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Automated Vehicle Safety Assurance - In-Use Safety and Security Monitoring

Task 1 - Road Incident Taxonomy

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Report details

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Executive Summary

It is anticipated that automated vehicles (AVs) will deliver improved safety compared to traditional human-driven vehicles. However, this is far from certain with the potential for the emergence of new types of collision involving AVs and challenges for other road users in interacting with vehicles that may not behave in a familiar manner. Even if a safety benefit is proven, this may be insufficient to win public trust if the incidents involving AVs are particularly unpalatable.

This report describes possible approaches to capture and categorise safety events involving low speed automated vehicles (LSAVs) as a means to provide the public with better evidence over their safety, regulators with evidence to strengthen decision-making in relation to LSAV operations, and developers with data to help improve the safety of LSAV behaviours.

Event type

Proving LSAV safety statistically is challenging when it is likely that early LSAV deployments will comprise a few vehicles operating in relatively constrained operational design domains. To strengthen statistical comparisons and deepen understanding of LSAV safety performance, it is likely to be necessary to go beyond collisions to include near-misses and other lesser safety-relevant violations. Seven event categories are proposed based on those used in naturalistic driving studies:

- Collision
- Near-collision
- Safety critical event
- Proximity conflict
- Non-conflict critical incident
- Safety-relevant violation
- Road rule violation

Further, it was suggested that the Collision category has five levels of severity ranging from Level 1: “Non-police-reported low-g physical contact” through to Level 5: “Police-reported collision with serious human injury or fatality”.

Leading and lagging measures were also defined in the context of automated vehicles; both types of measure are likely to be useful in understanding the risk associated with LSAV operation. Leading measures are events or behaviours that are assumed to provide an indication of future safety performance as likely precursors of future collisions (e.g. road rule violations, harsh braking etc.). Lagging measures reflect the true safety performance of LSAVs (e.g. collisions, near-collisions). The likely higher relative frequency of leading measures means they can be useful in predicting and mitigating future lagging measure events. It is proposed that lagging measures comprise police-reported collisions with leading measures being all other identified safety-related events that are statistically associated with such collisions.

Error rates for event classifications were considered, highlighting that any kinematic thresholds used to determine event severity may result in false positives / false negatives –

and that sub-threshold behaviours may still result in severe collisions due to unfortunate alignment of circumstances.

Event actors

It will be important to capture event actors – the road users and / or structures with which the LSAV is in conflict in the course of a safety event. This will help to establish why incidents occur and where risk accrues. It was proposed that the categories used in the police STATS19 coding scheme are appropriate for LSAVs, noting that enhancements to cover incidents involving new types of personal mobility would be useful. It is important to note whether or not an event involved harm (or potential harm) to humans (as occupants of the LSAV, occupants / users of other vehicles, horse riders, pedestrians etc.). It is envisaged that incidents placing humans at risk will require greater scrutiny than, for example, a rule violation by a single unoccupied LSAV.

Event manoeuvres

Similarly, the coding method used by the Road Accident In-Depth Study (RAIDS; TRL, 2012) for the observed manoeuvres in a collision provide a possible framework for recording vehicle movements in LSAV safety events.

Event causation

Beyond recording the severity, participants involved and physical characteristics of a safety event, it will be useful to determine why a collision occurred. In line with analyses of human-driven causes of collisions, it was suggested that safety events are classified according to whether the ADS experienced errors of perception, decision and / or action processes. Citing studies of advanced emergency braking (AEB) systems in London buses, it was further noted that false positive / false negative rates for emergency braking may be important and useful data in the context of LSAV operation.

Other contributory factors apart from or in addition to those associated with the ADS may be involved in safety events. The potential role of human factors, infrastructure, environment, other road users and cybersecurity in causing LSAV safety incidents were discussed. It will be important to capture non-ADS contributory factors to ensure that safety events are not erroneously attributed to failings of the ADS.

Event context

It was recognised that ADS data may be insufficient to determine why and how safety incidents occurred. Additional footage from any relevant third-party cameras (e.g. CCTV, smartphones, dashcams) or sensors may help to clarify why an incident occurred. Finally, the Haddon matrix (Haddon, 1972) and AcciMap (Rasmussen, 1997) techniques were cited as methods by which the context of more severe LSAV safety events could be analysed according to the broader factors (e.g. regulation, physical environment, socioeconomic factors etc.) that contributed to (or mitigated) risk over the time course of an event. Consideration of the factors within the cells of this matrix or across an AcciMap may help to understand why an event occurred and how it may be prevented in future.

Event response

When safety events occur, the speed and scale of response from LSAV operators and incident investigators should be proportionate to the severity of the incident. For a fatal crash, there should be swift and comprehensive action to understand why the collision occurred and mitigate risk of further similar collisions. This may include immediate cessation of all LSAV operations by the LSAV operator until the cause of the incident has been confirmed and the risk of future incidents has been mitigated. For vehicle-only safety-relevant violations, it may be sufficient for the incidents to be reported in regular safety reports and updates noted on how such incidents are to be avoided in future.

Summary of event taxonomy

Table 1 provides a summary of the potential features of a safety event to be recorded by an AV operator. The starting point is detecting and recording the occurrence of a safety event and classifying it according to event type. The level of detail captured in the subsequent categories depends on the severity of the incident, with more detail required for more severe events. For example, a full AcciMap analysis would be of limited value for a low-level road rule violation but could be very informative for a serious collision. It can be anticipated that events involving risk of harm to people would require more detailed analysis than those where no other road users were present.

Table 1: Safety event taxonomy summary table

Type	Actors	Manoeuvre	Causation	Context	Response
Collision (plus severity level) Near-collision Safety critical event Proximity conflict Non-conflict critical incident Safety-relevant violation Road rule violation	Vehicle type VRU Structure	Vehicle manoeuvre(s) that preceded the safety event	Errors of perception, decision and/or action by ADS Other error types e.g. human factors, other road users, cybersecurity etc.	Haddon matrix / AcciMap analysis	Noting safety event in regular statistical reporting through to immediate cessation of operations

Conclusion

This report has identified a wide range of data and analyses that could support safety assessments of LSAVs. This is justified for several reasons. Firstly, public opinion can swiftly turn against an innovative technology if it does not behave in line with expectation. A number of collisions that resulted in serious injuries or fatalities could greatly damage the reputation of AVs – even if overall statistics showed that they tended to be significantly safer than traditional vehicles. It is therefore necessary to have comprehensive evidence to support safety claims in the face of serious incidents. Secondly, AVs are data rich – an array of sensors, processing and communications systems produce abundant data feeds to support in-depth analysis of safety behaviours. Thirdly, regulators will need to carefully observe the early deployment of AVs to ensure that they deliver the anticipated benefits in line with expectations and to be able to revise regulations as necessary to support safe and efficient AV operation. Furthermore, developers will need information to improve and optimise their systems to prevent observed safety events happening in future whilst their employers / investors will want to ensure that their products and services are delivering so that they can scale quickly and deliver return on investment.

In closing, it is proposed that by

- recording safety events and road rule violations across a range of severities;
- considering event causation, including factors outside the ADS;
- reviewing external evidence;
- exploring the range of factors that contribute to risk before, during and after an event;
- initiating appropriate and proportionate responses to incidents;

…it may be possible to analyse LSAV behaviours with sufficient depth and clarity to provide confidence to the public, regulators and developers in the safety of LSAV operations.

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List of abbreviations

ADS:	Automated Driving System
AEB:	Advanced Emergency Braking
AV:	Automated Vehicle
CCTV:	Closed Circuit Television
DfT:	Department for Transport
HD:	High Definition
KSI:	Killed or Seriously Injured
LSAV:	Low Speed Automated Vehicle
NTSB:	National Transportation Safety Board
ODD:	Operational Design Domain
RAIDS:	Road Accident In-Depth Study
SAE:	Society of Automotive Engineers
VRU:	Vulnerable Road User

1 Introduction

1.1 Emphasis on safety

Elvik (2006) proposed a framework that set out the challenge of delivering road safety as identifying the problems that make the greatest contribution to collisions or injuries. Automated driving systems (ADSs) offer the promise of improved safety by addressing the mistakes and misjudgements made by human drivers. As such, safety is one of the key motivations for the development of ADS technology. For example:

> *"Streets are for everyone. That's why we're committed to making them a safer place to live, work, and play."*
>
> (Argo AI, 2021)

> *"Self-driving technology will change the world, most importantly by saving lives."*
>
> (Aurora, 2021)

> *"We're driven to safely connect people with the places, things, and experiences they care about."*
>
> (Cruise, 2021)

> *"We're creating a platform that will empower the industry to build automated driving systems that are safer, smarter, faster and at scale"*
>
> (Five, 2021)

> *"Fusion Processing continues to develop state-of-the-art technology to autonomise vehicles and improve the safety of vulnerable road users."*
>
> (Fusion Processing, 2021)

> *"Safety is the focus and foundation of everything we do"*
>
> (Motional, 2021)

> *"Our autonomy solutions are designed to create a cleaner, safer, more accessible future"*
>
> (Oxbotica, 2021)

> *"Autonomous driving is nothing without safe driving"*
>
> (Waymo, 2021)

Whilst this ambition is common, there is little agreement on what it means to achieve safer driving. The number of collisions involving ADS-equipped vehicles might be considered the simplest metric of safety. However, collisions are relatively rare for human drivers – Department for Transport (2021a) statistics for Great Britain indicate that there were 77 people reported killed or seriously injured (KSI) per billion miles driven in 2019 (or 1 KSI per 13 million miles driven). These figures include collisions involving intoxicated, fatigued or distracted drivers and those involving higher risk vehicle categories (e.g. motorcycles) so the true collision rate against which an ADS-equipped vehicle should be compared is considerably lower. With low-speed automated vehicles (LSAVs) likely to be initially deployed in small numbers and covering over short distances in tightly defined operational design domains, it will be challenging to make statistically robust comparisons of the number of collisions involving human driven vehicles to the number of collisions involving LSAVs.

1.2 Predictive approaches to road safety

An alternative approach is to consider the frequency of the occurrence of risky situations as a predictive indicator of potential collision risk. This approach was pioneered by Heinrich (1931), who analysed workplace injuries and incident data at an insurance company and proposed an 'accident pyramid' where for every major injury accident, there were 29 minor injury accidents and 300 no-injury accidents[1]. Frequencies of UK road crash injury severities for 2020 show a similar distribution with 1,460 fatalities, 22,069 serious injuries and 92,055 slight injuries[2] (DfT, 2021b).

Naturalistic driving studies (where individual drivers are monitored over extended periods) over the last twenty years have shed light on the association between risky driving and crash frequency. Dingus et al. (2006) used a case control approach analysing data from the '100-Car Naturalistic Driving Study' (referred to as the 100-car study), in which 100 vehicles were equipped with sensors, monitoring and recording equipment over a year, generating around two million vehicle-miles of driving and over forty thousand hours of data. Across this dataset, Dingus et al. observed 69 crashes, 761 near-crashes and 8,295 lower severity safety incidents; again, with the frequency in each category somewhat similar to Heinrich's pyramid – suggesting that the assessment of near misses and safety relevant incidents may help to predict the frequency and severity of collisions. This is especially true for LSAVs where the number of collisions may be very low; extending their evaluation to include the relative frequency of near misses and rule violations may help to give a better statistical assessment of their safety.

Consequently, there is likely to be value in collecting data from LSAVs on risky driving situations in addition to collisions. However, it is necessary to define such unsafe events to be able to establish metrics and data logging requirements that appropriately capture these events. Without a suitable definition, there is a risk of non-detection of collisions and safety critical events or an increased burden on developers/manufacturers to collect and transfer non-safety relevant data.

This report reviews research associated with driver monitoring and safety critical events and proposes definitions applicable in the realm of LSAVs. It also considers how other factors contributing to safety critical events might be classified

[1] It is emphasised that the causes of accidents may be very different between the severity categories.

[2] Although the COVID-19 pandemic affected road transport, the proportions of incident severity remained broadly similar (e.g. 2019: 1,752 fatalities, 28,435 serious injuries and 122,971 slight injuries; 2018: 1,784 fatalities, 29,574 serious injuries and 129,239 slight injuries

2 Event type

The approach to event classification applied in the 100-car study illustrates four key points of relevance for defining and categorising incidents involving LSAVs:

- The need to capture different types of risky driving including collisions but also near-collisions, evasive manoeuvres and behaviours that are incongruent with the operating location;
- Collision severity is an important consideration when classifying incidents; those causing injury / fatality to humans are considered the most severe;
- Drivers' perceptions and actions in the course of an event can influence its classification – for example, timely detection of a hazard and execution of an appropriate avoidance manoeuvre can turn a potential collision into a near-collision;
- Driving code violations (e.g. driving through a junction with the traffic light showing red; right-of-way violation; stop sign violation etc.) and human factors issues (e.g. distraction, inattention, fatigue etc.) are included in the analysis of each event.

2.1 Definitions

With these key points in mind, the following event definitions are proposed, each derived from Dingus et al. (2006). Note that for each event type, incidents are recorded where LSAVs collide / interact with other road users and where other road users collide / interact with LSAVs. Collision causation is recognised separately from the record of the event.

2.1.1 Collision

"An incident in which the LSAV makes contact with an object, either moving or fixed, at any speed, in which kinetic energy is measurably transferred or dissipated. Includes other vehicles, roadside barriers, objects on or off the roadway, pedestrians, cyclists, or animals."

The definition (derived from that for 'crash' in Dingus et al., 2006) suggests that a collision is indicated by a measurable transfer of kinetic energy – however, it is not proposed that kinetic energy is measured; rather that proxy indicators of kinetic energy transfer such as rapid acceleration or deceleration or simply displacement can be used to identify collisions.

Within this definition, the implications of a minor collision are very different to a collision in which a serious injury or fatality are a possible outcome. This is recognised in other taxonomies of driving errors and violations (e.g. Dingus et al., 2006, Khattak et al., 2021). Consequently, five levels of collision are proposed:

- *Level 1:* Non-police-reported low-g physical contact
    - e.g. vehicle strikes a kerbstone parallel to the direction of travel at low speed, no / negligible damage to kerbstone or vehicle.
- *Level 2:* Non-police-reported property damage only

  - e.g. vehicle strikes the rear of another vehicle, light damage to / both vehicles, no injury to any drivers / passengers.

- *Level 3:* Police-reported collision with vehicle / property damage only.
  - e.g. vehicle strikes another vehicle on a roundabout, either / both vehicles unable to proceed and blocking the carriageway, no injury to any drivers / passengers.
- *Level 4:* Police-reported collision with possible or slight human injury.
  - e.g. vehicle strikes a cyclist at low speed causing slight injury to the rider.
  - Injury assessed as 1-2 on the Maximum Abbreviated Injury Scale (Gennarelli, T. A., & Wodzin, E., 2008).
- *Level 5:* Police-reported collision with serious human injury or fatality.
  - e.g. vehicle strikes a pedestrian at high-speed causing severe, possibly fatal injury.
  - Injury assessed as 3+ on the Maximum Abbreviated Injury Scale (Gennarelli, T. A., & Wodzin, E., 2008).

This classification uses five levels (cf. four levels in Dingus et al., 2006) to separate killed or serious injury collisions from minor injury collisions[3]. The Maximum Abbreviated Injury Scale (MAIS; Gennarelli, T. A., & Wodzin, E., 2008) is the rating of the most severe injury suffered by a patient. A MAIS score of 3 or greater is the internationally accepted definition of serious injury in relation to road collisions.

2.1.2 Near-collision

"Any circumstance that requires a rapid, evasive manoeuvre by the LSAV (or any other vehicle, pedestrian, cyclist, or animal) to avoid a collision. A rapid, evasive manoeuvre is defined as steering, braking, accelerating, or any combination of control that is significantly greater than that expected in normal operation."

The definition does not include specific thresholds for what constitutes a 'rapid, evasive manoeuvre', unlike Dingus et al.'s (2006) definition for 'near-crash' from which this derived. The thresholds are likely to be highly dependent on the characteristics of the vehicle and use case.

2.1.3 Safety critical event

"Any circumstance that requires a collision avoidance response on the part of the LSAV or any other vehicle, pedestrian, cyclist, or animal that is less severe than a rapid evasive manoeuvre but greater in severity than a normal operation to avoid a crash. A

[3] The insurance industry also applies a similar categorisation of collisions; however, some insurers classify fatal collisions lower than serious injury incidents due to the greater economic and societal costs that may accrue for severe non-fatal injuries.

> *collision avoidance response can include braking, steering, accelerating, or any combination of control inputs."*

Dingus et al. (2006) defined a "normal manoeuvre" as one where control inputs fall inside the 99 percent confidence limit for control inputs expected for the same subject (LSAV, another vehicle, pedestrian, cyclist etc.). As with 'near-collision', it is likely that thresholds for an LSAV will depend on the vehicle type and use case, so thresholds are likely to be determined in that context, recognising the intention to categorise events less severe than near collision but represent relatively high dynamic responses from the vehicle (or another subject).

2.1.4 Proximity conflict

> *"Any circumstance resulting in extraordinarily close proximity of the LSAV to any other vehicle, pedestrian, cyclist, animal, or fixed object when, due to apparent unawareness on the part of the vehicle, driver, pedestrians, cyclists or animals, there is no avoidance manoeuvre or response. Extraordinarily close proximity is defined as a clear case in which the absence of an avoidance manoeuvre or response is inappropriate for the driving circumstances (e.g. speed, sight, distance, etc.)."*

An example of a proximity conflict for an LSAV would be if it overtook a slow-moving cyclist too closely to be considered safe or comfortable but where neither the LSAV nor the cyclist performed any specific avoidance manoeuvres.

2.1.5 Non-conflict critical incident

> *"Any action of the LSAV that increases the level of risk associated with driving but does not result in any of the events as defined above."*

Examples of non-conflict critical incident for an LSAV include control errors without proximal hazards being present or excessive speed – for example, if the vehicle unexpectedly veered across a broken white line into an oncoming traffic lane before returning to the correct lane with no other vehicles present.

2.1.6 Safety-relevant violation

> *"Road rule violations that have direct safety implications even if another event type (e.g. collision, near collision etc.) does not occur."*

Examples of safety-relevant violations for an LSAV include running a red light, cycle lane infringements, footway infringements, crossing double white lines and stopping on rail crossings.

2.1.7 Road rule violation

> *"Road rule violations not directly related to safety but that negatively impact the flow of traffic or safe movement of other road users."*

Examples of road rule violations for an LSAV include stopping in a yellow box junction, stopping on double red lines and using a bus lane without authorisation.

2.2 Event definitions summary table

Table 2 provides a summary of the definitions proposed for the seven event types.

Table 2: Summary table of event definitions

Event	Definition
Collision	An incident in which the LSAV makes contact with an object, either moving or fixed, at any speed, in which kinetic energy is measurably transferred or dissipated. Includes other vehicles, roadside barriers, objects on or off the roadway, pedestrians, cyclists, or animals. (NB Five levels of collision severity are also defined.)
Near-collision	Any circumstance that requires a rapid, evasive manoeuvre by the LSAV (or any other vehicle, pedestrian, cyclist, or animal) to avoid a collision. A rapid, evasive manoeuvre is defined as steering, braking, accelerating, or any combination of control that is significantly greater than that expected in normal operation.
Safety critical event	Any circumstance that requires a collision avoidance response on the part of the LSAV or any other vehicle, pedestrian, cyclist, or animal that is less severe than a rapid evasive manoeuvre but greater in severity than a normal operation to avoid a crash. A collision avoidance response can include braking, steering, accelerating, or any combination of control inputs.
Proximity conflict	Any circumstance resulting in extraordinarily close proximity of the LSAV to any other vehicle, pedestrian, cyclist, animal, or fixed object when, due to apparent unawareness on the part of the vehicle, driver, pedestrians, cyclists or animals, there is no avoidance manoeuvre or response. Extraordinarily close proximity is defined as a clear case in which the absence of an avoidance manoeuvre or response is inappropriate for the driving circumstances (e.g. speed, sight, distance, etc.).
Non-conflict critical incident	Any event that increases the level of risk associated with driving but does not result in any of the events as defined above.
Safety-relevant violation	Road rule violations that have direct safety implications even if another event type (e.g. collision, near collision etc.) does not occur.
Road rule violation	Road rule violations not directly related to safety but that negatively impact the flow of traffic or safe movement of other road users.

2.3 Leading and lagging measures

The events defined in 2.1 represent the occurrence of incidents of concern, their relative frequency should decrease over time as safety performance improves with LSAV operators seeking to reduce the likelihood of such events. Safety-critical events provide post hoc learning opportunities to improve LSAV behaviour to avoid such events. These are referred to as ‘lagging’ indicators of safety – measures that record the occurrence of negative safety outcomes. However, it is also useful to have measures that indicate the potential risk of future collisions – behaviours that are assumed to provide an indication of future safety performance as likely precursors of future collisions, such as road rule violations or harsh braking events that did not result in a collision or near-collision.

A challenge for automated vehicles is whether an event should be classified as a leading or lagging measure. For example, a harsh braking event that does not result in a collision may be categorised as a near-collision or safety-critical event. This could be considered to be a leading metric as a possible predictor of future collisions – for the vehicle to have needed to trigger harsh braking suggests a possible issue with perception or planning that risks resulting in more severe incidents in future. It could also be considered to be a lagging measure – harsh braking itself could be considered to be an undesirable outcome.

It is proposed that significant collisions are the critical metric against which vehicle safety performance should be assessed – and as such level 3 collisions or worse constitute the lagging measures. LSAV operators should still collect and analyse leading measures to provide an indication of future vehicle safety performance and to identify areas of LSAV operation and management that could be improved.

2.4 Error rates

It is also important to consider false positive and false negative rates for capturing and classifying LSAV safety events. Setting oversensitive thresholds for events could result in excess data collection of irrelevant data (false positives), making it harder to extract incidents that provide useful information from those that are inconsequential. If thresholds are too high, important events may be missed from data analysis (false negatives), resulting in a potential failure to recognise and address specific safety issues with LSAV operation (see also section 5.1.4).

Figure 1 shows a hypothetical frequency distribution curve for risky driving behaviours observed for an LSAV. The graph indicates that in this example, the vast majority of driving behaviours adopted by the LSAV are low risk.

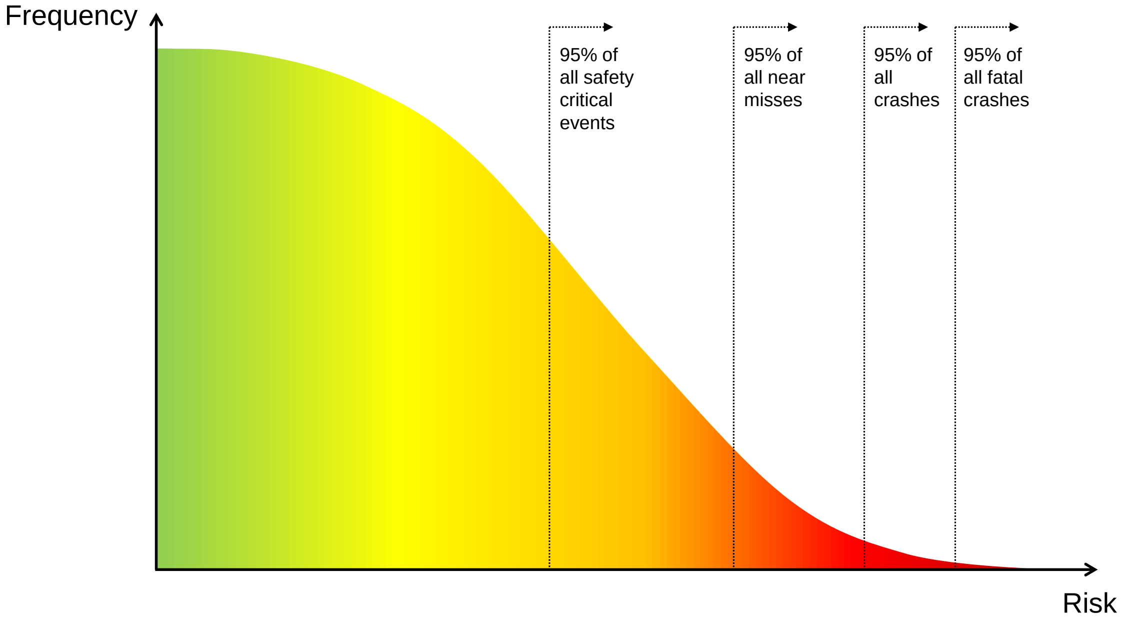

Figure 1: Hypothetical model frequency distribution curve for risky driving behaviours adopted by an LSAV

Moving to the right on the X-axis, we see that riskier driving behaviours are less frequent. The dashed vertical lines of the graph are intended to suggest that 95% of incidents occur as a result of higher risk behaviours towards the right of the graph and the majority of fatal incidents are observed at the extreme tail of the distribution. However, the graph is presented to indicate that although incidents tend to occur due to riskier driving behaviours, some safety critical events (including fatal collisions) may still occur when the LSAV is performing lower risk behaviours due to unfortunate alignment of circumstances (i.e. the 5% of events observed as a result of behaviours that are lower risk than the 95% threshold).

3 Event actors

An LSAV operating in an urban environment may record safety events involving a variety of road users, vehicle types and structures. Police reported collisions in Great Britain use the STATS19 form[4] to report the following categories of road user type when recording collision information:

- Car
- Taxi / Private hire car
- Van ≤3.5t mgw
- Goods vehicle 3.5t<mgw<7.5t
- Goods vehicle ≥7.5t
- Goods vehicle – weight unknown
- Motorcycle ≤50cc
- Motorcycle >50cc and ≤125cc
- Motorcycle >125cc and ≤500cc
- Motorcycle >500cc
- Motorcycle – cc unknown
- Electric motorcycle
- Pedal cycle
- Bus or coach ≥17 passenger seats
- Minibus 8-16 passenger seats
- Agricultural vehicle
- Ridden horse
- Mobility scooter
- Tram / Light rail
- Other

Pedestrians involved in an incident are recorded separately by the attending officer who notes their location, movement and whether or not they were working in road maintenance at the time of the incident.

It seems useful and appropriate for events involving LSAVs to use similar road user categories where possible and adding fixed structures (such as buildings, walls, lamp-posts etc.) struck (or narrowly avoided) by the LSAV. It is also worth noting whether vehicle was occupied or not – particularly for events where the actions of the LSAV would present risk of harm to its occupants.

Department for Transport statistics do not include a specific category for Micromobility vehicles (e-scooters, e-skateboards etc.) at present. The Society of Automotive Engineers (SAE) has produced a taxonomy of Micromobility vehicles (SAE J3194, 2019) that is gaining some traction. While such vehicles are, in their current form, not legal to use on UK roads (outside of officially sanctioned trials), it seems advisable that LSAV event actor categories align with those used in STATS19 and adds any appropriate Micromobility categories in line with any updates to STATS19 or updates from the Department for Transport.

[4] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/995422/stats19.pdf

4 Event manoeuvres

For more many decades, TRL has attended road collisions to gather additional data that can help to understand why and how incidents occurred and to help develop possible countermeasures to prevent their occurrence in future. The Road Accident In-Depth Studies project (RAIDS; TRL, 2012), which TRL manages on behalf of the Department for Transport, uses a specific coding system to characterise the most common types of incidents. This system uses fifteen different manoeuvre types (e.g. overtaking and lane change; collision with obstruction; merging) each with between one to seven different variants (e.g. cornering – lost control cornering right; cornering – lost control cornering left; cornering missed intersection or end of road). Each manoeuvre type also has an 'other' category for incidents that do not readily fit the descriptions of one of the variants.

A similar categorisation of manoeuvres for safety events involving LSAVs may be helpful for regulators in determining whether it is safe for operations to continue and for developers / operators in taking mitigating actions to prevent such events happening in future. If possible, it would be useful to develop a standardised, objective method by which vehicle data could be used to report event manoeuvre automatically when an event has been detected.

5 Event causation

Having established a set of definitions that capture safety-relevant event severity, actors and types for LSAVs, it is useful to clarify *why* each event occurred to help understand the chain of accountability for an event and to consider how such events might be prevented in future. Determining responsibility for causing an event can be challenging with fault potentially lying across multiple actors. However, in the deployment of LSAVs it will be vital to establish whether an incident was caused or influenced by operation of the vehicle or whether responsibility lay elsewhere.

For incidents where some degree of fault can be attributed to the LSAV, taxonomies of human driver error provide some guidance as to how errors of an ADS might be considered. Suggestions from a variety of researchers (e.g. Sabey & Taylor, 1980; Norman, 1981; Stanton & Salmon, 2009) centre on three key aspects:

- Perception – was all necessary information required to operate the vehicle detected in a timely manner?
- Decision – if all necessary information was available from the perception system, was this processed correctly such that appropriate actions were proposed?
- Action – if suitable actions were determined, were these enacted correctly?

This classification of ADS errors aligns with the concept of digital commentary driving proposed by BSI (Reed et al., 2021), which suggests that ADS-equipped vehicles should produce a standardised set of data parameters covering these categories when operating in an automated mode for the purpose of safety assurance.

5.1 ADS errors

5.1.1 Perception errors

Perception errors relate to a mismatch between the model of the environment determined by the ADS and the true environment. For example, an ADS may use a high definition (HD) map as a source of information about the road environment; recent changes to the environment (e.g. emergence of a pothole, fallen tree, landslip etc.) may render the HD map out of date – meaning that a source of information used by the ADS to guide behaviour is wrong.

Other examples of perception errors include:

- Sensor fault / occlusion / conflict
- Object incorrectly located / segmented / classified
- Object movement misperceived / future movement misjudged
- Traffic light state misread
- Errors in critical information stored on the vehicle / received from external sources

5.1.2 Decision errors

Decision errors relate to the incorrect selection of a particular action (or inaction). A behaviour judged as an incorrect decision may be the consequence of a perception error; for example, misjudging the approach speed of cross traffic when pulling out of a side road into a main road. Alternatively, the ADS may have perfect perception of the road environment but a programming error or a mis-trained algorithm may cause the ADS to select an incorrect action.

Other examples of decision errors include:

- Incorrect decision to pull away from a stationary position
- Incorrect decision to brake harshly approaching a junction resulting in risk of collision from following vehicle
- Incorrect speed choice for road surface conditions
- Incorrect speed choice for visibility conditions

5.1.3 Action errors

Action errors relate to faulty implementation of a decision; for example, the steering system applies inputs too slowly to correct lane deviations in a timely manner or insufficient brake force is achieved approaching a junction following a long series of downhill bends due to overheated brakes.

5.1.4 False positive / false negative errors

Knight et al. (2019) reviewed safety performance of London buses equipped with advanced emergency braking (AEB). The accurate performance of AEB systems in the context of buses is particularly important for three key reasons:

- Buses are typically large, heavy vehicles operating in urban environments, often with high densities of vulnerable road users (VRUs). Collisions between buses and VRUs can be fatal. Systems such as AEB that can reliably prevent such collisions are useful in reducing harm to VRUs and protecting the reputation of bus operators.
- Buses often carry many passengers with seats that do not have seatbelts and some of whom may be standing or even ascending the stairs to the upper deck. The sharp deceleration associated with emergency braking risks causing potentially serious injury to bus passengers.
- Buses operate in dense traffic environments. Triggering emergency braking systems risks causing collisions with following vehicles.

With these factors in mind, the authors noted the importance of the rates of false positive and false negative AEB applications. False positives are where the AEB system is applied when emergency braking was not required as no hazard was present ahead of the vehicle. False negatives are where the AEB system is not triggered when emergency braking was required in response to a hazard ahead of the vehicle. The sensitivity of the AEB system is critical in balancing these errors:

- An AEB system with **low** sensitivity is likely to have:
    - a lower false positive rate (reducing the risk of unnecessary injury to passengers or collisions from following vehicles)

    but may have…

    - a higher false negative rate (the system would fail to trigger in situations where emergency braking may be critical in preventing a collision).
- An AEB system with **high** sensitivity is likely to have:
    - a lower false negative rate (the system is more likely trigger in situations where emergency braking may be critical in preventing a collision)

    but may have…

    - a higher false positive rate (increasing the risk of unnecessary injury to passengers or collisions from following vehicles).

For a traditional vehicle with a human driver, it is possible that a vigilant human driver can intervene to prevent an incident even if the AEB system fails to trigger (i.e. the driver has acted to mitigate a false negative of the AEB system). For an AV, there may not be an operator able to intervene to prevent an incident in the event of a false negative – so it is likely that braking systems will be set to respond with high sensitivity to reduce the risk of false negatives. Trials of LSAVs have already resulted in injuries from false positive emergency braking incidents. In 2019, as part of Utah's Autonomous Shuttle Pilot, a passenger on an LSAV suffered injuries when the vehicle performed an unexpected and unnecessary emergency stop, causing them to be thrown to the ground and resulting in facial bruising and laceration (Claburn, 2019).

In the context of AVs, such false positives and false negatives may be attributable to errors of:

- perception – for example, incorrect prediction of pedestrian movement;
- decision – for example, incorrect application / non-application of emergency braking;
- action – for example, braking system does not respond in the expected manner).

With some LSAVs designed to carry ten or more passengers (standing or sitting unbelted) in urban environments, potentially mixing with VRUs and larger vehicles, false positives and false negatives of emergency braking systems may be important events to capture.

5.2 Other error types

Outside of errors made by the ADS, other factors may trigger incidents. This section reviews other potential contributory factors.

5.2.1 Human factors

Although a common contributory factor to road crashes involving traditional human-driven vehicles, it is often assumed that ADS-equipped vehicles will be much safer by avoiding many of the common mistakes made by human drivers. However, a further category of errors relates to action or inaction by humans involved in LSAV operation. Examples include:

- Programming errors in the ADS
- Incidents caused by / during remote operation
- Incorrect operation design domain specification
- Deliberate alteration of the physical environment to challenge an LSAV
- Misapplication of emergency stop systems
- Occupants incorrectly located within the vehicle

5.2.2 Infrastructure / Environment

Some incidents may be triggered by sudden, imperceptible or unexpected changes in the road environment. For example, a liquid spill from the vehicle ahead causes low road friction on an upcoming bend or recent vegetation growth obstructs viewing angles at a previously unobscured junction. An LSAV may encounter strong winds, sinkholes or flooded roads that will require the LSAV (or its operator) to detect and manage – including potentially aborting a trip or handing control over to a remote operator.

5.2.3 Other road users

Even though an LSAV may be perfectly maintained, operating comfortably within its operational design domain in fine weather and equipped with excellent perception, decision and action systems, there is still the risk that other road users may act in ways that lead to safety critical events; for example, a drunk driver swerves into the path of the LSAV or a pedestrian steps into the path of the LSAV closer than its shortest stopping distance, each resulting in an unavoidable collision. It will be important to capture evidence of such incidents to ensure responsibility for the event is attributed correctly and to see if there was anything the LSAV could have done differently to avoid or mitigate such events in future (even if it was not at fault).

5.2.4 Cybersecurity

Unauthorised access to and manipulation of LSAV systems may trigger safety critical incidents. Although these may be mediated by affecting perception, decision or action systems, it would be important to capture that the source of the error emanates from an external trigger and identify the if possible.

6 Event context

The definitions in Section 2 enable events in which LSAVs are involved to be recorded and categorised. Section 3 considers how LSAV incidents might be further classified according to causation factors. Further analysis may consider the wider environment, timeline and role of elements associated with an incident.

6.1 External evidence

For some types of error, data recorded on an LSAV may not fully or even partially capture evidence to describe the causes and / or effects of an event. Further information may be available from third party sources, particularly CCTV camera footage, any smartphone image or accelerometer data or data from other sensor / camera equipped vehicles in the vicinity of the event. Where available, such data may help to determine how and why an incident took place.

1.1 Wider analysis techniques

For more severe events, deeper analyses may be useful in drawing out all the factors that contributed to their occurrence. Two such analysis approaches are described – the Haddon matrix and AcciMap technique. Their more qualitative examination of aspects of event causation seems a useful counterpoint to the quantitative measures recorded by vehicle systems.

6.1.1 Haddon matrix

The World Health Organisation (2001) developed a 3×4 matrix for analysing motor vehicle crashes (based on Haddon, 1972). It considers:

- Three time periods
  - Pre-event
  - Event
  - Post-event
- Four dimensions
  - Human
  - Vehicle
  - Physical environment
  - Socioeconomic environment

By reflecting on causative and mediating factors in each of the twelve cells, interventions can be considered that could prevent such events happening in future or at least reduce their severity. Table 3 provides an example in which the technique is used to analyse a collision in which an unbelted, inexperienced, elderly male driver crashes an older, poorly maintained vehicle on a wet road having drunk an excess of alcohol at a social event.

Table 3: Example analysis of road crash using Haddon's matrix (adapted from World Health Organisation, 2001)

	Human	Vehicle	Physical environment	Socioeconomic environment
Pre-event	Inexperience Intoxication	Excessive tyre wear	Slippery road	Social acceptance of alcohol misuse.
Event	Not wearing a seatbelt	Poor occupant protection	Lack of roadside barrier	Ineffective enforcement
Post-event	Elderly driver	No eCall system present	Slow emergency response	Failure to capture and learn from incidents

Applying a structured analysis of this nature to safety events involving LSAVs could help to determine how and why such events occurred and to prevent them from happening in future.

6.1.2 AcciMap

On behalf of the RAC Foundation, Stanton (2019) reviewed eight different approaches for analysing road collisions using the 2018 fatal collision involving an Uber developmental automated driving system and a pedestrian (NTSB, 2019) as a case study. The outcome of Stanton's analysis was to recommend the AcciMap approach (Rasmussen, 1997), finding it was the best performer across criteria of ease of use, application time, training demand simplicity of interpretation, tools required and evidence of impact.

The AcciMap process begins by mapping the parties that potentially influenced the occurrence of the collision, using the following headings:

- International influences (e.g. international standards bodies)
- National committees (e.g. national standards bodies)
- Federal and state government
- Regulatory bodies and associations (e.g. state regulators)
- Company management and local area government (e.g. vehicle manufacturer, technology developer)
- Technical and operational management (e.g. technology developer engineers)
- Driving processes (e.g. driver, pedestrian)
- Equipment and environment (e.g. automated vehicle, road)

With the key actors identified, the relevant events, failures, decisions and actions are mapped across each participant, seeking to identify all the influences that contributed to the event.

7 Event response

When safety events occur, the speed and scale of response from LSAV operators and incident investigators should be proportionate to the severity of the incident. For a fatal crash, there should be swift and comprehensive action to understand why the collision occurred and mitigate risk of further similar collisions. This may include immediate cessation of all LSAV operations by the LSAV operator until the cause of the incident has been confirmed and the risk of future incidents has been mitigated. For vehicle-only safety-relevant violations, it may be sufficient for the incidents to be reported in regular safety reports and updates noted on how such incidents are to be avoided in future.

The precise nature of the response from an LSAV operator, AV regulators and incident investigators is for the DfT to consider working with the AV community but Table 4 provides an example of the actions that might follow in response to LSAV incidents of three different levels of severity.

Table 4: Example table of actions in response to events of three different levels of AV incident severity.

	Event type		
	Most severe →		Least severe
Action	**Fatal collision**	**Near-miss with pedestrian**	**Vehicle briefly crosses solid white centreline**
Operator response	Withdrawal of all operations involving the relevant LSAV type within one hour.	Operations paused at the affected location (LSAV operations elsewhere can continue).	Location and frequency of incident noted.
Reporting requirement	Incident immediately reported to police and AV regulator.	Incident specifically noted in monthly safety report to AV regulator.	Frequency reported in monthly safety report to AV regulator.
Incident investigation	Detailed, full cooperation by LSAV developer / operator with incident investigators.	Internal investigation by LSAV developer / operator to determine the cause of the event.	Internal review of incident to determine whether it was a one-off or part of a wider pattern.
Data sharing	LSAV developer / operator shares all relevant data with incident investigators and AV regulator.	LSAV developer / operator shares basic (e.g. location, perception, kinematics) data with AV regulator.	N/A
Resumption of service	Only when cause of incident has been established and any required risk mitigation actions have been verified by AV regulator.	Once the cause of near-miss has been identified and any required risk mitigations have been actioned. AV regulator notified of any updates to ODD / safety case.	N/A

8 Summary

Table 5 provides a summary of the potential features of a safety event to be recorded by an AV operator. The starting point is detecting and recording the occurrence of a safety event and classifying it according to event type. The level of detail captured in the subsequent categories depends on the severity of the incident, with more detail required for more severe events. For example, a full AcciMap analysis would be of limited value for a low-level road rule violation but could be very informative for a serious collision. It can be anticipated that events involving risk of harm to people would require more detailed analysis than those where no other road users were present.

Table 5: Safety event taxonomy summary table

Type	Actors	Manoeuvre	Causation	Context	Response
Collision (plus severity level) Near-collision Safety critical event Proximity conflict Non-conflict critical incident Safety-relevant violation Road rule violation	Vehicle type VRU Structure	Vehicle manoeuvre(s) that preceded the safety event	Errors of perception, decision and/or action by ADS Other error types e.g. human factors, other road users, cybersecurity etc.	Haddon matrix / AcciMap analysis	Noting safety event in regular statistical reporting through to immediate cessation of operations

9 Conclusion

The advent of automated vehicles operating at scale in public environments may contribute to a revolution in surface mobility, promising safer, more inclusive and more efficient transportation. Improved road safety is cited as a critical motivation and benefit of AV deployment by the current developers. However, although the controlled, cautious, optimised behaviour of AVs provides good reason for optimism that they might address some of the leading causes of road crashes, there are several countervailing concerns.

Firstly, while AVs may be less susceptible to the misjudgements, overconfidence, inattention and excessive speed that characterise a significant proportion of incidents involving human drivers, the risk of human error is not eliminated. In particular, there may be human errors in the programming and development of AVs that emerge post-deployment.

Secondly, it seems unlikely that the types, frequency and distribution of errors involving AVs will simply be a direct reduction of those observed involving human-driven vehicles. AVs are likely to have different and even new types of incidents compared to traditional vehicles as a consequence of depending on different sensory and decision-making systems.

Thirdly, it is unclear how human-driven vehicles and other road users may react to the presence and operation of AVs. Goodall (2021) observed that Waymo's AVs were more than four times more likely to be struck from the rear than traditional vehicles, with the suggestion that this was due to their AVs adopting behaviours that were counterintuitive for human drivers.

Furthermore, a common expectation of AVs is that they must decrease the risk of physical harm compared to human driven vehicles delivering an equivalent service (see recommendation 1, Bonnefon et al., 2021). In order to understand whether this aim has been achieved, it will be necessary to capture sufficient data to determine the level of risk posed by AVs and statistically confirm that it is less than that observed for traditional vehicles.

Even if statistical analyses confirm this outcome, it may be insufficient in the eyes of public opinion. Experience with other technologies (for example, genetically modified foods – see Stilgoe, 2011) show that their benefits can be overshadowed by public fear, uncertainty and scepticism in the face of potentially transformative innovations. Deeper analysis of safety events may be necessary to win public trust in addition to achieving a statistical safety benefit.

In this context, it will be important to identify and analyse safety events involving AVs to provide the public with confidence about the risks of their deployment, to provide regulators with the evidence to inform effective decision-making, and to provide developers with data to help optimise their AV systems.

The focus of this report was low-speed automated vehicles (LSAV) as a likely candidate for early deployment of AV technology. With LSAVs likely to be deployed in relatively small numbers and in relatively constrained operational design domains, the volume of data collection with which to address the statistical safety performance of LSAVs will be limited. It was therefore proposed that less severe safety-relevant events are also captured to provide additional insights into the safety performance of LSAVs. Naturalistic driving studies were cited as providing useful structure and definitions for safety event categories:

- Collision
- Near-collision
- Safety critical event
- Proximity conflict
- Non-conflict critical incident
- Safety-relevant violation
- Road rule violation

Further, it was suggested that the Collision category has five levels of severity ranging from "Police-reported collision with serious human injury or fatality" through to "Non-police-reported low-g physical contact".

Error rates were discussed, highlighting that any kinematic thresholds used to determine event severity may result in false positives / false negatives – and that sub-threshold behaviours may still trigger severe collisions due to unfortunate alignment of circumstances.

It will be important to capture event actors – the road users and / or structures with which the LSAV is in conflict in the course of a safety event – as this will help to establish why incidents occur. It was proposed that the road user categories used in the police STATS19 coding scheme are appropriate for LSAVs, noting that these may evolve with growth of Micromobility options (e.g. e-scooter, e-skateboard etc.). Similarly, the coding method used by the Road Accident In-Depth Study (RAIDS; TRL, 2012) for the observed manoeuvres in a collision provide a framework for recording vehicle movements in LSAV safety events.

Beyond recording the severity, participants involved and physical characteristics of a safety event, it will be useful to determine why a collision occurred. In line with analyses of human-driven causes of collisions, it was suggested that safety events are classified according to whether the ADS experienced errors of perception, decision and / or action processes. Citing studies of advanced emergency braking (AEB) systems in London buses, it was further noted that false positive / false negative rates for emergency braking may be an important and useful data in the context of LSAV operation.

Other contributory factors apart from or in addition to those associated with the ADS may be involved in safety events. The potential role of human factors, infrastructure, environment, other road users and cybersecurity in causing LSAV safety incidents were discussed. It will be important to capture non-ADS contributory factors to ensure that safety events are not erroneously attributed to failings of the ADS technology where this can be shown to have functioned appropriately.

It was recognised that data emanating from the ADS may be insufficient to determine why and how safety incidents occurred. Additional footage from any relevant third-party cameras (e.g. CCTV, smartphones, dashcams) or sensors may help to clarify why an incident occurred. Finally, the Haddon matrix (Haddon, 1972) and AcciMap techniques were cited as methods by which safety events for LSAVs could be analysed according to the broader factors (e.g. regulation, physical environment, socioeconomic factors etc.) contributed to (or mitigated) risk over the time course of an event. Consideration of the factors within the cells of this matrix or across an AcciMap may help to understand why an event occurred and how it may be prevented in future.

This report has identified a wide range of data and analyses that could support safety assessments of LSAVs. This is justified for several reasons. Firstly, public opinion can swiftly turn against an innovative technology if it does not behave in line with expectation. A number of collisions that resulted in serious injuries or fatalities could greatly damage the reputation of AVs – even if overall statistics showed that they tended to be significantly safer than traditional vehicles. It is therefore necessary to have comprehensive evidence to support safety claims in the face of serious incidents. Secondly, AVs are data rich – an array of sensors, processing and communications systems produce abundant data feeds to support in-depth analysis of safety behaviours. Thirdly, regulators will need to carefully observe the early deployment of AVs to ensure that they deliver the anticipated benefits in line with expectations. Furthermore, developers will need information to improve and optimise their systems to prevent observed safety events happening in future whilst their employers / investors will want to ensure that their products and services are delivering so that they can scale quickly and deliver return on investment.

In closing, it is proposed that by

- recording safety events and road rule violations cross a range of severities;
- considering event causation, including factors outside the ADS;
- reviewing external evidence;
- exploring the range of factors that contribute to risk before, during and after an event;
- initiating appropriate and proportionate responses to incidents;

…it may be possible to analyse LSAV behaviours with sufficient depth and clarity to provide confidence to the public, regulators and developers in the safety of LSAV operations.

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Automated Vehicle Safety Assurance - In-Use Safety and Security Monitoring

Abstract

This report describes possible approaches to capture and categorise safety events involving low speed automated vehicles (LSAVs) as a means to provide the public with better evidence over their safety, regulators with evidence to strengthen decision-making in relation to LSAV operations, and developers with data to help improve the safety of LSAV behaviours. it is proposed that by recording safety events and road rule violations across a range of severities, considering event causation, including factors outside the ADS, reviewing external evidence, exploring the range of factors that contribute to risk before, during and after an event, initiating appropriate and proportionate responses to incidents it may be possible to analyse LSAV behaviours with sufficient depth and clarity to provide confidence to the public, regulators and developers in the safety of LSAV operations.

Relevant Reports

- Automated Vehicle Safety Assurance - In-Use Safety and Security Monitoring Task 2 - Minimum Dataset Specification; https://doi.org/10.58446/nksn4732
- Automated Vehicle Safety Assurance - In-Use Safety and Security Monitoring Task 3 - Safety Monitoring Framework; https://doi.org/10.58446/sgxq7004
- Automated Vehicle Safety Assurance - In-Use Safety and Security Monitoring Task 4 - Post Event Investigation Process; https://doi.org/10.58446/egfa6491
- Automated Vehicle Safety Assurance - In-Use Safety and Security Monitoring Task 5 - Outcome Reporting; https://doi.org/10.58446/qlpq9096
- Automated Vehicle Safety Assurance - In-Use Safety and Security Monitoring Task 6 - Data Privacy; https://doi.org/10.58446/dwll8689
- Automated Vehicle Safety Assurance - In-Use Safety and Security Monitoring Task 7 - Change Control; https://doi.org/10.58446/bpdl3309

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