(Guéguen, Meineri, and Eyssartier 2015; Rasouli, Kotseruba, and Tsotsos 2017)
	Pedestrian seeking eye contact with driver		X	/	X	X	X		(Schneemann and Gohl 2016)
Indicating future trajectory	Pedestrian body positioning, head/leg movements	X	X						(Schmidt and Färber 2009)
	Use of turn indicators		X						(Lee and Sheppard 2016; Portouli, Nathanael, and Marmaras 2014)
Indicating that one will access a conflict space first	Speeding up	X	X	/					(Portouli, Nathanael, and Marmaras 2014; Várhelyi 1998)
	No change in car speed & lateral distance from pedestrian	X	X	/					(Fuest, Michalowski, et al. 2018)
	Flashing headlights		X	/					(Portouli, Nathanael, and Marmaras 2014)
Monitoring/checking	Pedestrian looking at car				X				(Rothenbucher et al. 2016; Merlino and Mondada 2019)
Providing information on own movement status	Numerical presentation of speed in eHMI		X						(Clamann 2015)
Yielding to let someone access a conflict space first	Slowing down	X	X	/					(Beggiato et al. 2018; Haddington and Rauniomaa 2014; Portouli, Nathanael, and Marmaras 2014; Rasouli and Tsotsos 2019; Schneemann and Gohl 2016; Várhelyi 1998)
	Early, clearly discernible deceleration	X	X	/					(Fuest, Michalowski, et al. 2018)
	Pedestrian stopping to give way to HAV	X	X	/					(Madigan et al. 2019)
	HAV showing LED light panel or other eHMI to indicate yielding		X	/					(de Clercq et al. 2019; Habibovic et al. 2018; Dietrich, Tondera, and Bengler 2019; Weber et al. 2019)
	Flashing headlights		X	X					(Haddington and Rauniomaa 2014; Portouli, Nathanael, and Marmaras 2014; Rasouli and Tsotsos 2019)
	Eye contact with pedestrian / other driver		X		/	X			(Rasouli, Kotseruba, and Tsotsos 2017)
	Hand signals, e.g., movement of hand in a palm-up open hand gesture		/	X					(Rasouli, Kotseruba, and Tsotsos 2017; Schneemann and Gohl 2016; Haddington and Rauniomaa 2014)

Then, we build on these concepts to provide a definition of "interaction", before making a more detailed parsing of the empirically observed behaviours reviewed above into a proposed taxonomy, leading on also to definitions of "implicit" and "explicit" communication. Throughout the presentation below, as well as in a final subsection, we discuss how the framework relates to the existing theoretical perspectives reviewed above.

Space-sharing conflicts: Extending the traffic conflict concept towards interactions

An important basic realisation, alluded to by some of the existing theoretical perspectives, is that *all* of the human-human and HAV-human interaction scenarios and behaviours mentioned in the theoretical and empirical literature reviewed above fundamentally refer to some form of arbitration of two or more road users' *order of access to some shared region of space*. Figure 1(a) illustrates a number of typical situations, where we refer to the contested shared regions of space as *conflict space*s. The need for an order of access comes about specifically to avoid collisions between road users, providing a direct connection to the traffic conflict concept as employed in TCT. However, in the types of situations exemplified in Figure 1(a) an objective collision course may often never arise; what is particular about these situations is rather that a collision course (and later collision) *could potentially arise depending on the behaviour of the involved road users*. We think that this type of situation is absolutely central to the phenomenon of interactions in traffic, yet no existing term, in the TCT repertoire or otherwise, seems to address it. We therefore propose the following term and definition:

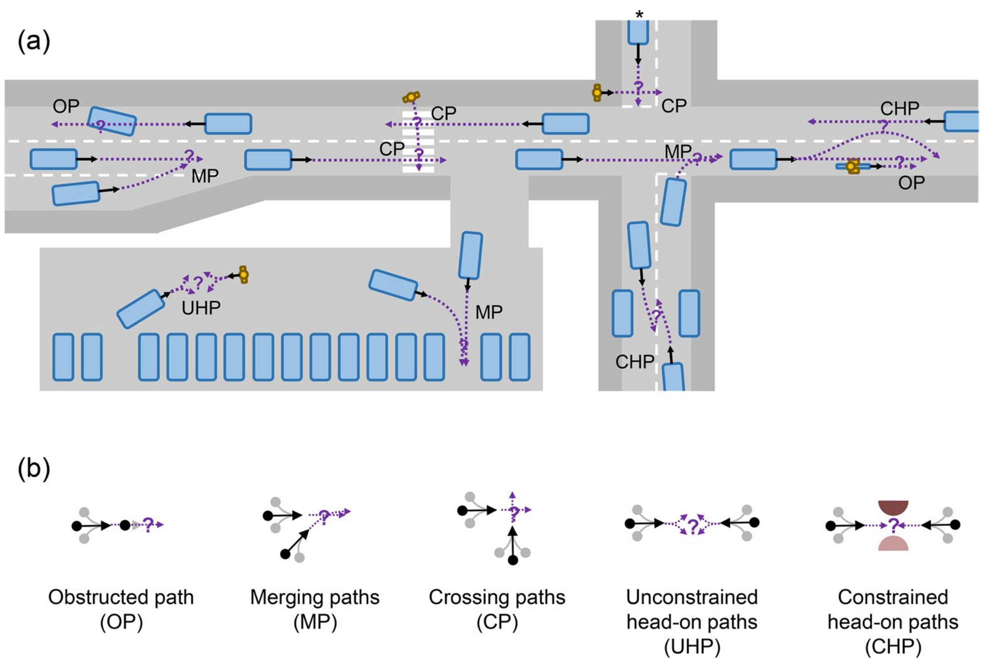

Figure 1. (a) Examples of space-sharing conflicts, with question marks denoting conflict spaces. (b) Five prototypical space-sharing conflicts. The lighter coloured arrows and objects denote possible variations within the prototypes.

Space-sharing conflict: An observable situation from which it can be reasonably inferred that two or more road users are *intending to occupy the same region of space at the same time* in the near future.

Note that this term as defined above inherently depends on the interpretation by an observer, for example one of the involved road users, or a third party observer. Each observer has limited information about the complete situation, due to limited perceptual abilities, and limited access to the intended future actions of others.

Because of the observer-dependence, the judgment of whether or not a space-sharing conflict is the case will vary not only with the traffic situation but also with the observer's access to information about it. A hypothetical omniscient observer with full information about both the external world and the brain states of the involved road users could in theory say for certain whether any given situation was an "actual" space-sharing conflict. However, for human observers there will often be uncertainty, and especially so for third party observers (e.g., researchers observing traffic interactions), since they do not have access to the covert intentions and desires of either party involved in the conflict. For these reasons, one might usefully talk of "obvious space-sharing conflicts" for non-ambiguous situations and well-informed observers, and "potential space-sharing conflicts" otherwise. As an extreme case of an obvious space-sharing conflict, consider two road users yelling at each other over who should park in a certain spot. As a more typical everyday example, consider the car entering Figure 1(a) from the top, marked with an asterisk (*): (i) if this car's driver sees the approaching pedestrian attending to a mobile phone, the driver might consider the situation an obvious space-sharing conflict, while (ii) the pedestrian, who has not seen the car, is not aware of any space-sharing conflict at all, and (iii) a third party observer who thinks the pedestrian has maybe seen the car and is intending to stop might judge the situation to be a potential space-sharing conflict.

At first glance, this uncertainty and observer-dependence might seem limiting for the usefulness of the space-sharing conflict concept, but we would argue instead that these aspects of the concept are crucial, in that they reflect the nature of the information that road users actually have access to and act upon. For a road user, it does not matter if a space-sharing conflict involving themselves is only potential in nature, or how the other involved party might see the matter; the road user still needs to act in some way so as to make the potential space-sharing conflict go away, from their own perspective.

Specifically, note that by definition, a space-sharing conflict is resolved, from a given observer's perspective, when the observer no longer judges that the involved road users are intending to occupy the same region of space at the same time. This can be either because the observer has acquired more information about the situation, or because one or more of the involved road users have changed their behaviour. This is analogous to how a traffic conflict by the TCT definition is resolved when one or more of the road users have changed their behaviour such that there is no longer an objective collision course. Thus, a situation which is defined as a traffic conflict in TCT will often also be judged a space-sharing conflict (unless the observer judges that, for example due to a red traffic light, the currently established collision course will soon be resolved).

Another observation that can be made from Figure 1(a) is that there is a limited number of different ways in which two road users can approach a conflict space, such that one can identify some basic prototypes for space-sharing conflicts. These are shown in

Figure 1(b). It can be noted that these five space-sharing conflict prototypes cover all of the 21 scenarios involving collision between two (or more) road users in the road crash typology proposed by Najm, Smith, and Yanagisawa (2007). Note also that if more than two road users are involved in a space-sharing conflict, the situation can include more than one prototype.

Defining interactions in road traffic

We can now build on the space-sharing conflict concept, to propose a definition of "interaction". We do this by noting that all of the behaviours listed in Table 1 arise as a *consequence* of a space-sharing conflict, prompting us to propose the following term:

> **Interactive behaviour:** Road user behaviour that can be interpreted as being influenced by a space-sharing conflict.

Here, "being influenced by a space-sharing conflict" should be interpreted as "would have been different or non-existent if the space-sharing conflict had not been the case".

It is clear from Table 1 that these interactive behaviours can often be understood as aiming to resolve the space-sharing conflict, either by trying to establish an order of access to the conflict space, or by gathering additional perceptual information to conclude that there is no space-sharing conflict.

We now propose that a useful definition of "interaction" can be obtained quite simply as a situation where two or more road users are both exhibiting interactive behaviour (defined as above) in relation to the same space-sharing conflict. In expanded form, we get the following definition:

> **Interaction:** A situation where the behaviour of at least two road users can be interpreted as being influenced by a space-sharing conflict between the road users.

A further expanded version, without reference to the space-sharing conflict concept:

> **Interaction:** A situation where the behaviour of at least two road users can be interpreted as being influenced by the possibility that they are both intending to occupy the same region of space at the same time in the near future.

It should be noted that these definitions relate strongly to Clark's (1996) concept of joint action, and to Goffman's (1963) concept of a focused interaction, although as discussed previously, in some interactions in traffic the "shared focus of attention" (i.e., the space-sharing conflict) can be very fleeting in nature, such that the interactions might verge on being "unfocused" according to Goffman's definition.

Crucially, if just one road user adapts their behaviour to another, this is not considered an interaction by the definition above, aligning with the emphasis on reciprocal coordination by the game theoretic and communication perspectives on interactions. Consider, for example, a situation where (i) a pedestrian waits for a car to pass before crossing the road, but (ii) the car driver passes the pedestrian without changing speed and without giving noticeable visual attention to the pedestrian, i.e., does not adapt their behaviour. Thus, the pedestrian exhibited interactive behaviour but not the car driver, and according to our proposed definition, this was not an interaction. However, there is room for interpretation. The example just given could, for instance, be classified as an interaction if the car driver was nevertheless judged to have perceived the pedestrian at some point, but to subsequently not look further at the pedestrian as part of a strategy to make it clear to the pedestrian that the car driver would not be yielding.

As should be clear from the definition and the above example, just like with the "space-sharing conflict" concept, the certainty of an observer's judgment of whether a given situation is an interaction or not will depend on how much detail is contained in the information the observer has access to. This aspect of the definition may be particularly important in a research context, where an annotator may readily be able to judge some situations as interactions by means of simple qualitative observation of road user trajectories and vehicle brake lights, from which it may often be obvious that two road users adapted their behaviour to one another. Other situations, however, might require highly detailed data, such as quantitatively recorded trajectories or even road user eye movements, to make a definitive judgment on whether mutual adaptation of behaviour was the case. In practice, researchers will need to adapt their data collection approach to how far into the subtleties of interactions their research objectives require them to go.

Taxonomy of road user behaviour in space-sharing conflicts

We now take a more detailed look at Table 1, to propose a taxonomy describing the different types of observed behaviour in a way that is more structured than the purposes identified in the leftmost column of the table.

First of all, one set of behaviours that stands out from the others in Table 1 are the ones serving the purpose of conveying thanks (e.g., hand gestures or eHMI indications). It is clear that road users sometimes also express negative sentiments (e.g., a rude gesture or honking at someone who advances into a space one intended to access first). Thus, we propose the following term:

> **Appreciation-signalling (A-S) behaviour:** Behaviour that can be interpreted by an external observer as giving information on how the road user appreciates, or not, the behaviour of another road user.

For all the other behaviours in Table 1, it may be noted that they all relate, in different ways, to one or both of two fundamental high-level tasks that any road user needs to perform in order to successfully manoeuvre through a space-sharing conflict, or indeed any traffic situation even if alone on the road, namely: (i) *perceiving* the traffic situation (e.g., "Monitoring/checking"; "Conveying awareness of others"), and (ii) *moving* in the traffic situation (e.g., "Adapting trajectory to avoid conflict space"; "Indicating future trajectory"; "Indicating desire that someone move a certain way"). Reading Table 1 even closer, we discern three basic types of *effects* of a behaviour in relation to each of those two tasks: (i) *achieving* own movement or perception, (ii) *signalling* to others about own movement or perception, and (iii) *requesting* movement or perception from other road users. When a behaviour has one of these effects on the perception or movement task in a given traffic situation, we will refer to that as the *impact* of the behaviour on the traffic situation. For the two *tasks* and three types of *effects* mentioned above, there are thus six different types of impact in total. We propose terms for each of these below, and a visual reflection of how the full set of seven types of behaviours may overlap is shown in Figure 2. Note that the

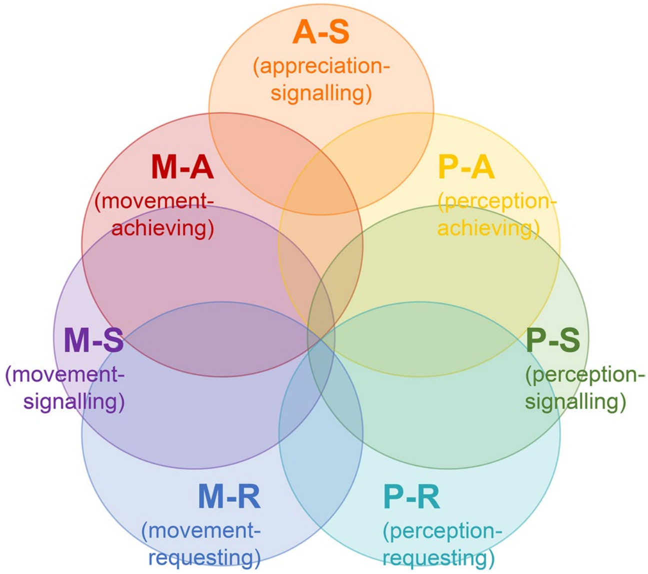

Figure 2. Illustration of the proposed taxonomy of behaviours in road traffic interactions, and some of the ways in which the different types of behaviours can overlap.

behaviour types are not mutually exclusive, i.e., a given behaviour can have more than one impact on the traffic situation; this will be further discussed below.

The proposed definitions are as follows:

> **Movement-achieving (M-A) behaviour:** Behaviour that determines how a road user moves (or does not move) in the world.

This definition applies to any human body or vehicle movement that has an effect on how the region of space occupied by the road user changes (or does not change), over time, and can typically be succinctly described in terms of positions, speeds, accelerations, etc.

> **Movement-signalling (M-S) behaviour:** Behaviour that can be interpreted as giving information on how a road user intends to move in the future.

Note that by this definition, any behaviour that provides information about a particular road user's potential future movement is movement-signalling, regardless of whether it is by means of mere movement in space, or symbolic gestures, and regardless of whether or not the road user actively intended (consciously or not) to give this information. Examples from Table 1 include (i) a pedestrian walking towards a road crossing, thus giving information about an intention to cross, or (ii) a human-driven car or HAV decelerating to yield to another road user, or (iii) the same vehicle also showing an external sign indicating the intention to yield (e.g., headlight flashes or some HAV eHMI).

> **Movement-requesting (M-R) behaviour:** Behaviour that can be interpreted as giving information on how a road user would like other road user(s) to move.

Typical examples from Table 1 include hand gestures to indicate that someone else should pass first, or the use of headlights or close following to indicate a desire for a lead vehicle to speed up or make space for overtaking. A similar everyday example is the siren and lights of emergency vehicles.

> **Perception-achieving (P-A) behaviour:** Behaviour that (together with the road user's perceptual limitations and other unobservable factors such as attentional status) determines what a road user perceives.

This definition applies to any human body or vehicle movement that has an effect on what the road user perceives or is capable of perceiving. Examples include head and eye movements, or a vehicle advancing in an intersection to get a better view of surrounding traffic. Exactly what a given road user ends up perceiving in a given traffic situation is of course far from being clearly inferable from overt behaviour; hence the parenthesis in the definition above.

> **Perception-signalling (P-S) behaviour:** Behaviour that can be interpreted as giving information on what a road user is perceiving.

Similarly to M-S behaviour, by this definition it does not matter whether the perception-signalling is "intentional". Examples from Table 1 include (i) driver eye or head orientation indicating that the driver is looking at a pedestrian while approaching a crossing, or (ii) a HAV activating an eHMI to indicate that the AV has detected a certain human road user.

> **Perception-requesting (P-R) behaviour:** Behaviour that can be interpreted as giving information on what a road user would like other road user(s) to perceive.

Here, examples include seeking eye contact, and the above-mentioned emergency vehicle siren and lights, in the sense that these can be interpreted as requesting road users to pay attention to the emergency vehicle. Activating a vehicle's hazard lights also serves a similar purpose.

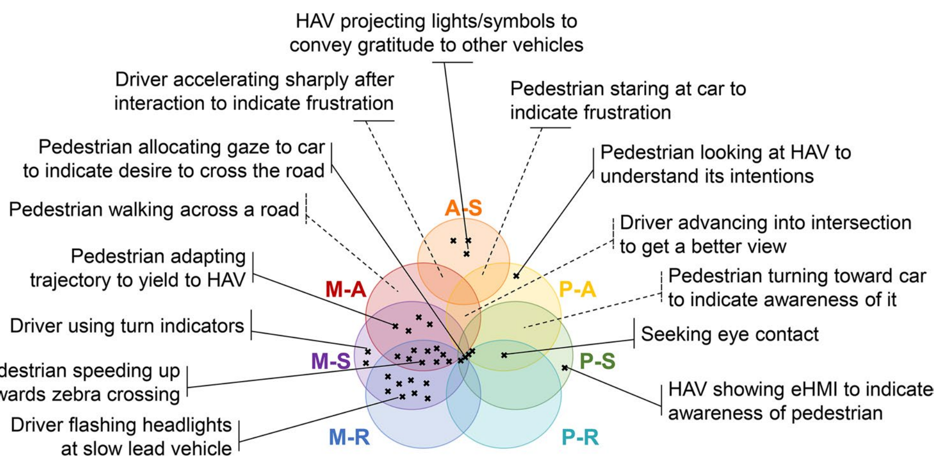

Figure 3. Example behaviours mapped onto the proposed taxonomy. Each black cross corresponds to one row in Table 1. Dashed lines indicate behaviours that were not reported in the reviewed empirical literature, but which are arguably familiar from everyday experience.

As already mentioned above, the seven types of behavioural impacts defined above are not mutually exclusive, rather the opposite. In Table 1, we have proposed a mapping of each empirically studied behaviour onto the proposed taxonomy, and Figure 3 provides a graphical illustration of this mapping. The exact numbers of empirically observed behaviours mapped from Table 1 to each part of Figure 3 is not important here, since they are likely determined to a large extent simply by the research interests of the cited authors (but it might be worthwhile to do such an analysis of an actual naturalistic dataset). However, it is interesting to note that some combinations have not been reported at all in the empirical literature. Most notably, there is an absence of reports of any pure M-R or P-R behaviours in the reviewed literature. A stationary bystander, such as a traffic police officer, could certainly exhibit pure M-R behaviour, but a road user who is responding to a space-sharing conflict with M-R behaviour (e.g., a hand wave indicating "you go ahead"), can arguably always be interpreted as simultaneously exhibiting M-S behaviour (e.g., "I will go after you"). Similarly, requesting someone else's attention (P-R) will either involve P-A/P-S (e.g., in the case of seeking eye contact), or M-R/M-S (e.g., an emergency vehicle siren).

In many cases where a behaviour maps onto multiple types of impact, we suggest that it makes sense to order these as *primary* and *secondary* impacts, to indicate which impacts an observer attributing intentions to the road user might interpret as the main intended impacts; this distinction is also reflected in Table 1 (but not in Figure 3). For example, in the yielding example just mentioned above, one could then say that the hand wave to encourage the other road user to cross is primarily M-R behaviour, and secondarily M-S behaviour. Another type of such collateral impact is that any behaviour that can be interpreted as being directed at another road user, can also be interpreted as a P-S behaviour indicating awareness of that other road user. This type of (tertiary) impact has been omitted from Table 1 and Figure 3 for clarity.

In relation to the concept of interactive behaviour introduced in the previous section, it can be noted that behaviours that are primarily M-A and P-A in nature can either be interactive in nature, when they arise or become modified in response to a space-sharing conflict, or non-interactive; i.e., a road user will need to exhibit M-A and P-A behaviours even if completely alone on the road, just to navigate the road environment. However, behaviours of which the primary impact is one of the other five in the taxonomy, will typically always be interactive in nature, since they tend to relate clearly to another road user in a space-sharing conflict.

Types of communication in space-sharing conflicts

In relation to the linguistic perspective of Portouli, Nathanael, and Marmaras (2014), it may be noted that any interactive behaviour of M-S, M-R, P-S, or P-R nature can be regarded as a communicative act that is simultaneously both a locutionary act and an illocutionary act (i.e., with an "impact on the world"). Furthermore, the behaviour taxonomy proposed here also allows us to make a further distinction, stringently defining two terms that have been much used, with sometimes vague meanings, in the emerging literature on HAV-human interactions:

Implicit communication: A road user behaviour which affects own movement or perception, but which can at the same time be interpreted as signalling something to or requesting something from another road user.

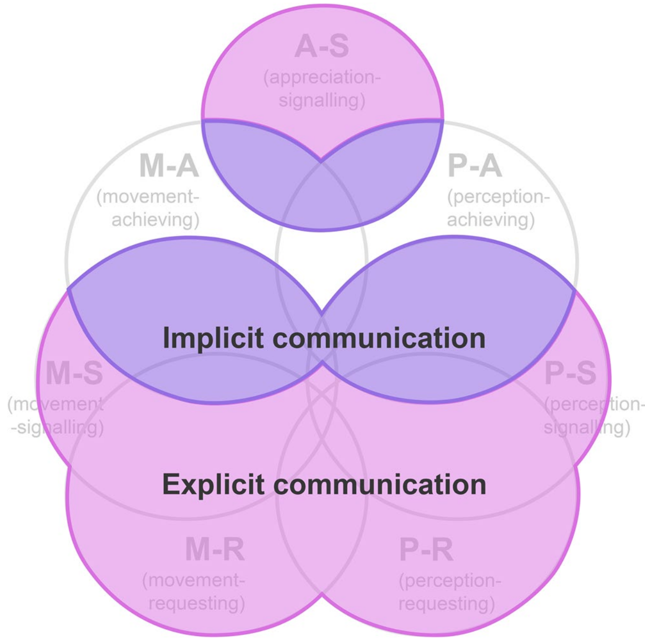

Figure 4. Illustration of the concepts of implicit and explicit communication, defined in terms of the taxonomy of behaviours defined here.

(Logically, this can be expressed as "(M-A or P-A) and (A-S or M-S or P-S or M-R or P-R)"). For example, decelerating to show intention to yield, or looking in the direction of another road user to make it clear that one has perceived that road user.

> **Explicit communication**: A road user behaviour which does not affect own movement or perception, but which can be interpreted as signalling something to or requesting something from another road user.

(Logically, this can be expressed as "not (M-A or P-A) and (A-S or M-S or P-S or M-R or P-R)") For example, use of hand gestures, vehicle lights, horn, HAV eHMI, verbal utterances, or any other means of communication that does not simultaneously alter the road user's movement or perception. Figure 4 provides an illustration.

Note that, unlike the human head and eyes, HAV sensors are typically not overtly directed towards that which is being perceived, such that there are no overt indications of perception-achieving that can give perception-signalling information. For any HAV design where this remains true, implicit communication by the HAV will thus only refer to how the HAV's *movements* in the world gives indications as to what it is doing and perceiving; i.e., for these HAVs there is nothing in the rightmost parts of the "implicit communication" areas in Figure 4 (P-A and P-S).

Relationship of the framework to existing theoretical perspectives

Already in the exposition above, we have discussed a number of ways in which our proposed conceptual framework aligns with and is compatible with existing theory. In brief, we have shown how the "space-sharing conflict" concept is a generalisation of the collision-oriented perspective on conflicts in traffic conflict theory, and we have shown how our proposed definition of “interaction”, derived from the idea of the space-sharing conflict, aligns with the emphasis on joint or focused attention and action in sociological theory, as well as with the emphasis on reciprocal coordination of order of access in communication theory and game theory. In this sense, our conceptual framework brings these different theoretical perspectives together into a single, and more complete, account of interactions.

Since our framework operates at this wider, unifying level, out of necessity it does not go as deeply into all aspects of interactions as the individual theories. As one example, the communication-oriented model of Portouli, Nathanael, and Marmaras (2014) provides a further fine-grained division of behaviours that are of M-R/M-S type in our terminology, differentiating between a first “directive” from one road user to another, and the “commissive” that then follows in terms of either acceptance or rejection of the directive. The other theoretical perspectives can provide further elaborations of other parts of our conceptual framework.

Furthermore, while our framework describes what space-sharing conflicts are, and what types of interactive behaviours road users engage in in order to resolve them, our framework is silent on the matter of exactly *what* interactive behaviours a road user might choose to adopt in a given situation, and *why*. The notion of interaction rituals in sociological theory points to one type of qualitative answer to these questions, and game theoretic models, and other mathematical models of interactions in the traffic simulation and HAV planning algorithm literatures (Elvik 2014; Sadigh et al. 2018; Schwarting et al. 2019; Markkula et al. 2018; Choudhury et al. 2007; Fox et al. 2018) provide possible quantitative answers. An important aspect here is that road users’ decisions on what interactive behaviours to adopt are clearly affected by the specifics of the traffic environment in question, as interpreted against the backdrop of the previously discussed shared reference frame, or common ground, of the interacting road users. Also individual factors such as gender and age matter in this respect (Plumert, Kearney, and Cremer 2007; Ābele, Haustein, and Møller 2018; Lobjois, Benguigui, and Cavallo 2013), as do factors related to human attention or capacity limitations, and secondary tasks and distractions (Janouch et al. 2018; Thompson et al. 2013; Ljung Aust, Fagerlind, and Sagberg 2012; Choudhary and Velaga 2017).

Conclusions and outlook

We have proposed a conceptual framework to support stringent research into road traffic interactions between humans, and between humans and interaction-capable automated vehicles. Core components of the framework include the concept of “space-sharing conflicts”, definitions of “interactive behaviour” and “interaction”, a taxonomy of behaviour in interactions, and a discussion of the implications of the proposed definitions and how the various concepts relate to each other. We have also provided definitions of “implicit” and “explicit” communication. Overall, the proposed framework brings together a number of key aspects of road traffic interactions—collision avoidance, order of access, coordination, reciprocity, and communication—which have previously been separately addressed by only partially overlapping theories. We suggest that our framework can therefore function as a comprehensive, cross-theoretical foundation, hopefully facilitating collaboration across disciplines.

One key aspect of our framework is that it adopts the same observer-dependence and uncertainty of information that is fundamentally inherent in each road user’s perspective on the world. We have chosen this type of approach since there are presently no clear-cut, objective ways of determining issues such as whether or not a given road user holds a certain "intention", or whether or not he or she is consciously aware of "giving information". Instead, the definitions proposed here highlight that road users' interactions are a complex set of phenomena which are far from completely scientifically understood, and that when it comes to observation of human interactive behaviour, third-party subjective interpretations will remain a necessary part of work in this area for the foreseeable future. One direct use of the proposed framework can be in naturalistic and controlled empirical studies of human interactions, where the proposed terms and definitions should be useful in bringing as much clarity as possible to methodologies, annotation schemes and data interpretation.

Another way to promote stringent and coherent discussion of human interactive behaviour is through development of mathematical models reproducing the human behaviour, deterministically or probabilistically. Such models can then be used in HAV algorithms or as simulated agents in tools for virtual testing of HAVs (Fox et al. 2018; Markkula et al. 2018; Sadigh et al. 2018; Schwarting et al. 2019). The present framework provides some structure also to these modelling efforts; we would argue that adequate models of human road traffic interactions will need to account in some way for the space-sharing conflict phenomenon itself, as well as for all of the types of behaviour enumerated in the behaviour taxonomy proposed here.

Something similar would seem to apply also to the design of the actual HAVs. There is currently work underway to develop guidelines and standards for how to design the interactive behaviour of HAVs, in many cases along related but less stringently formulated lines of thinking about interactions as those developed here (Schieben et al. 2019; Rasouli and Tsotsos 2019). The comprehensive and structured account provided here of how road traffic interactions function could therefore serve as a useful starting point when defining requirements for the interactive capabilities of HAVs.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the European Union's Horizon 2020 research and innovation program under grant agreement 723395 and by the UK Engineering and Physical Sciences Research Council under grant EP/S005056/1.

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Appendix

Table A1. Key terms and definitions from the theoretical literature on interactions in road traffic.

Term	Definition	Reference
Common Ground	"Knowledge, beliefs and assumptions that support a joint action and describes what it is that make joint actions work."	(Renner and Johansson 2006, 38)
	"Shared knowledge […] necessary for successful communication."	(Domeyer et al. 2019, 2)
Communication	"Mainly used to express intentions of initiating interactions."	(Fuest, Sorokin, et al. 2018, 709)
	"Any kind of signal between road users."	(Rasouli and Tsotsos 2019, 905)
	"Involves signals that are encoded by one interactant, sent over a noisy channel, and then decoded by another interactant."	(Domeyer et al. 2019)
Communicative interactions	"in cases of uncertainty […] drivers deliberately seek to interact with other drivers, so as to communicate their motion intent and coordinate towards a safe future motion plan"	(Portouli, Nathanael, and Marmaras 2014, 1796)
Coordination	"the attempt by multiple entities to act in concert in order to achieve a common goal by carrying out a script they all understand"	(Klein 2001, 70)
Conflict	"An observable situation in which two or more road users approach each other in space and time to such an extent that a collision is imminent if their movements remain unchanged."	(Amundsen and Hydén 1977)
	"Critical encounters in which TA [time to arrival] values are so low that the involved road users would collide if neither part took evasive action."	(Várhelyi 1998, 735)
	Situations where "(i) a pedestrian had to suddenly discontinue their standard crossing manoeuvre (i.e. had to return or start running to make it to the other side); (ii) a driver had to brake unexpectedly or sharply or had to change direction to avoid a collision; (iii) any situation where a driver or pedestrian was explicit in expressing their negative emotions about it (e.g. raised voice, offensive gestures)."	(Sucha, Dostal, and Risser 2017, 43 – 44)
Encounter	"A meeting between two road users"	(Svensson 1998, Glossary of Terms)
	"Situations in which the approaching car and the pedestrian could theoretically arrive at the meeting point at the same time (they are on a collision course)."	(Várhelyi 1998, 735)
Explicit communication	"The transmitter conveys his intention in direct signs to the receiver"	(Fuest, Sorokin, et al. 2018, 710)
	"Comprises specific signals which are not essential for the driving task itself but are used for interacting more directly with other road users (e.g. gestures, turn indicators, horn honking, flashing headlights)."	(Powelleit, Winkler, and Vollrath 2018, 149)
	"Can be achieved via different modalities (e.g. as visual, audio, or radio signals) which may convey information regarding the status of the vehicle, its belief regarding its surrounding, its intention, or advisory information for other road users."	(Rasouli and Tsotsos 2019, 909)

Focused interaction	"People are gathered in and collaborate to sustain a shared focus of attention."	(Goffman 1963, cited in Hviid Jacobsen and Kristiansen 2015, 78)
Illocutionary act	"Utterances which have a certain (conventional) force […] such as polite requesting, commanding, informing, warning, etc."	(Austin 1962, 108); see also (Portouli, Nathanael, and Marmaras 2014, 1797)
Implicit communication	"The content is not spoken out loud, but indirectly included in the message."	(Fuest, Sorokin, et al. 2018, 710)
	"Conveyed via the vehicle's motion (e.g. accelerating, decelerating, steering)"	(Powelleit, Winkler, and Vollrath 2018, 149)
	"Is realized by the state of the vehicle, such as deceleration, acceleration or distance to crosswalk, which can often show the intention of the autonomous vehicle."	(Rasouli and Tsotsos 2019, 909)
	"Any disturbance of [the] expected smooth motion that could not be attributed to road geometry or obstacles on the road"	(Portouli, Nathanael, and Marmaras 2014, 1800)
Interaction	"A traffic event with a collision course where interactive behaviour is a precondition to avoid an accident."	(Svensson 1998, Glossary of Terms)
	"Situation where road users adapt their behaviour ahead of the conflicting zone, leaving time and space for fluid movement while both users are on the street."	(Cloutier et al. 2017, 37)
	"Reciprocal actions of two or more entities."	(Fuest, Sorokin, et al. 2018, 709)
	"May involve tasks such as identifying other road users, analysing their behaviour, communicating with them, if necessary, predicting their future actions, and choosing an appropriate response accordingly."	(Rasouli and Tsotsos 2019, 900)
	"Involves anticipating and responding to others' conduct, thereby enabling both simultaneous and sequential action coordination."	(De Stefani, Broth, and Deppermann 2019, 4)
	"Any situation in which another road user enters an AV's path at a distance of no greater than 5 m or changes their behaviour in relation to the AV by altering their movement trajectory or coming to a stop."	(Madigan et al. 2019, 201)
Joint action	"Performed with a common goal, which is based on the involved participants' assumptions of the purpose and procedure of the action, and may or may not demand communication, but always coordination."	(Renner and Johansson 2006, 38)
Locutionary act	"Roughly equivalent to uttering a certain sentence with a certain sense and reference"	(Austin 1962, 108); see also (Portouli, Nathanael, and Marmaras 2014, 1797)
Potential conflict	"The road users are closer [than in an undisturbed passage] and have to cross each other's routes with a smooth and very early interaction."	(Svensson 1998, Glossary of Terms)
Strategic interaction	"When persons find themselves in a well-structured situation of mutual impingement where each party must make a move and where every possible move carries fateful implications for all of the parties. In this situation, each player must influence his own decision by his knowing that the other players are likely to try to dope out his decision in advance."	(Goffman, 1969, 100–101; cited in Hviid Jacobsen and Kristiansen 2015, 75)
Unfocused interaction	"People are copresent without being mutually engaged in a shared activity."	(Goffman 1963; cited in Hviid Jacobsen and Kristiansen 2015, 78)