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Research Paper

Risk assessment for road infrastructure

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Abstract
Several variables intersect to create the concept and goal of road safety. Understanding how they intersect and influence each other is key to road safety management, and to improving the algorithms at the heart of the nascent autonomous traffic. When a vehicle driver reacts to objects along the way, the effects of those objects include changes to the travelling velocity and to the position of the vehicle on the road. Calculating such interactions allows us to identify areas of active and passive risk, which can in turn serve to reduce the severity of traffic incidents and to assess the efficacy of safety solutions in use.
Keywords: *road safety, risk, discomfort, autonomous, efficiency, transport, travel, velocity, inertia.*

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I. Introduction

Transport infrastructure reflects the needs of a society. Built with available resources, it is determined by the particular goals of the participants of transport activities, and by technological advancements currently deemed socially acceptable. The existence of a technology is not tantamount to its practical acceptability. In theory, we are technologically ready to deploy autonomous transportation and, thanks to huge operational data resources already available, we are ready to optimize autonomous transport networks for efficiency and safety. This is not, however, what is happening: people's and organizations' habits and experiences force the continuation of existing solutions which are burdened with uncertainty of outcome.

Crashes and other incidents disrupting the flow of transport networks remain a constant major source of inefficiency and economic loss, to say nothing of the cost to human life and wellbeing, and the damage to the environment. Neither do environmental losses start with unplanned incidents within transport networks: the networks' very design impacts the environment, with the demands it places on natural resources, and influences theprocesses of production of vehicles, fuels, infrastructure, spare parts, or consumables.

It follows, that a key aim in transport development should be to minimize direct incidents which lead to the loss of value of material elements of transport, as well as to prolong the longevity of these material elements, and to achieve other measures which optimize economic and environmental costs.

II. The effect of an object on traffic

The common-sense belief that driver and vehicle behavior on the road is only influenced by road and traffic conditions is an oversimplification. In reality, every obstacle in the driver's sight changes the parameters of the journey, be it speed or vehicle location within the roadway, and leads to potential traffic flow disruptions and incidents. Every object within the driver's field of vision is subject to the driver's individual interpretation, based on their individual knowledge, experience, their current state of mind and perceptual ability. These dependencies are presented in chart 1.

When drivers encounter in their path a stimulus suggesting a change of direction (even if it is only informative, e.g., a sign advising of a left turn in 100 m), the trajectory of the vehicle they are guiding changes perceptibly. In gliding aviation, this finding has been incorporated as a crucial phenomenon to account for when training pilots: before they can land on an airstrip they must fly along a square trajectory between pre-set points A, B, C and D, and only commence landing when the airstrip is free for them. Inexperienced glider pilots often struggle to keep to the square trajectory (in commercial aviation this has long been circular: the commonly known circling) because, instead of being guided solely by their navigation instruments, they cannot ignore the airport, which is constantly within sight. This pull of the airport can lead to a change of course, inaccurate positioning for landing, mistimed landing, and even a collision with another aircraft.

Every object along the journey is interpreted by the driver of a vehicle as influencing the goal and the conditions of the journey. It can also bring memories and cause experiences without any direct relation to the journey but having an influence upon it. If the driver sees a vehicle which reminds them of one they were recently in collision with, this will cause an inadequate reaction. The influence can be negative as well as positive, leading to greater focus, or to inattention. The driver takes decisions and actions (pressing the accelerator, turning the steering wheel) which are often involuntary.

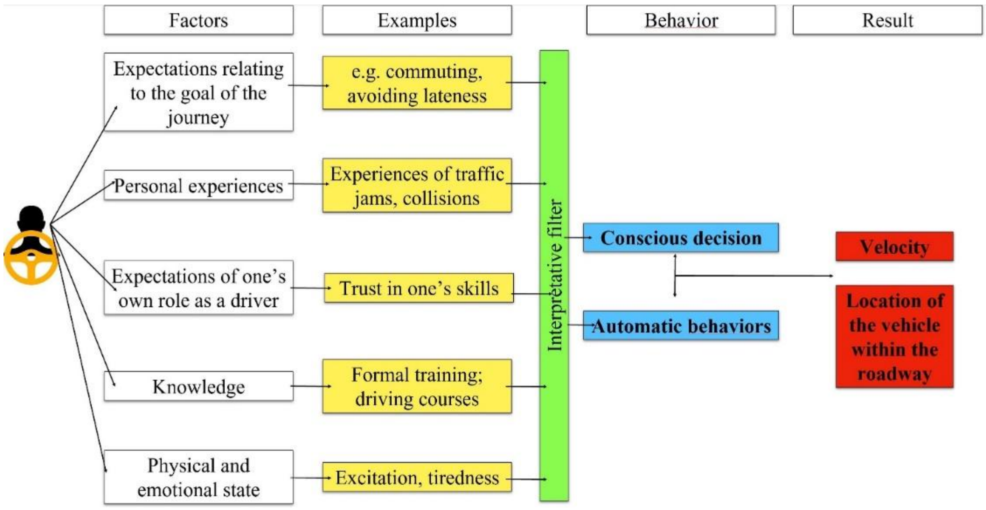

Chart 1.Object effect on driver behavior.

The above chart illustrates key elements which can influence the reaction to objects along a journey. Irrespective of how accurate the model, its effect will be a change of velocity (acceleration, deceleration) and a change of position within the roadway (lateral movement). These changes can be described as measures of discomfort. The greater the change (of velocity and position), the less comfortable this section of the journey is for the driver. The appearance of an object and its perception by the driver will cause changes whose frequency is measurable. The measure of discomfort,being the magnitude of velocity and position change over time and the frequency of change during the approach to a tunnel, is captured by the formula:

$$D = \frac{\Delta v}{\Delta t} \cdot d \cdot f$$

where:

D – is the measure of discomfort attributed to an obstacle, a road sign, or an incident along the way
Δv – is the change of velocity in [m/s]
Δt – is the time over which the velocity change has taken place [s]
d – is the distance of lateral movement in [m]
f – is the frequency of changes along the measured section in 1/[s]

The unit of driving discomfort is [m^2/s^2]. Drivers can make countless changes as the result of interpreting an object encountered en route so it is crucial to establish the length of the journey section influenced by a stimulus (during which it is visible and can be perceived) and then add the results for each calculated change. Factor identification in conventional transport is difficult and requires the road to be equipped with sensors; autonomous transport allows for live data collection from within vehicles.
The attempt to verify the observed relationships took place in the years 2019 and 2020. The author conducted observations of driver behavior on approaching two tunnels:

- a tunnel near an airport in Germany (two-way, 600 m in length),
- a city tunnel under a roundabout in Poland (segregated three-lane one-way roadways, 650 m in length).

The observations measured the change of the geometric center of vehicles relative to the geometric center of the road along a 200-meter section approaching the tunnel, and the speed of the vehicles. The approaching vehicles were photographed and filmed from above, at a distance of 200 m from the tunnel, and then again, 10 m from the tunnel. This general method allowed the observation of the change of trajectory on approaching the tunnel, dependent on the lane, signs, and traffic intensity. The following relationships were observed:

		Germany		Poland	
Number of observations		150		300	
Reaction to the tunnel	Axis of travel deviation “away from the obstacle” in the direction opposite to the sign	30	20%	130	43.3%
	Axis of travel deviation “away from the verge” in the direction opposite to the wall of the tunnel	10	6.7%	10	3.3%
	Axis of travel deviation “away from the vehicle” in the two-way traffic (typically towards the wall)	20	13.3%	None observed, due to the type of traffic	
	Change of direction attributed to inattention (most commonly the use of a mobile phone)	10	6.7%	23	7.7%
	Change of velocity (observable deceleration)	2	1.3%	43	14.3%
	Change of velocity (observable acceleration)	1	0.6%	23	7.6%
Mean deviation of the axis of travel from the axis of the road	Up to 50 cm in the direction opposite to the obstacle without crossing lane lines (number of cases)	75	50.0%	127	42.0%
	Up to 50 cm in the direction opposite to the obstacle, crossing lane line (number of cases)	15	10.0%	36	12.0%
Travel velocity	Within legal speed limit in km/h	80		70	
	Within legal speed limit in m/s	22.3		19.4	

Table 1. Comparison of observations of influence of a tunnel on traffic.

In both locations an axis-of-travel deviation away from the axis of the roadway was observed, typically away from the wall of the tunnel (20-40% of cases) and less frequently away from another vehicle (3.3-6.7% of cases). In c. 10% of cases the reaction was so strong that vehicles crossed lane demarcation lines.

The observed relationships are consistent with the findings of other researchers[1]. Minimal deviation remained within the limit of 10 cm, which could be seen in the tracks of tires on wet surfaces. Aside from the existence of the tunnel itself, other factors may have influenced driver behavior, such as construction details and lighting. The average vehicle axis deviation of 29-49 cm had already been observed in other behavioral analyses of drivers approaching tunnels [2, 3], as well as in simulated experiments. Test conditions enabled capturing on film the velocity changes during the time it took drivers to cover the 200 m section.

Axis deviation	**Velocity change**	**Germany**		**Poland**	
		Number	Percentage	Number	Percentage
Sum		**150**	**100.0%**	**300**	**54.3%**
>50 [cm]	+ 10 [km/h]	1	0.7%	12	4.0%
>50 [cm]	- 10 [km/h]	1	0.7%	11	3.7%
<50 [cm]	+ 5 [km/h]	10	6.7%	1	0.3%
<50 [cm]	- 5 [km/h]	1	0.7%	10	3.3%
<50 [cm]	No change of velocity	45	30.0%	45	15.0%
<25 [cm]	+ 5 [km/h]	13	8.7%	10	3.3%

Axis deviation	Velocity change	Germany		Poland	
		Number	Percentage	Number	Percentage
<25 [cm]	- 5 [km/h]	0	0.0%	21	7.0%
<25 [cm]	No change of velocity	45	30.0%	53	17.7%
No changes	No change of velocity	34	22.7%	137	45.7%
	Average number of changes per vehicle	0.3		0.8	
	Maximum number of changes per vehicle	3		6	

Table 2. Comparison of observations of velocity and position change.

As they enter the tunnel, drivers correct their vehicle trajectory. The range of changes fits within the interval of 0 (no velocity or position change) to 4 (several-fold change).

We can, therefore, establish that there is a relationship between objects encountered along a journey and the comfort of travel which, in the case of driving a vehicle, is manifested as changes to velocity and road positioning attributable to the object. For the purposes of this article, the notion of “object effect” will be used to illustrate this relationship. It can be expressed as the measure of discomfort in traffic, in [m2/s2], and it illustrates the predictable changes in driving behavior associated with the obstacle (a tunnel, a bridge, a road sign or other signage etc.).

Indicator values for the tunnel in Poland range from 1.11 to 5.56 [m2/s2], and for the tunnel in Germany they range from 1.04 to 4.16 [m2/s2]. Since drivers can make multiple changes (up to three in Germany and up to six in Poland) the sum of all changes must be considered for the final evaluation. Existing literature identifies similar indicators (“pathological discomfort” [4]) for traffic in road tunnels, and a relationship between factor magnitude and incident rate. Analyses of eight tunnels up to 1000 m long identify the average indicator level at 4-5.0 [m2/s2], with a constant deviation of 14% (from 4.3 to 5.7) and an average forced change of road positioning of 29 cm (ranging from 16 cm to 48 cm). The suggested indicator can be applied in practice.

III. The risk in transport

If revolutions come in cycles, like celestial bodies, then recent years seem to bear out the arrival of a new revolution to be visited upon homo sapiens [5]. After the Neolithic, agricultural and industrial revolutions, humanity has to measure up to the information and biotechnology revolution, together with the challenges and opportunities it brings. The intersection of big data and biotechnology facilitate increasing automation and the development of intelligent projects. More and more areas where humans had thought themselves irreplaceable become open to broadly understood automation, and robots and machines compete with humans for ever more jobs, scrutinizing us with their watchful cameras and sensors. They analyze enormous amounts of data and automatically model and re-model their behaviors to fulfil the objectives programmed at the moment of their creation. One of these key objectives is efficiency. Optimization paired with the ability to analyze big data [6] create algorithms capable of automating ever growing numbers of processes and activities and allow, in essence, the creation of new forms of life, both organic and inorganic, generated and developed without recourse to the languor of natural evolution. All these processes are changing the world around us and, in turn, we are forced to modify our perception of events and phenomena in our environment. Increasingly, it is not our direct reaction to a phenomenon, but rather expectations underpinning the algorithms assessing the phenomenon that decide our ultimate course of action. Take as example the 2007–2008 financial crisis. According to many experts [7] it was triggered not by objective causes but rather by a flippant approach to residual [8] risk: bullish market traders made decisions based on analyses whose security and control measures were frivolous at best. Soon enough, the dominant methods of analysis and of trading proved themselves tragically inadequate.

Risk is often mistaken for danger and seen as undesirable. If risk and danger were the same, the surest way to succeed would be to avoid risk. This is not the case. Risk avoidance does not lead to progress. Conversely, accepting risk which is too high (unacceptable) can lead to the same results as avoiding risk altogether. In legal and economic practice, the notion of “risk” can be found everywhere, from finance to security, and it attracts diverse definitions in professional literature and in the codes of law. In the areas of chemical safety and environmental protection, for example, certain legal systems [9] define risk as the “probability of a specified event at a specified time or in a specified situation”. Risk management models based on this type of definition (which implies that risk is the product of certainty of an event and its results) are informed by the belief that the future can be modelled with mathematical tools. If we define results and ascribe probability to them, we arrive at "risk". Conversely, if we cannot define results or their probability, "risk" turns out to be close to nil and negligible. Clearly, such a conclusion is incorrect. In effect, the magnitude of "risk" merely quantifies the degree to which we cannot foretell the course of an event or, at best, highlights the flaws of such a definition: such risk management becomes a case of statistics for the statistician's sake. To put it another way; if this method were truly effective, statisticians and economists would be able to predict economic downturns with certainty, as they always hope to.

IV. Risk as the influence of uncertainty on goals

International institutions which we have entrusted with regulating normative requirements have defined risk [10] as the influence of uncertainty on objectives, which we set as organizations, communities, or individuals. This definition presents one strict condition: the necessity to set objectives.

Without setting goals we cannot speak of risk, when defined as *the influence of the uncertain and the undefined*. We can only speak of danger. If we take action at risk of this danger, it becomes a hazard. If this hazard influences our goal - we have risk [11]. So, what is a goal? In my profession [12], I define a goal as a circumstance, value or state which meets several criteria. Firstly, my goal has to depend on me: I must have influence over it. Otherwise, it might be better described as a dream, not a goal. Let us illustrate this with the example of games of chance. Let us assume that a lottery has announced a jackpot of €10 million. If we make the winning of this jackpot our goal, we are justifying certain actions and investments, such as an analysis, or the purchase of lottery tickets. Ultimately, however, we have no influence over the outcome. Imagining that we win (i.e., achieve our goal) can boost our mood and nothing more. In reality, we have no influence over the lottery. The winning numbers are generated randomly according to a probability distribution which we can define with some accuracy, based on the history of numbers generated previously.

If we have no influence over achieving the goal, we can speak only of hazard or danger. It would therefore make sense to speak, in the context of games of chance, of the *hazard* of loss of investment (passive assessment) or the *danger* of failure (once we have purchased the ticket), instead of speaking of a risk of success. To practice risk management, we need a change of perspective. Personally, I win no less than €1,000 every year in lotteries. How? Simply by not playing. I analyze the risk of loss of capital resulting from the purchase of a ticket. My analyses show me that the probability distribution of loss of capital is negative, and I follow my findings.

The second criterion of a goal is its measurability, in at least two ways. First, comes the direct ability to measure the goal (give the goal a measurable value); second, is the distribution of this measure. If the goal behaves randomly (the distance of current values from the planned goal is greater than two standard deviations [13]), our influence over the goal's value is minimal. A good example of such a situation would be stock or cryptocurrency prices.

We can expect the market to behave in a certain way. For example, we can expect bitcoin to reach a certain value. However, the probability that it will fail to reach that value equals 50% (it will succeed, or it won't). This observation has led to the formulation of the **theory of inertia**[14] which postulates that our expectations and experiences can influence probability calculations and render them erroneous. According to the theory of inertia, a goal can reach one of three values: it can be *achieved*, it can be *unachieved*, or an *unplanned event* may occur. This follows the broader premise of quantum theory (event occurring is "+1"; event not occurring is "0"; unplanned event occurring is simultaneously "+1" and "0"). The resultant state is *fuzzy*, ambiguous, and contradictory. This state can be illustrated with a membership function of the expected value for the set of potential solutions. Measuring the goal (fixing its value) is not enough; it is also important to place this value on a timeline. The goal should also be "ecological", that is consistent with the system within which it exists. Goal "ecology" will also be the measure of how adequate the analysis is to the actual course of events. Describing and measuring the goal, and the premise that it is enough to *describe* a non-physical factor numerically in order to *manipulate* it like a number, enable us to attempt a definition of the algorithm which can illustrate the phenomenon we are studying. A key caveat is that we remain at a high level of generality as evidenced by, for example, the dispatch of Newton's laws of dynamics into space, towards galaxies we have identified but know nothing about. At the level of detailed analysis, the uncertainty model remains inadequate. Although deficient rules may be treated as an exception, the model is better suited to a new set of rules. Scientific achievements of the industrial era and, in particular, computational models used in modeling the future, are subject to the error of inadequacy because their degree of generality works with practical problems but is limited in modelling under conditions of uncertainty. Since the end of the 19thcentury it has been recognized that the existing models of reality must be perfected; this understanding led to the development of quantum theory [15]. Consequently, modelling risk, its measurement and management must also be perfected. Risk, similar to safety, is a state of the mind which is individual in character [16] and associated with goals. Ways in which an individual identifies goals and makes decisions can be irrational. Nonetheless, the mental processes of risk assessment and decision making can be seen as natural biotechnological algorithms and, as such, can be aided by artificial intelligence algorithms. Atom-level observations have led to the conclusion that the existence of a particle can be determined with certainty within a particular space, but not within a particular time frame [17]. This micro-scale relationship influences the macro scale of the world observable by us without, however, allowing observation with the classical-physics toolkit. We can only apply the lessons learned from the microsphere to the nanosphere [18] as conceptual translations. However, given the large number of possible quantum states, we can only observe their mean outcome and cannot draw conclusions until after completing the measurement. Although the process is challenging, it can nevertheless be successfully applied in the context of risk assessment and probability calculations, making this model better suited to unstable conditions. The undeniable benefit of considering quantum laws in the macrosphere is that event probability calculations are revised to allow for forecasting unlimited sets of potential solutions. One attempt at this type of modelling is the above-mentioned theory of inertia [19]. It is grounded in probability theory [20] and work by Richard von Mises, Henri Léon Lebesgue, Andrey Nikolaevich Kolmogorov and Melvin Dale Springer. It postulates that the probability of each possible outcome grows in accordance with Bernoulli's law of large numbers [21]. The influence of uncertainty on particular outcomes is in accordance with the Copenhagen interpretation [22] of quantum mechanics: only the measurement and attendant evaluations can change the knowledge available to the observer; the observed phenomenon is constant and always probable in every direction. More important than calculating linear probabilities is, therefore, defining all possible states and their consequences, as well as their uncertainty according to the expected distribution.

These conclusions are analogous to those used in risk assessment standards [23], which stipulate that risk should be assessed as the influence of uncertainty on goals, and uncertainty as deviation from expected outcome. Since, without a specific methodology, it is difficult to avoid the limiting influence of one's previous experience, every risk assessment which does not account for the issues discussed above is irrational.

V. Passive and Active Risk

In line with the above conclusions, we must define risk in the context of our goals, irrespective of our particular interest and the subject of our analysis (whether finance, data security or another field). It follows that we also have to redefine safety: we are safe when we are in a state free of unacceptable risk. It is a notional state in which we have ascribed the risk a magnitude which we are willing to accept. Building on the uncertainty model, we can refine the definition of risk as the influence of uncertainty on goals which is subjectively assessed by an individual or a group. The general condition of our cognition is such that, irrespective of our psychological perspective, the faith in our effectiveness and the conviction that our course of action is right, the results of our activity can only be predicted to a modest degree. It is much easier to avoid a major incompatibility with a goal than a minor one. If our goal is a specific limit on the number of errors in, for example, a manufacturing process, it will be easier to avoid a hundred additional errors than to avoid just one. Even if we choose to influence this goal by stopping the process, lack of information will have the greater influence, the closer we are to the goal. This is where cognitive deficiencies and erroneous assumptions become clear in their influence. It will, therefore, be useful to introduce into the analysis the concepts passive and active risk [24]. Passive risk is harder to modify because, as the process analyzed develops, new characteristics of this process transpire and the information we lack to achieve certainty changes. Risk understood as the influence of uncertainty on goals [25] can be visualized statistically. Risk can be shown as a possible event distribution in a graph in a Cartesian coordinate system, expressed as a plane under the curve which illustrates the distribution for a particular event. Assuming normal distribution for the given goal, we can present this as follows:

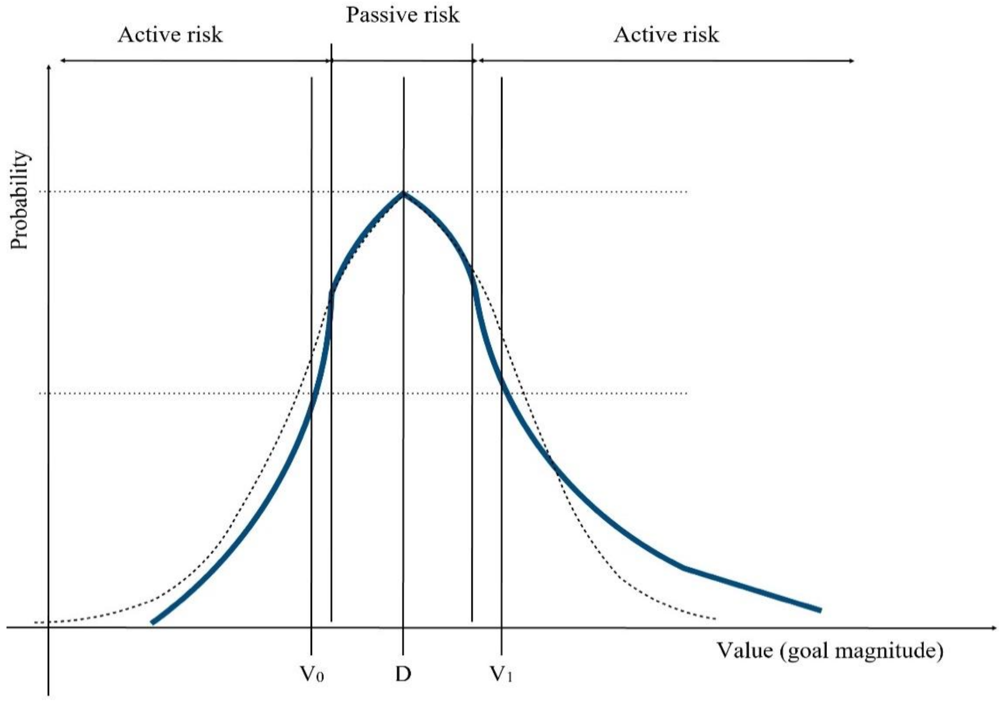

Chart 2. Risk-goal distribution

where:
D - value distribution mode - goal
V_0 - lower limit of expected goal value interval (50% probability)
V_1 - upper limit of expected goal value interval (50% probability)
Solid line - real probability distribution function
Dotted line - symmetric distribution function of expected values (positive and negative).
The difference between the solid line and the dotted line is the value resulting from our choice of action: the way in which we proceed towards the attainment of our goal (goodness-of-fit).
The degree of goal attainment will always fit within its distribution interval. The passive risk area (the difference in the area at the bottom of the graph showing expected distribution and real distribution) identified in the graph is determined by our choice of action. The frequency and range of reaction will depend on the frequency of observation of the parameters (elasticity of reaction). The more frequently we can perform analyses, the better we can limit passive risk by becoming aware of newly transpired characteristics and by filling in gaps in our knowledge, where possible. Minimizing passive risk should be our key goal and this postulate should be the key premise in every type of risk management, including risk management of transport networks and of individual vehicles.

VI. Managing risk of discomfort

Having established the measure of discomfort, we can make it the goal of risk assessment.
Assuming the value of 2.5-5 m^2/s^2 as the standard determinant for road traffic allows the management of traffic organization solutions and the improvement of autonomous traffic algorithms.
To assess the applications of the measure of discomfort, we assume that vehicles can be driven by drivers who:

- take decisions and, through a system of levers, pedals and switches steer the vehicle (manual driving),
- take decisions regarding key parameters of the intended journey (direction, speed) but their decisions are assisted or executed by computers (semi-autonomous driving),
- take decisions regarding the destination but all other functions are automated (autonomous driving).

Accordingly, application of the measure of discomfort would proceed as follows:

1. assess the influence of existing traffic organization and communication solutions (i.e., measure the changes in the section before the object, sign, or obstacle). The measurements of the influence of individual elements of the infrastructure and of changes to driver behavior (velocity and road positioning) must be standardized,

2. standardize the influence of the existing solutions and compare the expected influence with actual values and with risk assessment,
3. measure driver behavior *by the semi-autonomous vehicle* and issue warnings if tiredness or distractedness are suspected,
4. self-assess algorithmic discomfort *by the autonomous vehicle* in addition to measuring road positioning and distance to other vehicles, obstacles and other traffic participants. If discomfort indicators exceed the mean (drawn from existing observational data), this may be interpreted as increased danger and necessitate a change to velocity and positioning (distance),
5. use algorithmic discomfort *from multiple autonomous vehicles* travelling near each other to optimize collision avoidance behaviors.

Collision avoidance has been long discussed as a moral dilemma within the field of autonomous travel: what ought the vehicle to do when there is another collision ahead, or a human in the way? The solutions depend on the hierarchy of goals (saving the lives of vehicle occupants, saving the lives of people outside the vehicle, saving the vehicle). Depending on these choices, the result may range from accepting the risk of collision with another vehicle to accepting the risk of hitting a pedestrian. Observations show that such decision scenarios are ruled by similar perception processes to those present in the aforementioned “object effect”. Each driver’s behavior will be guided by the measure of discomfort and, consequently, can be predicted and managed.

VII. Conclusion

Safety is a state in which we have reached high or complete attainment of specific goals. Chief among these goals is the minimization of traffic incidents, casualties, and the resulting economic and environmental costs. As shown above, the closer we get to the goal of total safety, the harder it becomes to make improvements. If a stretch of road sees an average of *a hundred* incidents per annum, it is easier to reduce that number down to *one* – by tackling the low hanging fruit of safety measures – than to ensure that *one* drops to *zero*. This stems from the mathematical nature of risk, which is defined here as the area of passive risk. To manage safety very close to full attainment, we must find new methods and increase observation. Measuring discomfort, both for human-operated and for driverless vehicles, is one such method which opens new possibilities for approaching total road safety. It allows us to react to traffic situations and to calculate the influence of solutions in real time. This method formed the basis for the proposal to use discomfort measurements and equip tunnels with measuring instruments, which was nominated in 2021 for the Excellence in Road Safety Awards by the European Commission.

Changes in velocity and road positioning are a good measure of discomfort as a response to objects along the way. The proposed indicator $[m^2/s^2]$ remains constant throughout the range of velocities: the change it marks can be expressed as a fraction or percentage of the original speed of travel. This flexibility gives us greater analytical power over the observed data. While sudden braking from 100 kph or 40 kph will give different final velocities, it is the degree of deceleration that yields the relevant insights into discomfort and its implications. The unitless numeric value of this ratio becomes the key indicator for real time measurements.

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