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Cooperation for Ethical Autonomous Driving

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***Abstract*—The success in the adoption of autonomous vehicles is dependent on their ability to solve rarely occurring safety-critical corner cases. Vehicular communications (V2X) aim at improving safety and efficiency of autonomous driving by adding the capability of explicit inter-vehicular information exchange. We argue that V2X enables another important function, namely the support of ethical driving decisions. In this article, we explain our envisioned methodology of an ethical cooperative driving interaction protocol design (including what to communicate and how to act based on the received information). Cooperative manoeuvring empowered by the ethical V2X is a new research direction we promote in the autonomous driving research agenda.**

***Index Terms*—Cooperative vehicles, automated driving, V2X communications, vehicular safety, ethical dilemmas, ethical decision-making, autonomous driving ethics.**

I. Introduction

Autonomous driving has the potential to ensure safe future mobility. Autonomous decision making may properly manage road situations where humans make errors [1]. Still, there will be situations where accidents are hard or not even possible to prevent. Such situations could arise either due to limitations of vehicular automation, for example, insufficient sensing capabilities [2], or due to unsafe human behaviour, for example, poorly predictable actions of pedestrians [3]. Such situations are considered very unlikely but yet present. Nevertheless, autonomous vehicles must know how to respond to them, and we believe that such a response should obey ethical principles. Although ethical dilemmas in autonomous driving, such as trolley problems, have been widely discussed [4], the practical trajectory planning algorithms that embed ethical considerations have been relatively limited in the literature [5]–[7].

We argue that cooperation between vehicles is crucial for ethical trajectory planning. The cooperative manoeuvring paradigm [8], enabled by vehicular communications (V2X) [9], can help perform coordinated actions to meet certain ethical criteria in case of an unavoidable accident (collision between vehicles). The ethical reasoning behind resolving a specific dilemma is out of scope for this study. Instead, we provide means for deciding how an unavoidable crash can occur in order to meet formalized ethical requirements [10].

To take such ethical decisions or actions in case of an unavoidable accident, we use the notion of harm to characterize the severity of a crash. Loosely speaking, the harm can be seen as a metric that is defined by the relative velocities at the moment of the crash, the masses of the vehicles, the geometry of the scenario, and additional parameters that describe the physical collision. The harm (individual or total) can vary due to the evasive actions (the lack thereof) taken by the vehicles involved in the accident. If one can estimate the likelihood of different outcomes of the accident, given the collaborative approach and imperfections of the information flow between the cooperative vehicles, a probability distribution of the harm can be derived. For such a setting, the risk in the Safety of Intended Functionality (SOTIF) framework, which addresses the characterization of the technological limitations on vehicular safety [11], corresponds to the expected (average) harm.

V2X plays a central role in the context of ethical decision making, both for the actual manoeuvre coordination, for example, by allowing vehicles to agree on how to perform an emergency braking in a certain critical situation, but also for the respective harm assessment itself, by exchanging information required for computation of harm. In this article, we explain our envisioned methodology of an ethical cooperative driving interaction protocol design (including what to communicate and how to act based on the received information). Furthermore, we present an illustrative case study for emergency braking in a longitudinal driving scenario [12]. Our objective is to promote this new Ethical V2X research direction within the autonomous driving community.

II. Ethical Cooperative Manoeuvring

Motivation: Sudden Plan Change

Within the framework of cooperative manoeuvring, we consider the moment when a group of cooperating vehicles has agreed on their trajectories (for example, in a distributed cooperative intersection management scenario [13]) and starts implementing the agreement. If each vehicle sticks to the agreed-upon trajectory plan, safe collision-free driving is guaranteed, Fig. 1.

Naturally, these agreed-upon trajectories will incorporate safety gaps for possibly required adjustments of trajectories or if something does not go as foreseen during the execution of the cooperative plan [14]. However, such safety gaps are practically bounded since the interaction protocol between cooperative vehicles must provide meaningful driving functionality in the sense of traffic efficiency. In other words –

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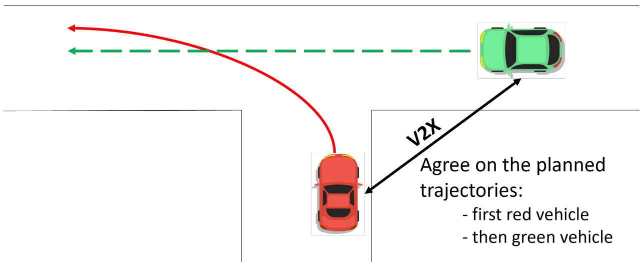

Fig. 1: Cooperative manoeuvring: planned trajectories

short gaps are not safe, while excessive gaps are not practical. Furthermore, replanning in response to something unforeseen in the plan relies on communication via a possibly error-prone V2X network. Thus, situations might occur where the inter-vehicular gaps are not sufficient, and a crash becomes unavoidable. Although very unlikely, these corner cases must be addressed by the autonomous vehicle motion planning logic.

Our analysis begins at the moment when a hazardous event occurs during the execution of a manoeuvre, for example, a sudden detection of a pedestrian by one of the vehicles. This requires one or more vehicles to choose another trajectory, for example, to perform an emergency braking. General emergency trajectory adjustment is mentioned in [8]. At the same time, the cooperative partners must be informed via the V2X communications, for example, by sending repetitive warning messages, about the need to modify the previously agreed-upon cooperation plan, Fig. 2.

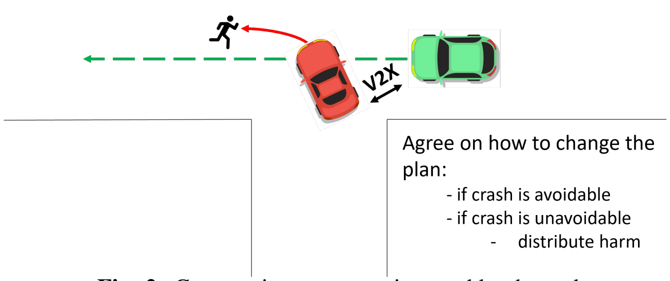

Fig. 2: Cooperative manoeuvring: sudden hazard

Design and Evaluation Methodology

Given the unreliability of information exchange and considering the mobility parameters of a specific scenario, it might be possible to avoid the accident. Let us denote the probability of this event as P. If an accident is impossible to avoid (consequently with the probability of $1 - P$), one might be able to reduce its severity. We characterize severity by using the notion of harm, H, which is something quantifiable. H is non-negative and is equal to zero if and only if there is no harm. Larger values of H indicate more harm. Ethical requirements can be embedded into the calculation of the harm H by assigning respective "priority" coefficients to each involved actor (vehicle, pedestrian, etc.). Harm values and the respective probabilities of such harm values allow for the calculation of the cooperative manoeuvring risk R, which is the expected harm.

Upon receiving the information about a hazard, the cooperative vehicle can react in two ways: either perform an evasive manoeuvre without agreeing with others ("normal") or agree on a cooperative resolution of the situation ("ethical"). The ethical approach, in general, requires an exchange of information between the vehicles (or even reaching a consensus), which takes time. Therefore, it is important to design ethical interaction protocols that distribute the harm in an ethical way, but do not worsen the outcomes of the accident with respect to the normal case. This leads us to the practical requirement on the risk reduction $R_n \geq R_e$, where R_n is the risk for the normal manoeuvring and R_e is the risk for the ethical cooperative resolution. This constraint or requirement is essential for the design of an ethical inter-vehicular emergency interaction protocol.

Such a protocol can be further evaluated against requirements on safety and ethics. For instance, the probability P of accident-free operation can be constrained not to fall below a certain threshold value P_{min}. Similarly, the probability Q that an ethical criterion, for example, that the total harm value does not exceed a threshold H_{max}, is met can be constrained not to be lower than a threshold value Q_{min}. Note that in such a setting, if $H_{max} = 0$, meaning that no harm is acceptable, the probabilities P_{min} and Q_{min} coincide.

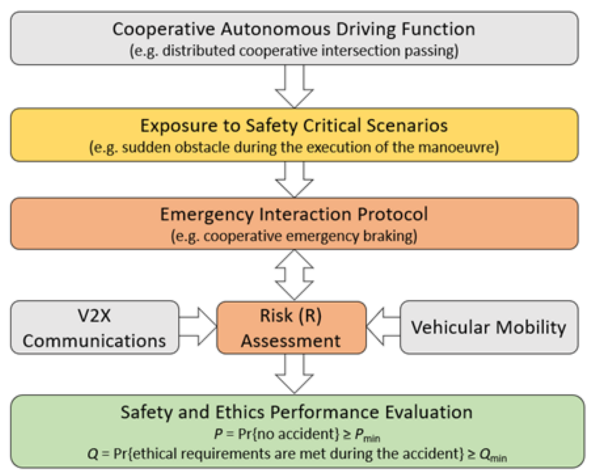

Fig. 3: Ethical cooperative driving

Due to the inherent unreliability of V2X communication, a warning message (or any other message) might not reach a specific vehicle in time or even before an accident occurs. In practice, on-board sensors (cameras, lidars, and so on) might be used to provide input for local decision making. However, the focus of this article is on V2X-enabled cooperative manoeuvring.

A summary of our methodological framework for the design and evaluation of ethical cooperative manoeuvring is provided in Fig. 3. For a specific cooperative autonomous driving function or scenario, the exposure to safety-critical scenarios can be analysed, and the frequency of respective hazards can be estimated (for example, via data-driven methods). If emergency replanning is needed, then one can aid in avoiding the accident or, if not possible, reduce its potential risk. Interestingly, although our framework focuses explicitly on the V2X communication for manoeuvre planning, a similar workflow can be envisioned for non-cooperative autonomous driving. However, the emergency ethical interaction still requires the V2X [10].

III. Case Study: Longitudinal Driving

Emergency Braking: Normal vs Ethical

For illustration, we consider a scenario of longitudinal driving with three cooperative autonomous vehicles, Fig. 4.

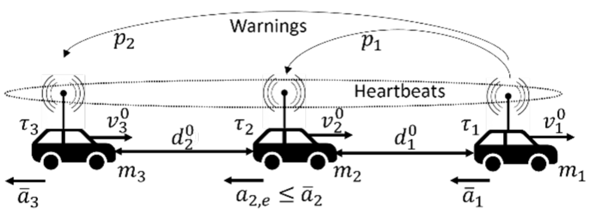

Fig. 4: Case study: braking in longitudinal driving

At the time instance τ_1, vehicle 1 initiates emergency braking with its maximum possible deceleration value $\bar{a}_1$ in response to an encountered obstacle. Simultaneously with braking, vehicle 1 starts sending warning messages periodically with a time period T to the other two vehicles, alerting them about the emergency and the consequent deviation from the planned trajectory. Due to noisy V2X communication, vehicles 2 and 3 experience packet loss with probabilities p_2 and p_3. As a result, the first warning message is not received at time $\tau_1 + T$, but rather at some random time instance later on. We define those time instances as t_2 and t_3 for the second and the third vehicle, respectively. The subsequent behaviour of vehicles 2 and 3 depends on whether the ethical cooperation between the vehicles is assumed or not. In either case, the third vehicle operates by applying its maximum possible deceleration value $\bar{a}_3$, whereas the second vehicle is not obligated to brake with its maximum deceleration value $\bar{a}_2$. The explicit choice of the deceleration value for vehicle 2 is described below.

- In the case of *"normal emergency braking"*, both the second and third vehicles immediately apply emergency braking upon receiving the warning/emergency message. Thus, the third vehicle enters emergency braking at time t_3 by applying its maximum deceleration value $\bar{a}_3$, and the second vehicle starts decelerating with $\bar{a}_2$ at t_2.
- When *"ethical emergency braking"* is performed, the vehicles will wait until scheduled times τ_2, τ_3 (in advance agreed-upon parameters) to start braking. Thus, vehicle 3 initiates braking at τ_3 with $\bar{a}_3$, whereas vehicle 2 starts braking at time τ_2 using some reduced deceleration value $a_{2,e} \leq \bar{a}_2$ that it chooses in order to meet the ethical criteria, namely, to reduce (or redistribute) potential harm for the involved actors. Obviously, ethical braking can be executed only if both vehicles receive emergency messages in time, i.e., when $t_2 \leq \tau_2$ and $t_3 \leq \tau_3$. However, it can happen that due to channel imperfections, the emergency message is not received in time by vehicles 2 or 3, meaning that $t_2 > \tau_2$ or $t_3 > \tau_3$. Therefore, ethical braking should be designed to address the potential failure of execution in order not to exacerbate the harm resulting from normal braking.

Risk Assessment for Decision-Making

To facilitate a comparative analysis between normal and ethical braking, we operate as has been previously mentioned, with the concept of risk. The risk can be formally defined as the expected value of harm, which involves the multiplication of harm by its associated probability and subsequent summation across all possible outcomes. In our case study, the first vehicle starts braking at τ_1, and without loss of generality, we assume that $\tau_1 = 0$. Simultaneously, it sends emergency messages to the following vehicles with a time period T. In this situation, all probable scenarios are encompassed by instances when these messages are received by vehicles 2 and 3. For each such possible outcome, the associated harm can be computed by considering the velocities at the moment of impact and the masses of the colliding vehicles [10]. Thus, following [10], the harm H_1 for vehicle 1 in the collision with vehicle 2 can be calculated as:

$$H_1 = \frac{m_2}{m_1 + m_2} \Delta v_1, \tag{1}$$

Here, m_1 and m_2 are masses of vehicles 1 and 2, respectively; $\Delta v_1 = v_2 - v_1$ – the relative velocity of the involved vehicles before the collision.

Assume, for now, that normal braking is scheduled. The total risk R_n related to normal braking can be written as the sum:

$$R_n = \sum_{i_2=0}^{N_2} \sum_{i_3=0}^{N_3} p_2^{i_2} (1-p_2)^{(1-\lfloor \frac{i_2}{N_2} \rfloor)} p_3^{i_3} (1-p_3)^{(1-\lfloor \frac{i_3}{N_3} \rfloor)} \cdot \cdot H((i_2+1)T, \bar{a}_2, (i_3+1)T, \bar{a}_3) \tag{2}$$

Here, $H((i_2+1)T, \bar{a}_2, (i_3+1)T, \bar{a}_3)$ is the harm associated with the case when the second vehicle starts emergency braking at the time instance $(i_2+1)T$ by applying deceleration value $\bar{a}_2$, and the third vehicle – at $(i_3+1)T$ by applying $\bar{a}_3$. The corresponding to this harm probability reflects the likelihood that the first reception of the warning by the second vehicle happens at the time $(i_2+1)T$, considering that all prior transmission attempts have failed. The same applies to the third vehicle but at time $(i_3+1)T$. The parameters N_2 and N_3 are the maximum number of time slots during which the emergency message can be received by vehicles 2 and 3, respectively, before a collision with neighbouring vehicles occurs. Thus, if vehicle 3 has not received the warning before the time N_3T, it collides with vehicle 2 somewhere between N_3T and $(N_3+1)T$, i.e., during the time interval until the next attempt for message reception. After a crash occurs, waiting for a message reception serves no purpose. This is why N_2 and N_3 set limits on the feasible time slots for consideration. Note that N_2 and N_3 are not constants and are dependent on the moments when the involved vehicles start decelerating. However, we omit the exhaustive details of variable dependencies for the sake of clarity and conciseness. When $i_2 = N_2$ (or $i_3 = N_3$), the associated probability corresponds to the scenario when the warning has not been received by the second (or third) vehicle throughout all N_2 (or N_3) time slots. In such cases, the denotation of harm indicates that braking starts at $(N_2+1)T$ (or $(N_3+1)T$), i.e., after a crash with neighbouring vehicles has occurred. This implies that the collision happens without the second (or third) vehicle applying any deceleration.

When ethical braking is scheduled with parameters τ_2, τ_3, and $a_{2,e}$, the associated risk R_e undergoes alterations in comparison to R_n. The risk R_e can be calculated similarly to (2); however, all the terms involved in the summation need to be divided into four groups:

- terms that remain unchanged from (1) since the message comes through after the planned τ_2 and τ_3, i.e., $t_2 > \tau_2$, $t_3 > \tau_3$. In this case, the normal braking is executed.
- terms that are replaced by a single term

$$(1-p_2^{\lfloor \frac{\tau_2}{N_2} \rfloor})(1-p_3^{\lfloor \frac{\tau_3}{N_3} \rfloor})H(\tau_2, a_{2,e}, \tau_3, \bar{a}_3) \qquad (3)$$

  since both vehicles receive warnings before planned τ_2 and τ_3, i.e., $t_2 \leq \tau_2$, $t_3 \leq \tau_3$. In this case, ethical braking is executed.
- terms related to unexecuted ethical braking due to vehicle 3 receiving the warning too late, i.e., $t_3 > \tau_3$ whereas $t_2 \leq \tau_2$. In such a case, vehicle 2 applies $a_{2,e}$ at τ_2 since it anticipates an ethical braking scheme to be performed. However, the third vehicle starts braking later than τ_3, i.e., as soon as it receives the warning.
- terms related to unexecuted ethical braking due to vehicle 2 receiving the warning too late, i.e., $t_2 > \tau_2$, whereas $t_3 \leq \tau_3$. In this case, the second vehicle applies $\bar{a}_2$ once receiving an emergency message, whereas vehicle 3 anticipates ethical braking to be performed, and instead of starting braking as soon as receiving the warning at t_3, it waits until τ_3.

Performance Evaluation

In our case study, within the ethical framework, the second vehicle chooses (if possible) $a_{2,e}$ such that the total risk R_e of ethical braking is lower than that for normal braking, R_n. To illustrate our approach, we conduct simulations using a range of varied parameters. The harm is calculated according to [10] under the assumption of equal ethical "priority" for all three vehicles. Figures 5, 6, 7 show three different scenarios. On the left in each figure, an example of risk calculation for ethical braking, R_e, versus the possible choice of $a_{2,e}$ is presented. Note that the units of the harm are omitted. In our assumptions, harm is measured in m/s, representing the product of vehicular masses ratio and the relative velocity at the moment of crash. Generally speaking, other harm models can be applied. For comparison, the level of risk for normal braking, R_n, is also depicted. Any risk that falls below this threshold, R_n, indicates a reduction of anticipated harm with respect to normal braking. Furthermore, depending on the system's initial conditions (velocities, inter-vehicle distances at the moment τ_1), it can even be possible to reduce risk to 0, as illustrated in Fig. 5.

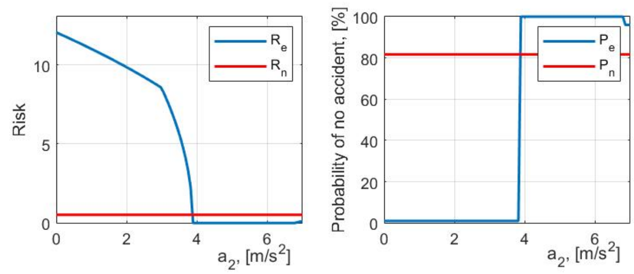

Fig. 5: Example 1. Comparison of ethical and normal braking. Left: risk. Right: probability of no accident versus possible choice of $a_{2,e}$

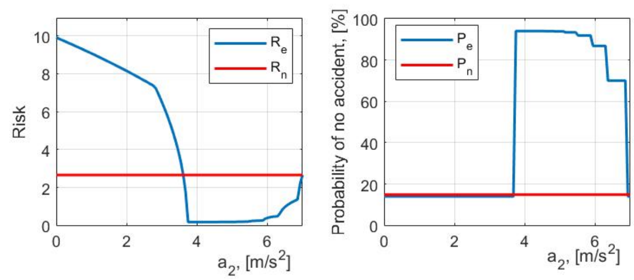

Fig. 6: Example 2. Comparison of ethical and normal braking. Left: risk. Right: probability of no accident versus possible choice of $a_{2,e}$. Here, $\tau_2 = \tau_3 = T$

On the right side of Figures 5-6, the corresponding probability, P_e, of no accident, i.e., the probability that $H_{max} = 0$, versus the possible choice of $a_{2,e}$ is plotted for ethical braking. Again, for comparison, the probability of no accident, P_n, for normal braking is also shown. Fig. 5 corresponds to the scenario when inter-vehicle distances are such that the probability of no accident for normal braking is more than 80%. However, cooperation between vehicles when the middle vehicle (based on the necessary information about neighbouring vehicles obtained via the V2X) chooses "the best" $a_{2,e}$ not only reduces average harm but also enhances the likelihood of avoiding any accident (zero harm). Thus, any deceleration value falling within the range between 3.9 and 6.8 m/s^2 can serve as a proper choice of $a_{2,e}$. With such $a_{2,e}$, the probability of no accident rises up to 100%, which is an excellent property of the studied ethical scheme.

For the second simulation example presented in Fig. 6, τ_2 and τ_3 are chosen as small as possible, i.e., $\tau_2 = \tau_3 = T$. This means that ethical braking is scheduled under the assumption that the very first warning transmission attempt is likely to result in successful reception by both followers. The probability of no accident for normal braking here is only about 15%. Such a scenario might correspond to the case when

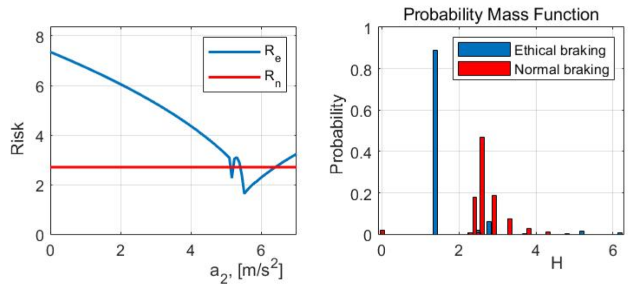

Fig. 7: Example 3. Comparison of ethical and normal braking. Left: risk. Right: probability mass function for "the best" choice of $a_{2,e} = 5.5\ m/s^2$

the emergency braking needs to be performed during some transition period of trajectories readjustment. Even for such small values of τ_2 and τ_3, cooperation between vehicles and the proper choice of $a_{2,e}$ allows for reducing risk more than 14 times, from 2.66 to 0.18. Simultaneously, the probability of no accident goes up from 15% to 94%. Note, for a case $\tau_2 = \tau_3 = T$, the risk for normal braking R_n equals R_e if maximum deceleration $\bar{a}_2$ is chosen for ethical braking, i.e., $a_{2,e} = \bar{a}_2$.

For the example 3 presented in Fig. 7, it is possible to choose $a_{2,e}$ such that $R_e < R_n$. However, even for "the best" choice of $a_{2,e}$ the probability of no accident for normal braking exceeds one for ethical. Namely, with ethical braking it is not possible to avoid collisions, whereas the probability P_n is 1.8%, indicating that $P_n > P_e$. However, it appears unreasonable to conclude that ethical braking is inferior to normal braking based on such a low probability P_n. A more rational approach might involve relaxing the stringent criteria on the value of tolerable H_{max}. Thus, with $H_{max} = 2$, the probability of not exceeding this threshold for ethical braking, Q_e, is remarkably higher than the respective one for normal braking, Q_n. As can be seen from the probability mass function, Fig. 7, with such a threshold, $Q_e = 88.7\%$, whereas $Q_n = 1.8\%$.

IV. Outlook

This article urges the need for the design of ethical cooperative interaction approaches, which include the V2X communication protocols as well as respective control actions. This field of research is still in its infancy and requires a combination of detailed vehicular dynamics, wireless communication, and crash modelling efforts. It is important to derive formal bounds not only on safe [15], but also ethical driving. In our case study, we focus on the unreliability of inter-vehicular radio communications as a source of the harm stochasticity. Nevertheless, our methodology can include other sources of uncertainties in sensing and actuation during autonomous driving. As an immediate future work direction, we aim to explore a communication model wherein the probability of message loss is dependent on the distance between transmitter and receiver. Additionally, the imprecision of the localization data and the sensitivity of the risk function will be analysed.

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