Autonomous Driving – more than just avoiding collisions



Roger Rivett discusses the challenges of having a fully autonomous vehicle using the current road infrastructure alongside non-autonomous vehicles and other road users. He examines whether changes could be made to the road infrastructure and extending the scope of the safety arguments, so that these are both more accommodating to autonomous vehicle technologies.

This article describes the motivation behind the creation of an ontological model of the public road transport system under the auspices of the Assuring Autonomy Internal Programme (AAIP), [1] and published on the AAIP website, [2]. That work results in a set of vehicle movement constraints that are being used in work being undertaken by the MISRA Safety Argument working group, [3].

There seems to be a general consensus among politicians and car manufacturers that the progressive introduction of Advanced Driver Assistance Systems (ADAS), [4], [5], finally leading to fully autonomous driving (AD), [6], will reduce harm to people, increase efficiency and reduce pollution.

Vehicles equipped with ADAS features started to be introduced in the 2000s. With these, a human driver is still fully responsible for the control of the vehicle. In the last few years, vehicles equipped with Automated Driving Systems (ADS) have started to be introduced. These have the capability to take over the responsibility for the control of the vehicle for parts of a journey. These are seen as a part of an inevitable development of the fully autonomous vehicle.

The Public Road Transport System

The Public Road Transport System (PRTS) is the public space used for automotive transport. This is a very rich environment with many different aspects. There are a variety of different types of users, who themselves are part of the PRTS. In addition to the road network itself, the PRTS has many different facilities that support and coordinate its users. The PRTS also includes broadcast information, the weather conditions and illumination levels.

The road network consists of many different types of road that traverse a variety of different settings from city to suburban to country. The road surface is made of different materials and also has words and symbols written on it. The road network has developed over centuries and while modern roads may be laid out in a geometric and somewhat logical manner, there still exits road dating back many centuries which are much less so.



Third Parties



In addition to the users of the road network there are many third parties involved in the wider system. Governments, and their agencies, create a legal framework for the design of the road network, the design and manufacture of the vehicles that use it and the behaviour of the people that are part of the PRTS. Standards bodies create standards for various other aspects of the PRTS including the design and construction of roads, vehicles and traffic information. The roads and vehicles are designed and built by different companies using many sub-suppliers and contractors. The roads and vehicles are maintained by organisations that did not design them. Broadcasters provide information used in planning journeys.

The Dynamic Driving Task and the Driving Enterprise

The Dynamic Driving Task (DDT)

Historically the task of driving a vehicle was not formally defined; it was a skill that had to be acquired. In most countries, there are measures to ensure that only those with a sufficient level of skill are allowed to drive and also measures to punish instances of poor driving. In the UK, the Highway Code was first launched in 1931 and, from 1934 onwards, passing a compulsory driving test was required before a driver was issued with a driving license. Legislation motivates the human driver to perform well by making poor driving an offence, examples include causing death by dangerous driving and driving without due care and attention.

More recently, vehicles have started to be equipped with ADS features which perform some aspects of the driving task. The term ADS itself is defined in SAE J3016, [7], as "*The hardware and software that are collectively capable of performing the entire DDT on a sustained basis, regardless of whether it is limited to a specific operational design domain*".

The term *operational design domain* (ODD) is defined by SAE J3016, [7], as: "*Operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics.*" The ODD is effectively a subset of the aspects of the Public Road Transport System mentioned above.

With the advent of Automated Driving Systems (ADS) equipped vehicles, the driving task has started to be defined more formally

With the advent of ADS equipped vehicles, the driving task has started to be defined more formally. SAE J3016, [7], uses the term Dynamic Driving Task (DDT) to capture all the aspects associated with controlling the movement of a vehicle along a public road. These include:

- Determining the destination of the journey and the sequence of vehicle manoeuvres necessary to reach it
- Monitoring the environment external to the vehicle to detect objects and events and determining the correct vehicle manoeuvre in response to what is detected
- Implementing the vehicle manoeuvres by control of the lateral and longitudinal motion of the vehicle
- Ensuring other road users are aware of the presence, and manoeuvring intention, of the vehicle

The Driving Enterprise

The DDT definition captures the key aspects of controlling a vehicle from the perspective of designing a control system, however there is more to using a vehicle to make a journey than this. Other necessary aspects include:

- Ensuring that the vehicle is roadworthy before embarking on the journey
- Deciding on whether or not to embark on the journey, and the route to be taken, given the anticipated weather conditions
- Matching the demands of the external environment with the capabilities of the vehicle when driving
- Dealing with issues encountered during the journey regarding the vehicle, the road infrastructure and the weather
- Interacting with other human beings using, or in the vicinity of, the road

This wider view of planning and making a journey is referred to as the Driving Enterprise (DE) and its aspects are now briefly considered further.

Embarking on a Journey

The UK government recommends that prior to every journey the vehicle's tyre pressure, engine oil level, screen-wash level, lights and fuel level should be checked. Journeys should also not be started, or continued, if the demands on the vehicle would exceed the Vehicle Operational Constraints. Such constraints include ground clearance, wade depth, turning circle plus the minimum and maximum external temperatures under which it is designed to operate.

Given a roadworthy vehicle, there are other decisions related to the journey that need to be made. One is the decision to start the journey and the route to be taken, based on the purpose of the journey and the information available prior to starting. This may be advance information received as off-board data concerning road and weather conditions that may be encountered during the journey. The trustworthiness of this information needs to be evaluated given that it may be false, ambiguous, out of date or misleading.

Matching the Vehicle Capabilities with the External Environment Demands



To perform the DDT it is necessary for the environment external to the vehicle to be sensed and understood. At any one time, the ability to sense has limits. Trees, vegetation and buildings may obscure line of sight. Weather phenomenon such as heavy precipitation, fog and mist also affect visibility. It is important that manoeuvres are not attempted at speeds which are inappropriate for what can currently be sensed.

As mentioned, all vehicles have Vehicle Operational Constraints and some of these may be adversely affected when the vehicle develops a fault. When determining the correct vehicle manoeuvre, it is necessary to take into account the current performance capability of the vehicle so a manoeuvre is not attempted that the vehicle is not capable of making or will not complete in sufficient time. Examples including driving round a bend too fast and not having sufficient time to complete an overtaking manoeuvre.

It is also necessary to be aware of any reduction in tyre grip on the road, which may arise due to the poor quality of the road surface or the affect of the current weather conditions. This is significant because reduced grip on the road may make it difficult or impossible to complete a manoeuvre.

Managing Issues During the Journey

The DDT has to be performed in a road infrastructure that may not be "text book". The roads or junctions may be long standing and not designed to current standards. The road surface may be less than ideal, for example potholed or untarmacked with raised ironwork; as mentioned above, this may affect tyre grip. The placement of instructive and informative signs may make them difficult to read, they may also be obscured, graffitied or not lit. The content of information provided in signs may be out of date.

Once a journey has been started, there is a continuous process of decision making regarding whether to continue the journey on the same route, change the route, change the destination or stop the vehicle. Such decisions may be made in response to issues related to the weather, road infrastructure and vehicle faults.

A change of route or destination may be prompted by an awareness that the weather or road situation ahead could prevent completion of the journey by the current route or to the current destination. This awareness may be as a result of information received as off-board data or as a result of what is sensed directly. It may also be because of a vehicle issue, e.g. insufficient fuel.

A decision to stop the vehicle may be prompted by the onset of extreme weather, encountering significant road damage or the occurrence of a significant vehicle problem.

If the vehicle problem is such that it diminishes its roadworthiness, then a decision has to be made whether to stop the vehicle or to continue driving more cautiously with the intention of getting the vehicle checked at a garage at a later date. Whenever a decision to stop the vehicle is made, then it should be brought to rest in a location where no harm can occur. The vehicle also needs to stop if it is involved in an accident.

Legal and Social Aspects

The use of the vehicle on the public roads is a social activity that is governed by civil and criminal law. The laws prescribe particular behaviour and require a certain standard of performance. In the UK, the driver is expected to drive in the way that would be expected of a competent and careful driver such that the driving is never dangerous. To not do so may break the law regarding dangerous driving.

The act of driving also has socially expected norms of behaviour. It is generally expected that the vehicle behaviour will demonstrate a sense of care, courtesy and consideration for other road users and not act maliciously. In the UK, to not do so may break the law regarding careless or inconsiderate driving.

There is also the need to balance the obligation to abide by letter of the law with the need to infringe the law in those circumstances that require it in order to avoid harm, for example moving into a "bus only" lane to avoid a collision with a person unadvisedly crossing the road.

The directions given by authorised people, e.g. police officers, should be followed. These may be counter to the desire of the driver and/or may also infringe the letter of the law. Such directions will be being given to achieve a more important social good. A decision also needs to be made whether directions from an ordinary member of the public should also be followed. These may be to achieve a greater social good, but may also be intended for harm or have criminal intent. It is also necessary to allow passage for emergency vehicles, this may also require infringing the letter of the law.

DDT & the Driving Enterprise Performed by a Human Driver

The vehicle roadworthiness is usually the responsibility of the vehicle owner. The pre-journey checks should normally be carried out by the driver, but in the case of a hire vehicle, these are the responsibility of the hire company.

When planning and making a journey, the other aspects of the DDT and DE are the responsibility of the human driver of the vehicle. These include not attempting to use the vehicle if the demands on the vehicle would exceed the Vehicle Operational Constraints, and assessing the trustworthiness of any off-board data that is available.

During a journey, all the sensing, understanding and decision making related to vehicle movement is the sole responsibility of the human driver. They are also responsible for handling any mechanical or electronic control problems with the movement control systems.

The expectation that the human driver can match the vehicle capabilities with the external environment demands is typically based on the fact that the driver is required to be trained. This may be coupled with being licensed to drive, and the fact that the driver is required to be fit to drive, including having adequate eyesight.

Human beings are able to perform the driving task, cope with problems and interact socially with other human users of the road because they possess general intelligence and a theory of mind. Mitchell, in her 2020 article, [8], notes that human understanding is built on a foundation of innate core knowledge of physics, gravity, object persistence, and causality. This enables humans to trace the relations between objects and their parts, think about counterfactuals and what-if scenarios, and act in the world with consistency. They are able to apply previous experience and learning to new situations. Possessing a theory of mind means that human beings have empathy for other human beings and gives them insight into their future behaviour and actions.

DDT & the Driving Enterprise Performed by a Level 5 Vehicle

SAE scale defines a 6 level taxonomy of driving automation [7]. On this scale, a fully autonomous vehicle is referred to as a Level 5 Vehicle. In such a vehicle, the ADS is responsible for the sustained and unconditional performance of the entire DDT, including when the ADS itself experiences faults or failures. Under no circumstances is the user expected to respond to a request to intervene, and there is no remote operator who can intervene.

As there is no action required of the user, the Level 5 Vehicle has to, not only perform the DDT, but also, address the full Driving Enterprise, while taking into account the Vehicle Operational Constraints. This includes making all the decisions related to the journey, as noted above.

The case where the vehicle is sharing the road with other users, including non-autonomous vehicles, 2 wheeled vehicles, pedestrians and animals, both wild and domesticated, is now considered.

Planning and Continuing a Journey

The pre-journey checks still have to be made by the owner/user of the vehicle prior to commencing the journey.

For a privately run vehicle, the owner, and/or user, decides the destination and any waypoints. If the Level 5 Vehicle plans the route, then it has the responsibility of taking account of off-board data, e.g. current traffic and weather conditions, and assessing its trustworthiness. It should not attempt to make demands on the vehicle that would exceed the Vehicle Operational Constraints.

The decision to start a journey, and continue a journey, in the light of off-board data and the situations encountered during the journey, is the responsibility of the Level 5 Vehicle. An incorrect decision may put the occupants lives at risk.

Vehicle maintenance

The vehicle owner still retains responsibility for ensuring the roadworthiness of the vehicle. Although, not having to perform the driving task themselves, may diminish their sense of responsibility as they will not directly experience any difficulties in controlling the vehicle.

If the ability of a human driver to detect mechanical problems, via mechanical vibration, a change in driving feel or a change in vehicle performance, is to be retained, then additional sensors and algorithms may be required. An alternative may be enforcing a more rigorous maintenance regime.

The underlying mechanical components currently in use have been developed for reliability and length of operational lifetime based on a human driving style profile. If the style of driving performed by a Level 5 Vehicle is significantly different to that of a human driver in particular aspects, e.g. greater use of friction brakes, then this may result in faster wear out of associated mechanical components. If this is the case, then the design of these components may need to be changed. Attempting to mimic the driving style of a human driver may be seen as too difficult or too restrictive.

Executing a Journey

All the responsibilities that would traditionally be with a human driver, are now the responsibility of the Level 5 Vehicle. It must discharge these without any human intervention in such a way that no human is injured; this includes both this vehicle occupants and all other road users.

As mentioned previously, these responsibilities are sensing the environment external to the vehicle and executing the appropriate manoeuvres while taking account of the Vehicle Operational Constraints and the demands of the road. Also, interacting socially with other human road users and handling problems presented by the weather, the road and vehicle faults.



The sensing capability of a Level 5 Vehicle may exceed that of a human driver in terms of having multiple sensors that may have a greater range and resolution and may not be degraded by low levels of illumination or by the presence of moisture in the air. However, understanding what is sensed does not have the benefit of general intelligence. A Level 5 Vehicle may also benefit from V2X (vehicle to everything) communications which provide information about the immediate environment external to the vehicle, including the disposition of other vehicles, [9], [10]. The trustworthiness of this information would need to be assured, as it is outside the remit of the Level 5 Vehicle.

Such "artificial intelligence" does not embody a theory of mind

A human driver utilizes their general intelligence to execute the journey, as mentioned above, while the development of Level 5 Vehicles draws heavily on machine learning. Such "artificial intelligence" does not embody a theory of mind; it is not based on an innate core knowledge of physics, gravity, object persistence and causality. Rather, it is based on a correlation between a huge number of data points. It does not form abstractions, which means that it cannot extrapolate previous experience onto novel situations. However, the legal threshold for acceptable driving performance is still currently based on what can reasonably be expected of a competent and careful human driver.

With a human driver, it is only the movement control systems that can experience technological failures, however, with an autonomous vehicle, the systems responsible for the autonomy can also experience technological failures. The software responsible for this may be hosted in a movement control system. Without the recourse to a human being, the vehicle has to handle both types of failure without harming anyone.

One can understand why the use of driverless vehicles is currently in closed environments and low speeds

From these considerations, it can be seen that producing a Level 5 Vehicle to operate in an unrestricted environment is going to be a significant challenge. It is not surprising that the current general road systems are only at Level 2 or Level 3, despite the predictions of a few years ago, [11]. One can understand why the use of driverless vehicles is currently in closed environments and low speeds as this removes many of the difficult issues. This is likely to remain the case for somewhile.

Level 5 Vehicle Deployment in an Unrestricted Environment

The implications of having a Level 5 Vehicle deployed in the current unrestricted environment, and the challenges it represents, have been described. If a Level 5 Vehicle is to be deployed in this way, and also have a credible safety argument, it may be better to take a different approach from just replacing a Level 0 Vehicle with a Level 5 Vehicle while leaving everything else the same.

Two different approaches that could be taken are briefly discussed. These are changing the infrastructure to be more accommodating to the ADS and extending the scope of the safety argument.

Infrastructure Change

Rather than trying to develop ADS vehicles that can work in the current road environment with its mixture of modern roads developed for human drivers, and historic road infrastructure, should it start to be developed so as to take into account the strengths and limitations of the ADS? Some possibilities are briefly considered.

The standards governing the construction of the road infrastructure, for example, junction design and signage on the road surface and on free standing signs, is currently based on the capabilities of humans. There may be opportunity for the standards to be optimised for the sensing capabilities of an autonomous vehicle. This may affect the placement of signage and the rendering of the information it conveys. It may also affect the layout of junctions and their associated road markings. If the safe operation of autonomous vehicles depends on the road infrastructure being constructed and maintained in accordance with specific standards, then there is greater obligation on those third parties responsible to adhere to those standards.

There may be an opportunity to optimise the rules of the road such that it is easier for autonomous vehicles to comply with them, and also to anticipate the behaviour of other autonomous vehicles. Such changes would be the responsibility of the government. The government may also have a role to play in licencing the operation of each model of autonomous vehicle in the same way that it currently licences human drivers.

Changes such as these could then be taken as the basis for assumptions in an extended safety argument as discussed in the next section.

Extending the Safety Argument

Currently the safety arguments that are produced for ADAS and ADS features for vehicles with human drivers, whether by the OEM or by a tier 1 supplier (company that supplies major parts or systems directly to an OEM), are purely a technical argument about the particular vehicle feature. The other aspects of the road transport system, (see section above entitled Third Parties), are deemed not to be in the scope of the argument, which is purely for the hardware and software installed on the vehicle. This is the scope required by ISO 26262 – Road vehicles – Functional Safety, [12]. Any assumptions concerning other aspects of the road transport system are usually implicit and not documented.

There is also an undocumented assumption that the human driver can cope with, and resolve, any issues arising from the actions, errors, etc, associated with all of the third parties. This is supported in law by the criteria – "was the behaviour of the driver what can reasonably be expected" as assessed by the driver's peers. That this is not an unreasonable expectation of a human driver was discussed, (see section above entitled DDT & the Driving Enterprise performed by a human driver), as were the difficulties that it presents to a Level 5 Vehicle.

An alternative approach could be for the safety arguments produced for ADAS and ADS features to explicitly identify the assumptions made concerning all relevant third parties. This would provide a greater understanding of the dependencies between third parties. It would also prompt the documenting of assumptions that one party makes about the responsibilities of others. For this to be beneficial, these third parties would need to state explicitly what can be assumed by the safety arguments produced for ADAS and ADS features and where appropriate, for those third parties to provide their own argument supporting those assumptions.

Based on what was discussed in the previous section about the infrastructure, topics about which assumptions might be made include:

- The rendering and placements of signs
- The physical limits of the roads, e.g. widths, radii, and the road markings
- Those aspects covered by the government licensing of vehicles
- The behaviour of other road users, based on the rules of the road

Some aspects of these may be stated in the existing standards, but currently they are not explicitly referenced as assumptions in the safety argument. It is also the case that some aspects vary from country to country.

It is the vehicle manufacturer who is ultimately responsible for the safety argument for the ADAS or ADS feature, as integrated into the vehicle. At present, organisations in the supply chain, particularly the tier 1 suppliers, do provide information to the vehicle manufacturer. This is on an *ad hoc* basis, and the content of the information is often subject to intellectual property rights considerations. The provision of information necessary for a strong safety argument could be made an enforceable obligation.

This enforceable obligation could be extended to the maintainers of roads and vehicles and also to the providers of information updated in real-time. Topics about which assumptions might be made include:

- The reliance on road maintainers to maintain the roads to the construction standard, provide adequate communication of a problem or close the road if necessary
- The reliance on maintainers' ability to leave the vehicle up to the manufacturer's specification after having performed a maintenance task
- The reliance on the providers of information updated in real-time for the information to be available, up to date, accurate and clear. Such information may concern possible and actual weather conditions or state of the roads.

Some of the changes discussed here may also support driving automation levels 3 & 4. These have the added complication, not addressed here, of the driver participating in the handover of the DDT with the vehicle, both to and from. They also have the complication of the human driver being responsible for monitoring the performance of the ADS or ADAS feature and intervening when necessary.

Concluding Remarks

The article has described how planning and completing a journey on the public roads in a vehicle, referred to as the Driving Enterprise, is more than just performing the Dynamic Driving Task, but also, involves many other activities. While the consequences for autonomous vehicles of these other activities are being mentioned by some other researchers, the main focus seems to be on developing particular technologies for the vehicle. It is hoped that this article has brought these issues to the forefront of more people's minds.

As a small contribution, two key ideas have been presented that could help progress the field toward full automation. The first is to change the design of roads and signage to better suit autonomous vehicles, without disadvantaging non-autonomous vehicles. The second is to include, in the safety argument for an autonomous vehicle, more of those aspects of the external world on which the vehicle, implicitly or explicitly, relies.

If there is an overall conclusion, then it is just that it might be best not to deploy a Level 5 Vehicle in the current environment. The roadmap from where we are now to a Level 5 Vehicle deployed in an unrestricted environment with all other road users is likely to be long and tortuous and beyond the scope of this article.

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