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THEORETICAL REVIEW

Determining the likelihood that fatigue was present in a road accident: A theoretical review and suggested accident taxonomy

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SUMMARY

Estimates in developed countries of the extent to which fatigue contributes to road accidents range from as low as 5% to as high as 50% of all accidents. Compared with other causes of road accidents (e.g., speeding, drink-driving), the variability in these estimates is exceptionally high and may be indicative of the difficulty in determining the likelihood of fatigue as a cause of road accidents.

This review compares differences in the way road accidents are classified as fatigue-related (or not) by expert panels and road safety regulators, highlighting conflicting conceptual approaches, lack of consistency, and the poor psychometric qualities of classification rules used across jurisdictions. In order to facilitate future research, the review then proposes a new theoretical approach and a potentially more logical accident 'taxonomy'.

A putative accident 'taxonomy' is proposed using two dimensions: (1) estimating the likelihood that a driver was fatigued at the time of the accident, and (2) estimating the degree to which accident phenomenology is consistent with fatigue-related error. This 'taxonomy' could assist accident investigators and road safety regulators to more reliably quantify the contribution of fatigue to road accidents, and may also assist researchers and regulators in the *post-hoc* interrogation of existing accident databases to better determine the relative incidence of fatigue-related road accidents.

Introduction

Understanding the role that fatigue plays as a causal factor in road accidents is a critical first step towards better understanding, and thereby better managing, the risks associated with fatigue. There is no doubt that fatigue contributes significantly to the significant social and financial costs associated with road traffic trauma. However, the extent to which fatigue contributes to road accidents in developed countries has been variously estimated from as low as 5% to as high as 50%, with median values typically falling between 15% and 25% [1]. Compared with other causes of road accidents (e.g., speeding or drink-driving), the variability in these estimates is exceptionally high. This variability most probably reflects the definitional difficulties associated with determining whether or not an accident is fatigue-related – especially when retrospectively interrogating accident databases.

To date, there have been a number of regulatory responses to this issue, with limited success. For example, the Model Minimum Uniform Crash Criteria project in the US (https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812433), which is one of the largest attempts yet to establish common criteria in the forensic epidemiology of road accidents, has been unable to establish 'accepted criteria' for determining whether or not accidents are fatigue-related. The authors state in the executive summary (p. 1):

> *"Unfortunately, the use of State crash data is often hindered by a lack of uniformity. Sharing and comparing data between localities, States, and the federal government can be very difficult when the data elements used by separate agencies to describe the same crash characteristic have different definitions or attributes."*

With respect to national crash data in the US, there are presently no standardized criteria for determining whether or not an

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accident is fatigue-related. Indeed, the national regulatory bodies have ostentatiously eschewed establishing such criteria due to the lack of consensus around the issue. This lack of clarity is reflected in other jurisdiction as well.

For example, a report from the Australian Transport Safety Bureau (ATSB) [2] notes the inherent challenges associated with fatigue-related accidents (p. 6):

> *"Crash outcomes and crash data collection methods also complicate the identification of fatigue-related crashes. In fatal crashes, there may be no surviving witnesses to give an account of the crash, or the surviving driver may be influenced by possible legal consequences of the crash. The crash itself is also sufficient to alter arousal levels and may eliminate any evidence of impairment due to fatigue. In addition, crash investigations do not routinely collect information on length of time spent driving, details of rest breaks or previous work and rest schedules of the drivers involved"*

According to the same report, judgements as to whether or not accidents are fatigue-related are often based on: 1) subjective evidence (from accident investigators without formal training), or 2) indirect, proxy or surrogate measures of fatigue used in *post-hoc* analyses of accident databases.

Therefore, determining whether fatigue has contributed to an accident is potentially problematic – not least because it is difficult to determine reliably whether someone was fatigued at the time of an accident (Connor, Whitlock, Norton et al., 2001). Unlike speeding and drink-driving, fatigue is an internal psychological state that cannot (yet) be directly measured. Moreover, drivers surviving fatigue-related accidents may have been either (a) unknowingly alerted by the event; (b) unaware of the fact that they were fatigued and/or had fallen asleep; and/or (c) unwilling to declare that fatigue was a causal factor.

Because fatigue cannot be measured directly, fatigue is typically inferred from subjective assessments in individual accident investigations or from *post-hoc* surrogate measures typically derived from accident database studies. Not surprisingly, the estimated incidence of fatigue-related accidents varies as a function of the criteria used to define them [2,3]. Predictably, the tighter the definitional criteria, the lower the incidence generally. Across the developed world, significantly different criteria for determining whether or not an accident is fatigue-related are used in different jurisdictions.

In the following section, we use a sample of different criteria drawn primarily from Australian sources. While clearly not a comprehensive global assessment of different criteria, this is not the purpose. The purpose of the comparison is to illustrate (a) the diversity of definitional criteria even within a single country, and (b) the corollary that these definitional criteria are, at best, opportunistic, tend to be contradictory, and often exhibit poor psychometric properties. The criteria sets are drawn from Australian State Government defined criteria for interrogating road accident databases and published criteria developed by Australian and other 'expert groups' convened to define operational criteria for determining whether or not accidents were fatigue-related. A comprehensive empirical assessment of these criteria across multiple jurisdictions is beyond the scope of this paper but would likely serve only to further reinforce the lack of consistency illustrated by the current convenience sample.

Criteria for determining whether or not an accident is fatigue-related

Australian State Government criterion sets for defining fatigue-related accidents

For many years, the Australian Transport Safety Bureau has been responsible for collating data related to road traffic accidents in Australia. In doing so, they had to rely on a set of operational criteria for defining an accident as fatigue-related that differed significantly between Australian state jurisdictions [2].

In New South Wales, a crash is assessed as being fatigue-related if:

- The vehicle's controller was described by police as being asleep or drowsy; and/or
- The vehicle performed a manoeuvre which suggested loss of concentration of the controller due to fatigue, that is:
  - The vehicle travelled onto the incorrect side of a straight road and was involved in a head-on collision (and was not overtaking another vehicle and no other relevant factor was identified); or
  - The vehicle ran off a straight road or off the road to the outside of a curve and the vehicle was not directly identified as travelling at excessive speed; and
  - no other relevant factor was identified for the manoeuvre.

In Queensland, a crash is assessed as being fatigue-related if:

- A single vehicle crashes in 100 km/h or higher speed zone during typical fatigue times (2pm–4pm or 10pm–6am); or
- The reporting officer considered that fatigue was a contributory factor in the crash.

In Western Australia, a crash is assessed as being fatigue-related if:

- Police or the driver stated that fatigue was a likely cause;
- A vehicle travelled to the incorrect side of the road and was involved in a head-on collision while not overtaking another vehicle; or
- The vehicle ran off the carriageway and the vehicle was not directly identified as travelling at excessive speed and there were no other factors identified as causing loss of control (e.g., alcohol, road condition, tyre blow-out, sun glare, side wind, headlights, driver condition, broken screen).

In Tasmania, fatigue-related accident statistics are based on:

- police reporting of inattentiveness or
- the driver allegedly being drowsy or falling asleep.

In South Australia, the Northern Territory and the Australian Capital Territory, fatigue statistics are based only on police reports that indicate fatigue was considered a contributing factor by the investigating officer(s).

In Victoria, there are no explicit criteria defined, and no surrogate measures are used other than witness reports. In this jurisdiction, driver fatigue is defined as:

- the involuntary and progressive withdrawal of attention from road and traffic demands. There is no surrogate measure based on time of occurrence or type of crash although witness accounts, especially in fatal crashes, are used to identify fatigue-related crashes.

The contradictory nature of these definitional sets has long been observed [4,5]. It is also worth noting that no police officers in any of the jurisdictions covered receive any formal training in using the criteria for determining whether an accident was fatigue related.

Expert group criterion sets for defining fatigue-related accidents

In an attempt to resolve the prevailing ambiguity and provide a more systematic approach, at least three major efforts by expert groups have been undertaken in the last two decades to standardise or operationalize definitional criteria for fatigue-related accidents.

In 1989, Haworth and colleagues [6] analysed coronial records of truck accidents to estimate the extent to which fatigue contributed to trucking accidents. As part of the study they suggested the following five criteria to define a fatigue-related accident:

1) extended driving hours,
2) (driver, witness or police) evidence of falling asleep at the wheel,
3) (driver or witness) comments about tiredness,
4) driving right of centre in the absence of elevated blood alcohol concentration,
5) night-time driving.

In 1995, UK researchers Horne and Reyner [4,5] identified five criteria for determining a fatigue-related crash:

1) Vehicle ran off the road and/or collided with another vehicle or object,
2) Absence of corrective action (e.g., skid marks or breaking),
3. Driver reported the point of run-off or the object hit prior to the crash,
4) Witness reports of lane drifting prior to accident,
5) Lack of plausible alternative explanation.

In 1997, a US Expert Panel on Driver Fatigue and Sleepiness suggested a modified version of this [7]:

1) The crash occurred late at night, early morning or mid-afternoon,
2) Higher than expected severity,
3) Involved a single vehicle leaving the road,
4) Occurred on a high-speed road,
5) No attempt at corrective action,
6) Driver was the sole occupant of the vehicle.

In 2002, an expert group convened by the Australian national transport safety regulator, ATSB, introduced an explicit combination of inclusion and exclusion criteria. According to the ATSB criteria, an accident can be considered fatigue-related based on the following hierarchical process.

Inclusion criteria:

1) A single vehicle crash,
2) Occurring between 12am and 6am or 2pm–4pm, or
3) Involves a head-on collision where neither vehicle was overtaking at the time.

Exclusion criteria:

1) Occurred on a road with a speed limit <80 km/h,
2) Involved a pedestrian,
3) Involved an unlicensed driver,
4) Involved a driver with a blood alcohol concentration greater than 0.05%.

The logical and operational difficulties associated with these criterion sets is self-evident but, importantly, illustrates the challenges even when expert groups are asked to establish forensic criteria for fatigue-related accidents.

Discrepancies and communalities

If we consider all of these operational definitions of fatigue, it is clear that there is relatively little consistency between jurisdictions or expert groups in defining a fatigue-related accident. It is also clear that many of the criteria are somewhat illogical or contradictory and have been developed as convenient proxies of relative likelihood rather than a set of logical criteria. For example, the ATSB exclusion criteria (2) and (3) rule out accidents that involve a pedestrian or unlicensed driver. While it would clearly be absurd to suggest that an unlicensed driver cannot have a fatigue-related accident, it is a compromise that serves to exclude drivers for whom inexperience may be a more likely explanation of the road accident.

If we try to identify the common themes across these jurisdictions and expert groups there are some commonalities – although not a lot. Broadly speaking, the definitional criteria fall into two categories: inclusion and exclusion. For inclusion criteria, there are three broad classes of criteria:

- Incident Reports. These involve reports of fatigue or fatigue-related behaviours at or around the time of the incident, including:
  - o Driver reports: where a driver reported falling asleep immediately prior to the accident.
  - o Witness reports:
    - ▪ where someone observed the driver asleep immediately preceding the accident,
    - ▪ where someone observed driving behaviour consistent with fatigue such as steering, lane or speed variability, delayed braking, or exaggerated correction.
  - o Police officer reports: where a police officer investigating the accident reasonably formed the belief that the accident was fatigue-related.
- Accident phenomenology indicating physical evidence of the vehicle being operated in a manner consistent with driver fatigue.
  - o Lane departure: where a car left the steering land and either crossed into the path of oncoming traffic or left the roadway.
  - o Absence of, or exaggerated, corrective action, where a driver:
    - ▪ failed to undertake corrective action immediately preceding the accident, or
    - ▪ performed an exaggerated over-correction that resulted in an accident,
  - o Travelling on a high-speed road (>80–100 km/h) in a non-urban setting,
  - o A single-vehicle accident,
  - o A single-driver accident.
- Predisposing factors indicating an a priori elevated level of fatigue
  - o Time of day: where the accident occurred in either the early hours of the morning (12am–6am) or afternoon (2pm–4pm),
  - o Long driving time.
  - o Other factors thought to predispose individuals to elevated levels of fatigue (e.g., shift work, extended working hours, reduced sleep opportunities, sleep disorders such as primary or secondary insomnia and obstructive sleep apnoea, type two diabetes, medication use, etc.).

For exclusion criteria, two broad classes of criteria are seen:

- Universal exclusion [4,5] (i.e., no other apparent cause),
- Specific exclusions
  - o Occurred on a speed-restricted or urban road with a speed limit <80 km/h,

o Involved a pedestrian,
o Involved an unlicensed driver,
o Involved a driver with high blood alcohol concentration.

These criteria either individually or conjunctively are unlikely to have high levels of specificity or sensitivity in determining whether an accident is fatigue-related. It is beyond the scope of this paper to address the somewhat self-evident limitations of the criteria outlined above, but readers are referred to an excellent critique of the issues published elsewhere [3].

In our opinion, all of these definitional criteria suffer from a fundamental limitation. In general, their authors have all taken an opportunistic approach, developing objective criteria that can be applied retrospectively to pre-existing accident databases to determine the estimated incidence of fatigue-related crashes. While the logic behind these approaches is not difficult to fathom, i.e., what are the characteristics that define a typical fatigue-related crash, they also assume that most fatigue-related accidents will exhibit the characteristics of a 'typical' accident and, critically, that few will not.

Unfortunately, this is frequently not true. Fatigue can impair driving performance and lead to accidents in many ways that these criteria will not capture reliably [3]. For example, while archetypal accidents happen in a single vehicle at high speed on a country road, it is obviously possible to have a fatigue-related accident while driving in a 60 km/h zone involving a pedestrian in a urban setting. As a consequence, and depending on the set of criteria used, the estimated incidence of fatigue-related crashes will vary significantly and, in most cases, will likely be underestimated.

For example, in the Australian and US expert criteria for accidents, which are outlined in Table 1, condition (1) fails to acknowledge that people can be fatigued at any time of the day. For example, if a driver had stayed up all night and gone to work and fallen asleep whilst driving at 8:30 am, this would not be considered a fatigue-related accident under ATSB criteria [2]. Similarly, if a driver made a risky decision to overtake due to fatigue-related impairment, this would not typically be considered a fatigue-related accident.

Likewise, according to ATSB Condition (3), an accident is not deemed to be caused by fatigue when:

- the speed limit is under 80 km/h,
- a pedestrian is involved. or
- the driver is unlicensed or intoxicated.

In other jurisdictions, similar problems exist. For example, some criteria may indicate that an accident is not considered fatigue-related if it occurs within 100 km of the general post office (GPO) in a capital city. Or, as is the case in Queensland, 'driver fatigue is identified by the officer,' but officers are not provided a systematic manner for determining this.

There is also potential for conflicting responses to criteria — for example, when a driver reports fatigue but the accident occurs in an urban setting and accidents in an urban setting are not considered to be fatigue-related. How is one to resolve the competing or conflicting interpretations? It would be difficult, if not impossible, to provide a hierarchy of rule interpretation for any of the example criteria sets.

Incidence estimates and policy making

Absent a consistent, well-accepted operational definition and/or methodology for determining whether an accident is fatigue-related, it is difficult to provide quantitative data illustrating the link between specific practises and fatigue-related accident risk. This lack of data often requires regulators and others to develop policy from:

- first principles,
- inference from a small group of scientific studies with limited generalisability, or
- an amalgam of limited scientific knowledge, industry experience, political expediency, anecdote, prejudice, and ideology.

It is our view that it would be very useful to develop a standardized, international framework for operationally defining the criteria to determine whether an accident is fatigue-related. Given the importance of accurate incidence data in policy making, we should try and develop an approach to accident investigation and analysis that will improve the accuracy of determining whether or not an accident is fatigue-related — both prospectively and, ideally, retrospectively.

While it is true that prospective approaches will lack an underpinning database of accidents for some time, eventually we should have sufficient events to provide reliable statistical estimates of:

- the relative frequency of fatigue-related accidents; and/or
- the likelihood that any given accident is fatigue-related.

Table 1
Inclusion and exclusion criteria.

	Inclusion criteria										Exclusion criteria				
	Reports			Accident phenomenology					Risk factors		Specific criteria				UNIVERSAL CRITERIA
	Driver	Witness	Police	Depart Lane	No Corrective Action	High Speed	Single Vehicle	Single Driver	Time of day	Driving Time	1	2	3	4	
Expert: Monash	Yes	Yes	Yes	Yes						Yes				Yes	
Expert: UK	Yes	Yes		Yes	Yes										Yes
Expert:: US					Yes	Yes	Yes	Yes	Yes		Yes				
Expert: ATSB				Yes			Yes		Yes		Yes	Yes	Yes	Yes	
NSW			Yes	Yes											Yes
QLD			Yes			Yes	Yes		Yes						
WA	Yes		Yes	Yes											Yes
Tas	Yes		Yes												
SA/NT/ACT			Yes												
Victoria	Yes	Yes													

Until this has been achieved, we will continue our long tradition of fatigue-related policy decisions based on limited, flawed and/or non-existent evidence.

At present, there is no consensus on consistent criteria for determining whether or not an accident is fatigue-related. Historically, those interested in the likelihood of an accident being fatigue-related had to 'make do' with the data that was collected/available. Here, our goal is to proactively establish a conceptual framework around which criteria for whether or not an accident is fatigue-related might eventually evolve. By initiating a theoretical discussion in this area, we hope to convince researchers and regulators to question the validity of current approaches and to consider developing new models that, if widely adopted, might lead to a more accurate understanding of the role of fatigue in road accident epidemiology.

Toward a novel conceptual framework

Establishing a novel framework for a standardized approach to classifying fatigue-related road accidents as fatigued (or not) could initially be approached from first principles (i.e., derived from the disciplines of law, fatigue science and human factors). In our view it would be appropriate to stary with a slightly modified version of the high-level inclusion criteria outlined for the New South Wales jurisdiction (as described above).

Inclusion criteria:

- The vehicle's controller was described by witnesses as being asleep or drowsy; and/or
- The vehicle performed a manoeuvre that suggests loss of control of the operator due to fatigue.

In addition, it would seem necessary to adopt universal exclusion criteria that identify other, more likely, causes of the accident that are clearly not themselves related to fatigue. While this is a somewhat open-ended aspiration, it is important that alternative explanations be plausible and preferably have stronger corroborating evidence than a fatigue-related explanation.

Exclusion criteria:

- Mechanical failure most likely caused the accident,
- Non-fatigue-based impairment due to medical conditions, drugs or alcohol most likely caused the accident,
- Road conditions most likely caused the accident,
- Other road users most likely caused the accident,
- Environmental factors most likely caused the accident,
- Other causes not linked to fatigue most likely caused the accident.

Using these criteria, we can see logically independent principles that could be modified slightly and used conjunctively. That is, for an accident to be considered fatigue-related, it must be demonstrated that:

1) the driver was fatigued at the time of the accident,
2) the nature of the error(s) that led to the accident is consistent with the type of errors made by a fatigued individual,
3) There was no other more likely, *non-fatigue-related* cause of the accident.

If the answer to the first two questions is yes, and to the third, no, then it follows logically that the accident is highly likely to be fatigue-related.

Estimating the likelihood that the accident is fatigue-related

To demonstrate forensically that (1) and (2) are true and, therefore, that the accident is indeed fatigue-related, is not straightforward. From a practical perspective, it is rarely the case that these requirements can be demonstrated unequivocally. Thus, it is also important that the uncertainty in determining these requirements is acknowledged. This can be achieved by expressing the answers to (1), (2) and (3) above as a likelihood estimate for each dimension rather than a categorical yes/no condition.

A barrier to adopting such a likelihood approach is that current sets of criteria typically use surrogate measures in an archetype-based, dichotomising manner. For example, when a specific set of criteria indicates that an accident in an urban setting or on a low speed road is not to be classified as fatigue-related, it is really being used to classify whether or not the accident is a 'typical' or archetypal fatigue-related accident. Depending on the proportion of accidents that are 'typical', dichotomising multiple overlapping and often contradictory criteria can make it very difficult to achieve high levels of specificity or sensitivity, let alone validity or reliability in determining whether an accident is fatigue-related. If a significant proportion of accidents is not 'typical,' then the use of dichotomizing criteria is unlikely to produce satisfactory estimates.

It may therefore be useful to take a more holistic approach to determining the likelihood that (1) and (2) are true. If information pertinent to (1) and (2) is aggregated *in toto* and we weigh the overall evidence to form a judgement on the likelihood of (1) and (2), it may be possible to improve the psychometric properties of the estimates. Psychometric theory would suggest that a rating scale from 1 (highly unlikely) to 5 (highly likely) for each of the conditions (1) and (2) – i.e., whether the driver was fatigued and whether the nature of the accident was consistent with a fatigue-related error – may provide a more reasonable approach.

Toward a Fatigue Likelihood Scale (FLS) for fatigue-related road accidents

Robust test construction is an integral component of psychometric testing [8]. Expert rating scales (on a spectrum of highly unlikely through to highly likely) may provide a simple but effective strategy for assessing the pertinent information relevant to whether the driver was fatigued, and whether the nature of the accident was consistent with a fatigue-related error. The possibility of this is described here in the context of a fatigue-related road accidents.

Based on theoretical work from our group [9], the likelihood that a driver is fatigued at the time of an accident can be determined from three levels of 'proxy' indicators of fatigue:

- Level 1: The sleep opportunity afforded by the working time arrangements;
- Level 2: The recovery value of sleep obtained during sleep opportunities;
- Level 3: Behavioural indicators of fatigue immediately prior to the accident.

For a more detailed discussion, see Leveson et al. [10]. Furthermore, in the event of frank evidence of sleep onset while driving, this should be considered a *prima facie* case of fatigue. The three proxy indicator levels together with *prima facie* fatigue form a logical hierarchy that can be used to systematically estimate the likelihood that an individual was fatigued at the time of an accident.

Level 1. A systematic accident investigation should address the nature of the sleep opportunity, based on time of day and the duration of work and rest, afforded by the working time arrangement (if any) prior to the accident. In addition to work-rest and sleep-wake data, the analysis should also include driving times and any break times during work shifts. This is especially true for any work shifts immediately prior to the accident. The required duration of working time information from before the accident is bound to be case-specific; it would be reasonable to look at the working time arrangement over the two weeks prior to the accident or, at a minimum, since the last 'reset' break (i.e., depending on jurisdiction typically a period of at least 30–36 h off typically including two night sleeps). Ideally, these data could be analysed using log books and/or other forms of corroborating data (e.g., payroll data, secondary employment activities) and subjected to expert opinion or fatigue likelihood assessment software in which such expertise is formally embedded (e.g., bio-mathematical modelling software [11] [12]).

Level 2. Working time arrangements typically indicate only the timing and duration of sleep *opportunities*, from which only the average timing and duration of sleep may be inferred. Individual behaviour for any given working time arrangement may differ significantly [13]. Accident investigation should address forensic evidence on (a) the actual amount of sleep obtained by the individual driver involved in the accident, (b) the time of day that the accident occurred, and (c) any other factors that may compromise the recuperative value of any sleep obtained by an individual (e.g., concurrent medical or psychiatric conditions known to reduce the duration and/or recovery value of an individual's sleep opportunity) [14]. This can often be undertaken by systematic investigation of sleep/wake in the 3–4 days prior to the accident and the time of day (circadian timing) of the accident. This could include interviews of the driver's work colleagues, family and friends. It could also include forensic investigation of phone, internet and GPS data, video footage, credit card activity, electronic logs of vehicle movement, and other electronic data indicating individual actual waking behaviours prior to the accident.

Level 3. The timing and duration of sleep and wake is a leading indicator of fatigue, but there can be significant individual differences in the need for, and recovery value of, sleep. Behavioural indicators of fatigue in the period immediately prior to the accident can potentially provide more pertinent information on an individual's likely level of fatigue. Near miss events are the most obvious measure of this. There are however additional, subtler, leading indicators available. Physiology (e.g., EEG, eye movement behaviour, electrodermal activity), behaviour while driving (e.g., voice quality, posture, social interactions) and driving performance (e.g., speed and lane variability, situational awareness) can be affected by fatigue in relatively predictable ways prior to a fatigue-related accident. Surviving drivers and passengers can often recall changes in physical, mental and emotional state (e.g., postural changes, yawning, eye closure, or reduced verbal interaction). Similarly, driving performance changes (e.g., steering lane variability, speed and gear changes, etc.) often presage fatigue-related accidents. Forensic examination of leading indicators of fatigue (behavioural signs and symptoms or fatigue-related impairment in task behaviour prior to the accident) or recorded data indicating task impairment consistent with elevated levels of fatigue – as well as interviews of drivers, fellow passengers, other road users and, increasingly, inspection of roadside video footage – can provide corroborating evidence of fatigue-related changes in driving behaviours in the period immediately preceding the accident. Post-event analysis of GPS and/or vehicle monitoring systems may provide further evidence of fatigue-related impairment.

Observed Sleep Onset. If there is clear, corroborated evidence that the individual fell asleep in the period immediately prior to the accident, then this fact alone should be considered indicative of a very high likelihood of fatigue – assuming loss-of-consciousness due to a medical condition (e.g., epilepsy, heart attack, narcolepsy) has been ruled out. Unfortunately, in most accidents, this is a relatively rare piece of forensic evidence. This level of evidence typically requires a surviving passenger, other driver or video footage in order to be assigned primacy in the estimation of fatigue levels. That being said, while surviving driver reports are more common with improved vehicle safety features (air bags etc.), they should be assessed with scepticism. There are often good reasons why a driver may erroneously disclose or conceal falling asleep. For example, a driver might not report falling asleep when the fatigue was due to non-work factors and/or secondary employment and there was potential personal accountability or even liability for the accident. Alternatively, a driver might use fatigue to mask another, less socially acceptable, cause such as inattention due to using a mobile phone or other distraction. It is also possible that drivers may have experienced some level of amnesia in the accident and inadvertently confabulate their response.

Given the complexity and ambiguity of the factors that need to be addressed in assessing the four criteria above, a survey/checklist approach may be inappropriate at this stage. At least initially, it may be more appropriate to develop a standardized template of factors to be addressed holistically at each level of the analysis. Use of a structured interview template might be the easiest way to combine the flexibility of a relatively open-ended process with the rigour of a comprehensive assessment of all the relevant factors [15].

By systematically building an evidence 'gestalt' from levels 1–3 and any reports of observed sleep onset, it may be possible to develop a relatively detailed picture of the likelihood that a driver was fatigued. Converging evidence may be found across levels, in which case determining the likelihood and the extent to which a driver was fatigued could be straightforward. Conversely, in some cases there will be little or no data at one or more of the levels, and the certainty of the conclusion will be less clear. This can be reflected in the proposed relative likelihood assigned to the fatigue estimate.

There is potential for contradictory evidence to be found. For example, level 1 working time data may suggest a low level of fatigue, while level 2 and 3 data may suggest high levels of fatigue. Where there is contradictory evidence, higher-level data (i.e., from levels 2 and 3 and observed sleep onset) would typically be assigned primacy over lower-level data. This reflects the greater predictive value of behavioural indicators of fatigue over more indirect indicators of fatigue.

The picture built up through the use of a structured investigation addressing the levels of data suggested above could potentially be used by accident investigators to make an estimate of the likelihood of the presence of fatigue at the time of the accident. To establish a Fatigue Likelihood Scale (FLS), the following 'anchors' could be used to score the likelihood of the presence of fatigue on a scale from 1 to 5:

- 1/5. Highly unlikely to be fatigued.
  - negative level 1–3 evidence;
  - no observed sleep onset.

- 2/5. Unlikely to be fatigued.
  - inconclusive level 1–3 evidence;
  - no observed sleep onset.

- 3/5. Possibly fatigued.
  - positive level 1 evidence;
  - inconclusive level 2 and/or level 3 evidence;
  - no observed sleep onset.

- 4/5. Likely to be fatigued.
  - positive level 2 evidence;
  - inconclusive level 3 evidence;
  - no observed sleep onset.

- 5/5. Highly likely to be fatigued.
  - positive level 3 data, and/or
  - corroborated evidence of observed sleep onset.

Towards a Fatigued Driver Error Likelihood Scale (FDELS) for driving

Having established the likely level of the presence of fatigue, next it is important to establish the nature of the error that caused the accident and the likelihood that it is due to fatigue. This is not always straightforward, as the effects of fatigue on real-world tasks and error behaviour can be subtle, complex and highly variable [16,17]. While the effects of fatigue on task performance and error are an important area of research [18–23], this topic is beyond the scope of the present paper.

Determining whether the accident phenomenology is consistent with a fatigue-related error is important, as a serious error of logic could be made in determining the role of fatigue in an accident investigation. Where a driver is demonstrably fatigued at the time of an accident, the accident is sometimes assumed to be fatigue-related *ipso facto*. This conclusion may not always be correct – sometimes a driver may be fatigued without this being the primary cause of the accident. For example, if a tired driver was hit by a second driver going through a red light at an intersection under the influence of alcohol, it is probably not a fatigue-related accident despite the fact that the driver was fatigued at the time.

On the other hand, there are aspects of accident phenomenology that increase the likelihood that the error that lead to the accident was due to fatigue. For example, if the vehicle is travelling on a country road and leaves the lane without evidence of corrective action (e.g., no braking), then this would be highly consistent with falling asleep while driving. Similarly, drifting onto the wrong side of the road and crashing into oncoming traffic without corrective action would be highly consistent with a fatigue-related accident as well. In contrast, an accident that clearly demonstrated braking well before hitting a pedestrian may be counter-indicative of having fallen asleep.

The first step in determining whether the error that lead to the accident is fatigue-related will be to exclude other, better, or more likely explanations that are clearly not related to fatigue (e.g., obvious and corroborated evidence of poor road conditions, mechanical failure, error by another driver, intoxication, or medical conditions that provide a more plausible explanation for the accident). It is also important to rule out other potential causes of distraction or inattention (e.g., children in back seat, mobile phone use), provided it is evident that these are not themselves related to fatigue.

The extent to which non-fatigue-related, alternative causes of an accident can be ruled out may be used to estimate the likelihood of a fatigue-related error. To establish a Fatigued Driver Error Likelihood Scale (FDELS), the following phenomenological 'anchors' could be used to score the likelihood of fatigue-related error on a scale from 1 to 5:

1/5. Very low likelihood of fatigue-related error based on positive identification of other, more likely, non-fatigue-related causes.

2/5. Low likelihood of fatigue-related error due to other, non-fatigue-related causes being more likely or competing explanations.

3/5. Possible fatigue-related error of judgement, while alternate, non-fatigue-related explanations are less compelling. Investigation indicates that the accident resulted from either:

- unnecessarily risky behaviour,
- incorrect prediction of other road users' behaviour (e.g., assuming another driver will stop, or assuming there will not be a train at a level crossing based on prior experience).

4/5. High likelihood of fatigue-related error due to corroborated/objective evidence of limited loss of – or failure to update – situational awareness [24]. Investigation indicates that the accident resulted from a failure to maintain an accurate mental map of the driving environment, or to appreciate important changes in driving conditions, in the absence of non-fatigue-related explanations. This would usually be corroborated by evidence of a failure to:

- maintain correct lane position for easily anticipated changes (e.g., changes in road direction),
- maintain correct velocity of vehicle (especially where speed zone changes or changes in road direction/slope require only minor adjustments),
- avoid relatively obvious hazards (e.g., other proximate road users, parked vehicles, or road furniture),
- respond quickly especially to unexpected (e.g., low probability) events,
- inhibit inappropriate driving behaviours.

5/5. Very high likelihood of fatigue-related error due to corroborated/objective evidence of significant or total loss of situational awareness or complete failure to respond to changing circumstances, in the absence of any other, competing explanations. This would usually be corroborated by objective evidence of:

- significant loss of control of the vehicle on the roadway (e.g., considerably increased steering lane variability, or vehicle crossing/leaving the lane),
- absent, delayed, or exaggerated corrective action in the context of imminent danger.

Applying the FLS and FDELS scales

The FLS and FDELS scales as presented have the potential to serve dual purposes. For police investigations and criminal, coronial and/or civil proceedings, the two scales can be considered independently since a judge, coroner or jury will be responsible for synthesizing the information into a holistic judgement as to the likelihood that an accident was fatigue-related. However, where the scales are to be used to interrogate accident data(bases), it may be useful to combine the two scales. As is the case with other forms of multi-dimensional risk/likelihood assessment (e.g., ISO 31000 [25]), the FLS and FDELS could be combined into a single likelihood estimate, forming a one-dimensional Fatigue Accident Likelihood Scale (FALS).

It is worth noting that many of the criteria sets described previously include time of day of the accident as part of the accident phenomenology. Here we have chosen (arbitrarily) to instead address the issue of time of day as part of estimating the likelihood that the driver was fatigued (see levels 1 and 2 above).

We have done this to help maximize the degree of independence between the FLS and FDELS. Even so, the two scales are not orthogonal (e.g., it would be disproportionately improbable to have a high likelihood of fatigue-related error without a high likelihood of the presence of fatigue). The inter-dependence between the FLS and FDELS is however internally consistent (synergistic), such that a multiplication of the scores on the two scales would form a new, one-dimensional, ordinal scale with both construct validity and face validity. We propose that this may be done by taking the geometric mean of the FLS and FDELS scores:

$$\text{FALS} = \sqrt{(\text{FLS} \times \text{FDELS})}$$

A minimum FALS score of one represents a highly unlikely fatigue-related and fatigue-error-related accident, whereas a maximum FALS score of five represents a highly likely fatigue-related and fatigue-error-related accident. See Table 2 for a look-up table of FALS values based on FLS and FDELS scores.

Implementation and qualification for administrators

Buxton, Hartley and Buxton [26] have noted that "police (as the primary accident investigators of most major accidents) may not be sufficiently trained to detect the incidence of fatigue and may have neither the time nor the resources to examine individual crashes to the extent required" (p. 7). While the approach outlined above is more systematic than is currently the general practise, accident investigators should be appropriately qualified in the use of the methodology.

Indeed, the potential legal, social and political implications of implementing a scale like the FALS highlight the need for accident investigations to provide the most objective, reasonable estimations of fatigue likelihood. Accordingly, it would be desirable that accident investigators were required to demonstrate competency with using the proposed framework. To achieve this, consideration of supplementing the methodology with appropriate curricula should be considered, and would ideally employ the principles of competency-based assessment [27].

This paper has explored fatigue-related accidents from the perspective of determining whether an individual's driving performance was impaired as a consequence of fatigue. Whilst this driver-focused perspective is fundamental, it should be noted that in occupational contexts this is increasingly seen as only part of the issue of accident causation. Increasingly, the role of organizations is considered as an element of the causal pathway. For several decades, our understanding of accident causation has moved beyond a focus on the individual's actions to include the ways in which organizations fail to adequately manage fatigue-related risk [28]. Modern safety management perspectives acknowledge the need to adopt a systems approach, which constructs accident causation as arising at least in part from failures in organizational risk-management processes [29,30] With respect to fatigue-related accidents, the systems approach is increasingly influencing both the way in which organizations manage fatigue-related risk, and the subsequent focus of investigations if an accident occurs within this context [9].

Table 2
Look-up table for FALS scores based on FLS and FDELS scores.

		FLS score				
		1	2	3	4	5
FDELS score	1	1.0	1.4	1.7	2.0	2.2
	2	1.4	2.0	2.4	2.8	3.2
	3	1.7	2.4	3.0	3.5	3.9
	4	2.0	2.8	3.5	4.0	4.5
	5	2.2	3.2	3.9	4.5	5.0

Practice Points

We proposed a more systematic approach to determining whether an accident is fatigue-related based on semi-quantitative analysis using two relatively distinct dimensions. That is, in deciding whether an accident is fatigue-related we must determine:

- To what extent was the driver fatigued immediately prior to the accident?
- To what extent was the accident phenomenology (other than issues related to driver fatigue) consistent with fatigue-related error?

We argue that by systematically addressing each of these questions, it is possible to formulate a semi-quantitative estimate of the likelihood that fatigue was a contributory cause to the accident. While clearly imperfect, this approach is a first step toward a more coherent taxonomy for fatigue-related accidents.

Research Agenda

Future research could focus on improving the sensitivity and specificity of the forensic investigation. It may be useful to convene an expert panel to help shape how we may optimize and standardize the classification of accidents as fatigue-related (or not). An expert group could help validate and improve (or reject and replace) the methodology outlined above. This may be a fruitful avenue toward further development of a systematic, standardized approach for police, accident investigators, expert witnesses, lawyers, judges and policy makers interested in determining the likelihood that an accident is fatigue-related.

An expert panel could be specifically tasked with developing some of the ideas presented in this paper in order to provide a more broadly endorsed approach comprising well-validated:

- criteria defining the likelihood that a driver was fatigued,
- criteria defining the likelihood that the accident phenomenology is consistent with fatigue-related error,
- estimation of the likelihood that an accident was fatigue-related on a one-dimensional scale,
- methodology for undertaking an investigation and classifying whether or not an accident is likely to be fatigue-related,
- curricula and training programs for accident investigators to ensure a valid and reliable method of assessment and interpretation.

Conflicts of interest

Professor Drew Dawson receives royalty payments from Inter-Dynamics for fatigue modelling software marketed under the name of FAID(c), occasionally works as a paid consultant providing advice to companies on best practise approaches to managing the risks associated with shift work and fatigue, and derives income from phone and web apps marketed under the name of 'the fatigue calculator'. Dr Amy Reynolds, Professor Hans Van Dongen and A/Professor Matthew Thomas have no conflicts to disclose with direct relevance to this manuscript.

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