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A systematic review of definitions of motor vehicle headways in driver behaviour and performance studies

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A B S T R A C T

Headway is a safety measure commonly used to investigate driving behaviour and driver performance. Its purpose is to reflect the following distance or time between a leading and following vehicle in traffic. It is therefore associated with drivers' response time, such as in braking or swerving, during safety critical events. In the literature, distance and time headway are defined in different ways, despite standard definitions in the traffic engineering literature, which prompted this systematic review of headway definitions across a range of study designs, in order to recommend approaches to improve the accuracy and reproducibility of headway definitions used in road safety contexts. PRISMA guidelines were followed to search four databases (EMBASE, COMPENDEX, SCOPUS and MEDLINE) for studies that reported on headways or discussed methodological approaches. The search and filtering of abstracts identified 110 articles for a qualitative synthesis. Four broad approaches to measuring headways were detected: studies using simulation, roadside external features, on-road features, and on-vehicle features. Studies were coded as to whether they included written explanation, mathematical statements, or pictorial depictions of headway. Only 49.6% of studies contextualised headway sufficiently for reproducibility. Reproducibility is crucial for accurate interpretation of research findings and comparisons across studies. It is recommended that headway definitions should a) exclude vehicle or parts of vehicle lengths, b) include reference points (e.g., bumper/axle/rear), c) have a consistent terminology, and d) include the accuracy of headway measuring devices to report the precision of a study's findings.

1. Introduction

Headway refers to the following distance or elapsed time between two consecutive moving vehicles. Accurate measurement of headway is important due to its multifaceted applications in road safety, particularly in terms of investigations into driver behaviour to prevent crashes. Short headway is identified as one of the primary causes of rear-end crashes (Lee, Llaneras, Klauer, & Sudweeks, 2007; McDonald, Seacrist, Lee, Loeb, Kandadai, & Winston, xxxx; Michael, Leeming, & Dwyer, 2000; Naji, Xue, Lyu, Wu, & Zheng, 2018). Rear-end crashes are one of the most common crash types, accounting

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for nearly one-third of reported crashes across multiple studies and jurisdictions (Foss, Martell, Goodwin, & O'Brien, 2011; Lee et al., 2007; Meng & Qu, 2012).

When headway is less than a driver's reaction time, the possibility of a rear-end crash is likely if the lead vehicle suddenly brakes (Wang et al., 2011). Road safety authorities often recommend maintaining time headways of three seconds to account for drivers' preparedness to respond to avoid a crash (Centre for Road Safety – NSW, 2014; Council, 2019; Faulks, 2012). It is estimated that the risk of a rear-end crash can be reduced up to 50% with a one-second advanced warning (Park, Chen, & Hourdos, 2011). A headway threshold is also used to distinguish free flowing from closer vehicle-following traffic scenarios (Ambros & Kyselý, 2016; Wu, Jiang, Hu, & Lu, 2011), which requires precise and reproducible measurement.

Headway is also considered an indicator of driver performance as it reflects driver concentration level, attention by the driver on the traffic ahead, and drivers' acceptance of the distance between their vehicle and the one ahead. A driver maintaining a short headway might not have adequate time to respond, such as by braking or swerving, and so there is greater risk of a crash (Jamson, Tate, & Jamson, 2005). Thus, headway is commonly used as a safety factor in determining crash risk due to distraction by secondary tasks (Hofman et al., 2012; Pouyakian, Mahabadi, Yazdi, Hajizadeh, & Nahvi, 2013) or the effect of inclement weather or low visibility conditions (Al-Ghamdi, 2007; Rosey, Aillerie, Espié, & Vienne, 2017). As such, headway is a variable commonly used in car-following models in driver assistance technology to improve advanced driver assistance systems or adaptive cruise controls (Ivanco, 2017; McGehee, Dingus, & Horowitz, 1994).

Traffic engineering has a long history of traffic flow modelling in which vehicle headway is a fundamental measure and is usually defined as the time between two successive vehicles in the same lane as they pass the same point, measured from the same common feature of both vehicles (Li & Chen, 2017). This includes car-following models that combine engineering and human factors perspectives to create well-defined probabilistic headway distribution models. Despite these firm foundations, in modelling headway, the definitions used in studies focused on driver behaviour or performance are inconsistent, lack precision, with no standard measuring process for headway applied. It can be measured in terms of either distance or time. Distance headway, for example, might be measured by the distance between the rear bumper of the leading vehicle to the front bumper of the following vehicle at a fixed point in time. Time headway, related to distance headway, might be measured in terms of the time it takes for the following vehicle to reach the position of the lead vehicle. A more specific measure of time headway is time to collision (TTC), which also takes vehicle speed into account and measures the impending risk of collision in terms of the time to the point of collision if no evasive actions are taken (Vogel, 2003). In practice, many different measuring methods of distance and time headway are used in existing studies which limits comparisons between studies and the understanding of safety implications. For example, studies have measured either time or distance from the bumper of the lead car to the bumper of the following car (Ding, Zhu, Wang, & Jiao, 2017; Song & Wang, 2010; Taieb-Maimon & Shinar, 2001), from the axle of the lead car to the axle of the following car (Mitra & Utsav, 2011; Summala, 1980) or from a range of other points (He et al., 2014; Hofman et al., 2012).

Multiple equivalent terms for headway are used in the literature. For example, distance headway is also known as car-following distance, inter-vehicle spacing or distance gap (Fleming, Allison, Yan, Lot, & Stanton, 2019; Hutchinson, 2008; Rudin-Brown, 2006; Veldstra, Bosker, De Waard, Ramaekers, & Brookhuis, 2015). The time gap is sometimes called inter-vehicular time (IVT) (Navarro, Osiurak, & Reynaud, 2018), while Yousif and Al-Obaedi (Yousif & Al-Obaedi, 2011) used time headway to calculate 'clear spacing' or 'following distance'. The headway measurement from rear to rear is called tailway (Ambros & Kyselý, 2016) but not widely used.

The application of various measuring devices also governs the measurement of following distance, such as the use of inductive loops or radars, which have inherent limitations in measuring headway. For example, some devices such as single loop detectors cannot adjust for different vehicle lengths (Mitra & Utsav, 2011), as they cannot detect whether the passing vehicle was a passenger car or heavy vehicle which limits the ability to accurately adjust for vehicle length (Yousif & Al-Obaedi, 2011). Headway quantifying devices also generally have measurement errors (Ding, Zhu, Wang, & Jiao, 2019; Jeong & Liu, 2017), which might lead to imprecise findings, and so clear, reproducible headway definitions and corresponding analyses are critical for understanding and comparing outcomes across studies. Moreover, intervention strategies such as new advanced driver assistance systems can be difficult to implement without such standard and precise headway measures.

In order to consolidate common headway definitions and to make recommendations on accurate reporting of headway, the primary objective of this study was to systematically review how headway has been defined in practice across studies of driver behaviour and performance. The secondary objective was to critically evaluate various headway measuring approaches used in the research literature. Based on the findings, recommendations are identified to improve headway definition accuracy and reproducibility in road safety contexts.

This study systematically searched and reviewed published articles on driver behaviour and performances studies of headway and summarized the headway definitions and measuring techniques used. The mathematical depictions and pictorial illustrations found in the literature were detailed followed by a comparison of TTC and time headway. Based on the findings, four recommendations were drafted for future studies to help define headway in a consistent and reproducible manner.

2. Methods

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed for this review (Moher, Liberati, Tetzlaff, & Altman, 2009), which provide a framework to detect, assess and review articles commonly used for systematic review. Two authors searched four research databases (EMBASE, COMPENDEX, SCOPUS and MEDLINE) using search terms (vehicl* AND safe*) AND (tailgat* OR headway* OR "car* follow*" OR platoon* OR "vehicl* follow*" OR "time-to-collision") for articles published in English since 1980. The research databases were chosen since Compendex has a focus on engineering literature, Medline and Embase cover life sciences, and Scopus is the largest abstract and citation database of peer-reviewed literature. The search was conducted on 26 September 2018 and updated on 15 July 2020.

Studies were excluded from the review if headway or related terms were not discussed, defined or analysed. Studies that did not investigate driver behaviour or performance were also excluded from this review, which included studies using crash statistics or the development of new models that did not assess driver behaviour. This review did not include the related body of literature on the theoretical basis of headway for traffic planners and engineers. Documents that were abstracts only were retained where headway was considered either as a predictor or as an outcome variable in studies of light passenger vehicles (private cars, utility vehicles, SUVs, passenger vans) in moving traffic on roads or in simulator studies that reported headways. Studies without a focus on passenger vehicles, such as heavy vehicles, motorcycles or bicycles, were excluded. Passenger vehicles are the largest group of vehicles on the road and they are the usual focus of general driver behaviour research. Given the large volume of studies identified for this group, no further groups were explored. In addition to original research, reviews and theoretical papers that used secondary data sets to discuss headways and driving behaviour or performance were retained.

The review was conducted by two authors who searched, screened, and summarised articles independently. Disputes were resolved through discussion and unresolved differences were adjudicated by a third author. For each included study, information was collected on the headway definition, measuring device and headway measuring method.

It was expected that the measuring approach for headway, and therefore its accuracy, would vary with the method by which headway was obtained, such as simulator studies being able to calculate more precise measures of headway compared to on road studies. Therefore, four broad study types were selected for within-group critical evaluation and recommendations: simulation, roadside external features, on-road features and on-vehicle instruments. Each of these is described below in more detail.

Simulation studies refer to the use of a simulator consisting of, at minimum, a steering wheel, pedals (brake/acceleration), a virtual instrumented dashboard that resembles that in a real vehicle, direction indicators, sound systems and display screens using software that can measure relevant driving behaviours and performance, including headway (Jamson et al., 2005; Mollu et al., 2018).

Roadside external features include devices set on or near roads that can measure vehicle and driving parameters such as headway, speed, vehicle type, plate number, acceleration, and lane swerve (Al-Ghamdi, 2007; Bella, Calvi, & D'Amico, 2014; Ding, Zhu, Wang, & Jiao, 2018). These include video cameras, active and passive infrared beams, optical character recognition (OCR) devices, time stamps from surveillance videos, and traffic counter classifiers (Al-Ghamdi, 2007; Hajbabaie, Ramezani, & Benekohal, 2011; Michael et al., 2000; Song & Wang, 2010).

On-road features include inductive loops, particularly double-loop detectors that are used to collect traffic data (Shariff, Puan, & Mashros, 2016). Other features may include pneumatic tubes with time recorders (Summala, 1980), traffic analyser (Ding et al., 2017), magnetometers (Hainen et al., 2013) and automatic traffic counters (Nordiana, Raha, & Johnnie, 2012).

On-vehicle features include instrumented vehicles, commonly used in naturalistic driving studies. This includes the use of video recorders, radar or headway detection devices (e.g., Mobileye) to study car-following behaviours (Fitch, Grove, Hanowski, & Perez, 2014; Naji et al., 2018; Seacrist et al., 2018). These include vehicles provided for the study or instruments installed in a participant's vehicle for a limited period.

3. Results

The search identified an initial 5442 documents with an additional six documents extracted from references of the reviewed articles. Duplicate articles were removed which resulted in 1029 unique records. The overall focus of this review was on how headway is measured and interpreted, and subsequently applied in translational efforts, to address safe driver behaviour. A PRISMA flowchart of the identified and included articles is given in Fig. 1.

Following title and abstract screening, 200 articles from 1029 unique records met criteria for a full-text review. A total of 110 articles were included for qualitative synthesis and reasons for excluding the remaining 90 articles are summarised in Table 1. Where the same study was published in multiple forms, such as in a conference proceedings and in a peer-reviewed journal, the journal article was included. The screening authors agreed on the inclusion/exclusion of 96.5% (193/200) of documents, while the remaining seven articles were adjudicated by a third author.

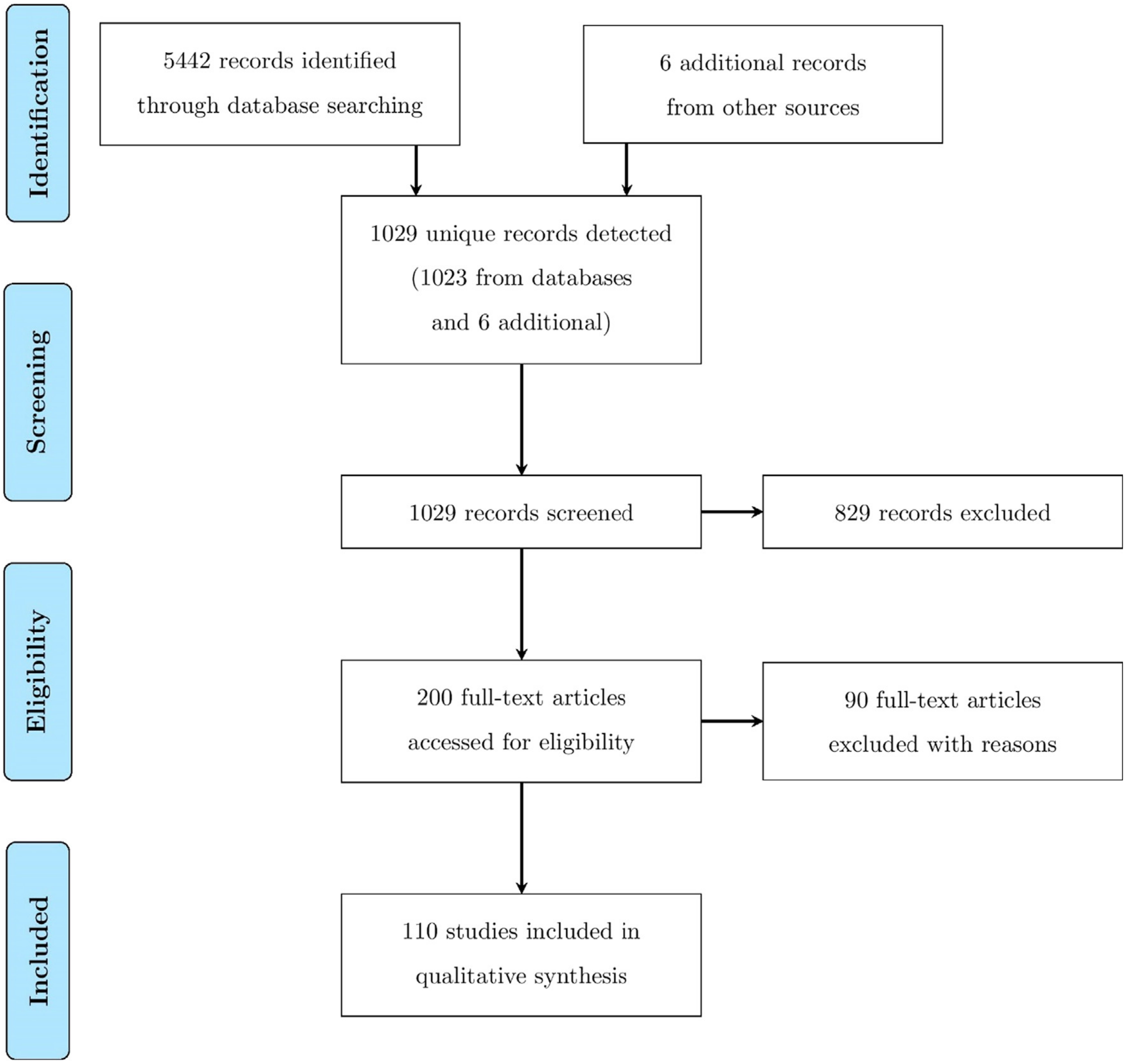

Fig. 1. PRISMA Flowchart for the systematic review of headway studies.

3.1. Summary of headway definitions

A summary of headway definitions for the included studies is given in Table 2, where 10 unique definitions for headway were identified across all studies. While some definitions were more commonly used than others, there are studies with unique definitions not utilized anywhere else. Almost one-third (34 out of 110) of the reviewed studies did not include any definitions of headway or the headway definition they provided was insufficient, such as the time it takes to reach the position of the lead vehicle - which fails to detail reference points or consideration of vehicle length.

Time or distance headway measured from the front vehicle's front bumper to the following vehicle's front bumper was the most common measuring method (18.2%, 20/110 studies). Distance headway between rear of the leading vehicle and front bumper of the following vehicle was used in around 16.4% of the reviewed studies and 5.5% used measures directly from on-vehicle devices (Table 2). Nearly one-fifth of the studies used only time-based measures of headway. Other less common measuring techniques include axle to axle distance, rear to rear distance and data extracted from video images. Some studies defined headway in terms of both time and distance.

Measuring devices such as simulators (Mollu et al., 2018), infrared camera (Al-Ghamdi, 2007) or inductive loops (Shariff et al., 2016) were used in studies; however, very few studies explained the measurement accuracy of those devices. For example, only one reviewed study featuring instrumented vehicles gave an accuracy range for headway measurements (Zhang, Wu, Yan, & Qiu, 2016). The accuracy of these measuring devices could vary over scenarios, such as weather and time of the day (Limited, 2012).

Table 1
Reasons for excluding studies following full-text review with number (percent) and study references.

Reason for exclusion	Article count (%)	References
Headway was not analysed or not discussed as behavioural/ performance factor in detail	47 (52.1)	Abbas, Higgs, Medina, & Yang, 2011; Abbas et al., 2011; Abbas et al., 2011; Abbas et al., 2011; Abbas et al., 2011; Al-Kaisy, Kreider, & Pothering, 2013; Al-Kaisy et al., 2013; Al-Kaisy et al., 2013; Al-Kaisy et al., 2013; Al-Kaisy et al., 2013; Aria, Olstam, & Schwietering, 2016; Aria et al., 2016; Aria et al., 2016; Aria et al., 2016; Aria et al., 2016; Assi, 2018; Assi, 2018; Assi, 2018; Assi, 2018; Assi, 2018; Bajčetić, Tica, Živanović, Milovanović, & Đorojević, 2018; Bajčetić et al., 2018; Bajčetić et al., 2018; Bajčetić et al., 2018; Bajčetić et al., 2018; Bartrim et al., 2020; Bartrim et al., 2020; Bartrim et al., 2020; Bartrim et al., 2020; Bartrim et al., 2020; Ben-Yaacov, Maltz, & Shinar, 2000; Ben-Yaacov et al., 2000; Ben-Yaacov et al., 2000; Ben-Yaacov et al., 2000; Ben-Yaacov et al., 2000; Brookhuis, 1998; Brookhuis, 1998; Brookhuis, 1998; Brookhuis, 1998; Brookhuis, 1998; Caro, Cavallo, Marendaz, Boer, & Vienne, 2009; Caro et al., 2009; Caro et al., 2009; Caro et al., 2009; Caro et al., 2009; Chee, Lee, Patomella, & Falkmer, 2019; Chee et al., 2019; Chee et al., 2019; Chee et al., 2019; Chee et al., 2019; Clark, Pidgeon, Alexander, Rogich, Wagner, & Jensen, 2013; Clark et al., 2013; Clark et al., 2013; Clark et al., 2013; Clark et al., 2013; Collet, Guillot, & Petit, 2010; Collet et al., 2010; Collet et al., 2010; Collet et al., 2010; Collet et al., 2010; Deng, Wu, Cao, & Lyu, 2019; Deng et al., 2019; Deng et al., 2019; Deng et al., 2019; Deng et al., 2019; Donmez, Boyle, & Lee, 2006; Donmez et al., 2006; Donmez et al., 2006; Donmez et al., 2006; Donmez et al., 2006; Fallah Zavareh, Mamdoohi, & Nordfjærn, 2017; Fallah Zavareh et al., 2017; Fallah Zavareh et al., 2017; Fallah Zavareh et al., 2017; Fallah Zavareh et al., 2017; Fiorani, Mariani, Minin, & Montanari, 2008; Fiorani et al., 2008; Fiorani et al., 2008; Fiorani et al., 2008; Fiorani et al., 2008; Fiorani, 2007; Fiorani, 2007; Fiorani, 2007; Fiorani, 2007; Fiorani, 2007; Foroutaghe, Moghaddam, & Fakoor, 2020; Foroutaghe et al., 2020; Foroutaghe et al., 2020; Foroutaghe et al., 2020; Foroutaghe et al., 2020; Gao, Meng, & Xu, 2013; Gao et al., 2013; Gao et al., 2013; Gao et al., 2013; Gao et al., 2013; Ghasemi, Jalayer, Pour-Rouholamin, Nowak, & Zhou, 2016; Ghasemi et al., 2016; Ghasemi et al., 2016; Ghasemi et al., 2016; Ghasemi et al., 2016; Green, 2013; Green, 2013; Green, 2013; Green, 2013; Green, 2013; Hamann, Price, & Peek-Asa, 2020; Hamann et al., 2020; Hamann et al., 2020; Hamann et al., 2020; Hamann et al., 2020; Irwin, Leveritt, Shum, & Desbrow, 2014; Irwin et al., 2014; Irwin et al., 2014; Irwin et al., 2014; Irwin et al., 2014; Kim & Yang, 2019; Kim & Yang, 2019; Kim & Yang, 2019; Kim & Yang, 2019; Kim & Yang, 2019; Kim & Yang, 2019; Kim & Yang, 2019; Kim & Yang, 2019; Kim & Yang, 2019; Kim & Yang, 2019; Kovaceva, Isaksson-Hellman, & Murgovski, 2020; Kovaceva et al., 2020; Kovaceva et al., 2020; Kovaceva et al., 2020; Kovaceva et al., 2020; Lanning, Melton, & Abel, 2018; Lanning et al., 2018; Lanning et al., 2018; Lanning et al., 2018; Lanning et al., 2018; Lee, McGehee, Brown, & Marshall, 1980; Lee et al., 1980; Lee et al., 1980; Lee et al., 1980; Lee et al., 1980; Lerner, Steinberg, Huey, & Hanscom, 2000; McGehee, Dingus, & Horowitz, 1992; McGehee et al., 1992; McGehee et al., 1992; McGehee et al., 1992; McGehee et al., 1992; Miyajima, Angkititrakul, & Takeda, 2013; Miyajima et al., 2013; Miyajima et al., 2013; Miyajima et al., 2013; Miyajima et al., 2013; Molloy, Molesworth, & Williamson, 2019; Molloy et al., 2019; Molloy et al., 2019; Molloy et al., 2019; Molloy et al., 2019; Montgomery, Kusano, & Gabler, 2014; Montgomery et al., 2014; Montgomery et al., 2014; Montgomery et al., 2014; Montgomery et al., 2014; Naji et al., 2018; Naji et al., 2018; Naji et al., 2018; Naji et al., 2018; Naji et al., 2018; Papantoniou, Papadimitriou, & Yannis, 2015; Papantoniou et al., 2015; Papantoniou et al., 2015; Papantoniou et al., 2015; Papantoniou et al., 2015; Pariota et al., 2016, 2017, 2016, 2016, 2016, 2016, 2017, 2017, 2017, 2017; Prat, Gras, Planes, Font-Mayolas, & Sullman, 2018; Prat et al., 2018; Prat et al., 2018; Prat et al., 2018; Prat et al., 2018; Schreiner, 2006; Schreiner, 2006; Schreiner, 2006; Schreiner, 2006; Schreiner, 2006; Scott-Parker, Jones, Rune, & Tucker, 2018; Scott-Parker et al., 2018; Scott-Parker et al., 2018; Scott-Parker et al., 2018; Scott-Parker et al., 2018; Sun & Wang, 2002; Sun & Wang, 2002; Sun & Wang, 2002; Sun & Wang, 2002; Sun & Wang, 2002; Uchiyama et al., 2012; Uchiyama et al., 2012; Uchiyama et al., 2012; Uchiyama et al., 2012; Uchiyama et al., 2012; Unverricht, Samuel, & Yamani, 2018; Unverricht et al., 2018; Unverricht et al., 2018; Unverricht et al., 2018; Unverricht et al., 2018; Veldstra et al., 2015; Veldstra et al., 2015; Veldstra et al., 2015; Veldstra et al., 2015; Veldstra et al., 2015; Viano & Parenteau, 2018; Viano & Parenteau, 2018; Viano & Parenteau, 2018; Viano & Parenteau, 2018; Viano & Parenteau, 2018; Wu & Thor, 2015; Wu & Thor, 2015; Wu & Thor, 2015; Wu & Thor, 2015; Wu & Thor, 2015; Yannaccone, 2020; Yannaccone, 2020; Yannaccone, 2020; Yannaccone, 2020; Yannaccone, 2020
Theoretical or methodological papers with no headway definition or discussion of behavioural/ performance aspects of headway	21 (23.3)	Braaksma, Ridley, & Jones, 1987; Chen, Du, Zhao, & Pei, 2010; Derbel, Mourllion, & Basset, 2012; Dong, Luo, Cui, & Bao, 2019; He, Qin, Liu, & Sayed, 2018; Hourdos, Garg, Michalopoulos, & Davis, 1968; Huang, 2019; Jafaripournimchahi, Sun, & Hu, 2020; Jehn & Turochy, 2019; Jiang, Liu, Zhang, & Li, 2018; Li et al., 2018, 2020; Munigety, 2020; Roy & Saha, 2018; Schoemig, Heckmann, Wersing, Maag, & Neukum, 2018; Seidowsky, Aron, Cohen, & Morin, 2007; Shariff et al., 2016; Silvano, Koutsopoulos, & Farah, 2020; Stylianou & Dimitriou, 2018; Xu & Qu, 2014; Yang, Zhu, & Sun, 2017
Headway was a criterion for data curation, but was not analysed or discussed	15 (16.7)	Albert et al., 2018; Aswad Mohammed et al., 2019; Bella & D'Agostini, 2010; Bondallaz et al., 2016; Feenstra, Hogema, & Vonk, 2008; Figueira & Larocca, 2020; Jung, Jang, Yoon, & Kang, 2014; Kim, Tak, Choi, & Yeo, 2018; Kusano, Chen, Montgomery, & Gabler, 2015; Leong & Muhammad, 2019; Leong, Azai, Goh, & Shafie, 2019; Li, Lu, Yang, Zhang, & Liu, 2015; Smith, Mansfield, Gyi, Pagett, & Bateman, 2015; Tan, Gong, Qin, & Niu, 2019; Wada et al., 2007

Table 1 (*continued*)

Reason for exclusion	Article count (%)	References
Related to another included article	6 (6.67)	Gouy, Diels, Reed, Stevens, & Burnett, 2013; Brackstone, McDonald, & Sultan, 1999; Horrey et al., 2006; Jung, Qin, & Noyce, 2011; Mitra & Utsav, 2015; Molloy, Molesworth, & Williamson, 2018
Not accessible	1 (1.1)	98
Total	90	

3.2. Mathematical and pictorial depiction of headway

Given the considerable variation in the definitions used for headway in previous studies, it is important to evaluate the implications of these through mathematical statements used in various studies. Few studies used mathematical representations of headway definitions and not all of those studies included all necessary components in their equations to clearly define headway. Reference points, for example, were not often mentioned in headway definitions.

A diagram illustrating various headway definitions used in the reviewed studies is given in Fig. 2. This includes the reference points and the distances measured.

The gap headway is the shortest distance between consecutive vehicles, while the other distance headway definitions are determined by the distance between consecutive vehicles' front bumper, front axle or rear bumper, which include the partial lengths of at least one vehicle. In mathematical terms, distance headway (ΔDH_{kl}) is the difference in space between the reference points (bumper, axle or rear) of the lead () and following vehicles (f)

$$\Delta DH_{kl} = x_k - x_{fl} \quad (1)$$

where x_k is the position of the lead vehicle () at point k (e.g., bumper/axle/rear, denoted b, a, r in Fig. 2) and x_{fl} is the following vehicle (f) at point l in the same lane. This distance portion could be converted to time headway using $\Delta TH_{kl} = \Delta DH_{kl}/v_{ft}$, where v_{ft} (ms^{-1}) is the speed of the following vehicle at time t. Similarly, time headway could be transformed to distance headway (Brouwer & Ponds, 1994). However, this definition of headway may or may not include the length of the vehicle (Bella et al., 2014; Vogel, 2003).

The gap headway can be approximated using the other measures by accounting for vehicle length. For example, distance gap ΔD_t measured from the rear surface of the leading vehicle to the front surface of the following vehicle adjusted for vehicle length L_{kl} is

$$\Delta D_t = v_{ft} \times \Delta TH_{kl} - L_{kl}. \quad (2)$$

The vehicle length L_{kl} does not necessarily refer to the full vehicle length of a single vehicle and is possibly comprised of partial lengths of the lead and following vehicles. It could be zero depending on the reference points, in which case distance gap and distance headway are the same The gap headway could be converted to time gap by $\Delta T_t = \Delta D_t/v_{ft}$.

3.3. TTC and time headway

Time to collision (TTC) is a special case of time headway, which takes into account the speed of the vehicles. TTC is often used in car following studies as a measure of driver behaviour and performance. It could be argued that TTC is more informative than time or distance headway as it considers the relative speed of the vehicles at a given time, whereas time headway uses the following vehicle's speed (Leblanc, Bao, Sayer, & Bogard, 2013).

TTC is the time taken for a vehicle to collide with the leading vehicle if other factors remain unchanged, i.e., both vehicles are in the same lane moving in the same direction (Vogel, 2003). TTC is measured using the relative distance and relative speed between consecutive vehicles using Newtonian equations (Hayward, 1971; Hydén, 1987; Mamdoohi, Zavareh, Hydén, & Nordfjærn, 2014; Minderhoud & Bovy, 2001) as;

$$TTC_{kl} = \frac{x_k - x_{fl} - L_{kl}}{v_{ft} - v_t} = \frac{\Delta DH_{kl} - L_{kl}}{v_{ft} - v_t} = \frac{\Delta TH_{kl} v_{ft} - L_{kl}}{\Delta V_t} = \frac{\Delta D_t}{\Delta V_t}. \quad (3)$$

Note that when the following vehicle is moving at a slower speed than the leading vehicle, i.e., $v_{ft} < v_f$, then TTC_{kl} is negative and the vehicles will not collide.

Li et at. (Li, Jiang, & Lu, 2011) demonstrated TTC was related to time gap by,

$$TTC_{kl} = (v_{ft}/\Delta V_t) \times \Delta T_t \quad (4)$$

where ΔT_t is the time gap between two consecutive vehicles (rear of lead to front of following vehicle) and ΔV_t is the difference in speed between following and leading vehicles at time t (Qin, Dong, Xu, Zhang, & Leon, 2018).

A similar association between time gap and TTC was formulated by Vogel (Vogel, 2003) as,

Table 2
List of headway definitions found in the studies following full-text review with number (percent) and study references.

Headway Type	Headway Definition	Article count (%)	References
Time	Front to front/ front bumper to front bumper	15 (13.6)	Aron, Billot, El, & Seidowsky, 2015; Dimitriou, Stylianou, & Abdel-Aty, 2018; Ding et al., 2017, 2018, 2017; Hajbabaie et al., 2011; Michael et al., 2000; Nordiana et al., 2012; Ramezani Khansari, Tabibi, & Moghadas, 2018; Simons-Morton, Lerner, & Singer, 2005; Song & Wang, 2010; Stylianou & Dimitriou, 2016; Van Winsum & Heino, 1996; Von Buseck, Evans, Schmidt, & Wasielewski, 1980; Zhu, Wang, & Wang, 2016
	Time it takes to reach the position of the lead vehicle	14 (12.7)	Ben-Yaacov, Maltz, & Shinar, 2002; Fu, Gasper, & Kim, 2013; Li, Xing, Wang, & Dong, 2017; Maltz et al., 1899; Mamdoohi et al., 2014; Navarro et al., 2018; Ni, Kang, & Andersen, 2010; Peng, Lu, He, & Gu, 2017; Risto & Martens, 2014; Rosey et al., 2017; Tscharn, Naujoks, & Neukum, 2018; Vogel, 2003; Xie, Zhao, Li, Lu, & Jiang, 2018; Yousif & Al-Obaedi, 2011
	Time gap/ instantaneous measure of time between rear of lead to front of following	11 (10)	Bella et al., 2014; Glendon, 2007; Hofman et al., 2012; Kang, Kim, Moon, Lee, & Lee, 2008; Khaisongkram, Saigo, Raksincharoensak, Nagai, & Sato, 2011; Li et al., 2011; Morita, Sekine, & Okada, 2006; Postans & Wilson, 1983; Radwan & Kalevela, 1985; Yan et al., 2018; Zhang et al., 2016
	Measured directly from device (e.g., Mobileye) with no further specification provided	5 (4.55)	Ding, Zhu, Wang, & Jiao, 2019; Ivanco, 2017; Lewis-Evans, De Waard, & Brookhuis, 2010; Rosenbloom & Eldror, 2014; Tivesten & Dozza, 2015
	Axle to axle distance/ front axle to front axle	2 (1.81)	Mitra & Utsav, 2011; Nissan & Karl, 2008
	Mean time maintained between lead and following vehicle	1 (0.9)	Jamson, Westerman, Hockey, & Carsten, 2004
	Lead vehicle's back axle to following vehicle's lead axle	1 (0.9)	Summala, 1980
Distance	Gap between rear of lead to front bumper of the following vehicle	18 (16.4)	Ambros & Kyselý, 2016; Brackstone et al., 2009; Broughton, Switzer, & Scott, 2007; Duan et al., 2012, 2013; Gouy et al., 2013, 2014; He et al., 2014; Horrey & Simons, 2007; Hutchinson, 2008; Leblanc et al., 2013; Luo, Cheng, & Wang, 2015; Pouyakian et al., 2013; Qu, Kuang, Oh, & Jin, 2014; Souders, Charness, Roque, & Pham, 2020; Wang, Liu, & Zheng, 2014; Yannis et al., 2013, 2016
	Front to front/ front bumper to front bumper	1 (0.9)	Horrey, Lesch, Garabet, Simmons, & Maikala, 2017
Both time and distance	Front to front/ front bumper to front bumper	4 (3.64)	Das, Maurya, & Budhkar, 2019; Taieb-Maimon & Shinar, 2001; Wang, Xiong, Lu, & Li, 2015; Wu et al., 2011
	Measured directly from device (e.g., Mobileye) with no further specification provided	1 (0.9)	Jeong & Liu, 2017
	Axle to axle distance/ front axle to front axle	1 (0.9)	Vogel, 2002
	Rear of lead to rear of following vehicle	1 (0.9)	Yeung & Wong, 2014
	Video image reconstruction	1 (0.9)	Lin et al., 2008
None	Not defined or insufficient information	34 (30.9)	Ahmed & Ghasemzadeh, 2018; Al-Ghamdi, 2007; Brackstone & McDonald, 2007; Bunce, Young, Blane, & Khugputh, 2012; Caird et al., 2014, 2018; Chen, Fu, Xu, & Yuan, 2020; Dastrup, Lees, Bechara, Dawson, & Rizzo, 2010; Economou et al., 2020; Fitch et al., 2014; Fleming et al., 2019; Gao et al., 2020; Ha, Kang, & Park, 2003; Hogema & Van Der Horst, 1997; Jamson et al., 2005; Kaber, Liang, Zhang, Rogers, & Gangakhedkar, 2012; Lansdown, 2019; McGehee et al., 1994; Morris & Pilcher, 2016; Pampel et al., 2015; Pantangi et al., 2020; Probst, Brandt, & Degner, 1986; Qin, Yang, & Zheng, 2018; Rakauskas et al., 2008; Risto & Martens, 2013; Rudin-Brown, 2006; Seacrist et al., 2018; Shangguan, Wang, Liu, & Wang, 2019; Shino, Kamata, Nagai, Michitsuji, & Mora, 2008; Wang et al., 2011; Yang, Wong, & McDonald, 2015; Ye & Zhang, 2009; Zheng, Zhu, He, He, & Liu, 2019; Zokaei et al., 2020
	Total	110	

$$TTC_{kl} = \frac{v_{ft}}{v_{ft} - v_t} \times \Delta TH' \tag{5}$$

where $\Delta TH' = \Delta TH_{kl} - L_{kl}/v_{ft}$. From equations (4) and (5), time gap cannot be larger than TTC since $v_{ft}/\Delta V_t > 1$. These equations imply that there exists a theoretical relation between TTC and time headway. However, the empirical evidence in the literature suggests otherwise (Bella et al., 2014; Vogel, 2003).

From separately collected data, both Vogel (Vogel, 2003) and Bella et al. (Bella et al., 2014) observed that there was no significant correlation between time headway and TTC. The conclusions drawn by the authors was that time headway is a measure of potential risk, i.e., short time headway could be maintained without a crash; whereas, TTC measures impending risk, i.e., a short TTC will result in a crash (Bella et al., 2014).

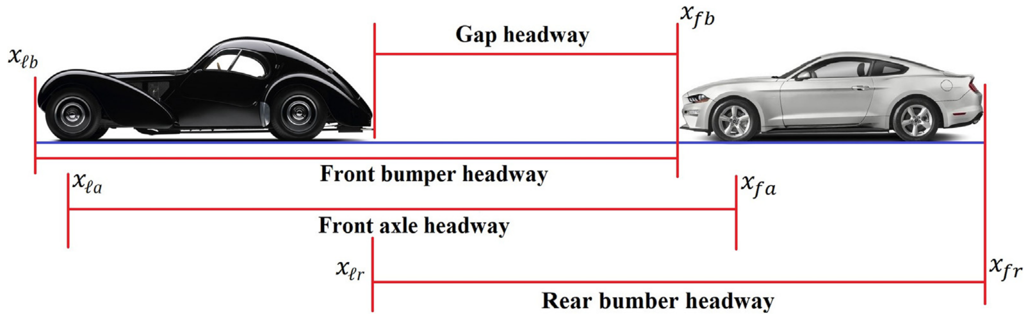

Fig. 2. Definitions of distance (or time) headway measured longitudinally between reference points x_{ij} for the vehicle order $i = ,f$(leading = , following = f), and vehicle reference points $j = b, a, r$ *(bumper = b, axle = a, rear = r).*

3.4. Headway definition by type of study

The included studies were categorised by four methods of headway measurement in Table 3, along with the proportion of studies where headway was clearly defined. Studies with inadequate information to reproduce their headway definition were considered unclear or undefined. This could be due to a lack of contextualisation of reference points of headway measure (e.g., bumper/axle/rear), a lack of explanation of the measurement accuracy of headway (e.g., whether adjusting the measure for vehicle length), or if it was unclear whether the measured distance adjusted for vehicle length, which were considered necessary for reproducibility.

Only 37.2% of simulation studies and half of the studies with on-vehicles features clearly defined headway. Other study designs had clearer headway definitions including 54.2% of roadside external features studies and 70.0% of studies using on-road features.

4. Discussion

The objective of this study was to systematically review and summarise the definitions of headway and the different approaches used to measure headway in studies that focused on driving behaviour and performance. A qualitative synthesis found considerable inconsistency in headway definitions and measurements. Over half of the reviewed studies failed to clearly define headway. Although simulation studies were expected to incorporate clear and systematic definitions, this study type had the lowest proportion of articles with clear, reproducible headway definitions. The results of this systematic review highlight serious issues for headway studies that may lead to a lack of clarity in interpreting their results.

This review identified three major issues with the current literature. First, many measures include the length of either the leading or following vehicle which adds noise or systematic bias to measuring headway. Second, the terms used for headway or the methods used to compute headway are highly inconsistent with differing reference points used, so it is often unclear what is being measured. Third, the accuracy of headway measuring devices was rarely considered. Each of these issues will be discussed in more depth below.

4.1. Vehicle lengths

The inclusion of vehicle length in headway introduces two biases: (a) it does not measure the actual distance between two vehicles, and (b) vehicle length on road varies over traffic fleets and adds error to the measure. For example, two of the bestselling passenger vehicles in Australia in 2019 were the Ford Ranger (length = 5.30 m) and the Hyundai i30 (4.34 m) (Chamber, 2020). If the 2-seconds rule of safe headway is considered (Michael et al., 2000), distances covered by a vehicle travelling at 60 km/h would be 33.33 m. The estimation method used for headway may not reflect the true gap between two vehicles if the headway measure was taken from the front of the lead vehicle, therefore not taking into account variable vehicle lengths. Thus, a 14% overestimation of headways (Ford Ranger 15.90% and Hyundai i30 13.02%) at 60 km/h would be observed in this case. The error would be even greater at slower speeds such as in congested traffic.

This issue is exacerbated when comparing studies where the distribution of vehicle lengths differs substantially. For example, 75% of the vehicles in New South Wales, Australia are passenger vehicles and the rest are campervans, light commercial vehicles and heavy trucks Australian Bureau of Statistics. (Australian Bureau of Statistics. (2019) (2019), 2019) (2019), 2019. The lengths of these vehicles vary considerably, so making headway measures that include them are highly variable and inaccurate. Moreover, heavy vehicles are more likely to be observed on highways compared to inner suburbs, so headway measures may vary depending on the location of the testing (Bontempo, Cunha, Botter, & Yoshizaki, 2014; Holguín-Veras, Amaya Leal, Sánchez-Diaz, Browne, & Wojtowicz, 2018). Headway measuring devices that add the length of the vehicles, and do not take account of different measuring reference points, creates a systematic bias making their mea-

Table 3
Distribution of articles for various types of headway measurement showing counts (percent) of studies in each category.

Measurement for headway	Headway definitions	Headway clearly defined n (%)	References
Simulation	43	16 (37.2)	Albert et al., 2018; Bella & D'Agostini, 2010; Dimitriou et al., 2018; Ding, Zhu, Wang, & Jiao, 2017; Fleming et al., 2019; Glendon, 2007; Gyou et al., 2013; He et al., 2014, 2018; Hofman et al., 2012; Jamson et al., 2005; Jeong & Liu, 2017; Jung et al., 2014; Kang et al., 2008; Kim et al., 2018; Leong et al., 2019; Li et al., 2011; Maltz et al., 1899; Mamdoohi et al., 2014; Mitra & Utsav, 2015; Molloy et al., 2018; Morita et al., 2006; Navarro et al., 2018; Ni et al., 2010; Peng et al., 2017; Pouyakian et al., 2013; Ramezani Khansari et al., 2018; Rosey et al., 2017; Seidowsky et al., 2007; Smith et al., 2015; Summala, 1980; Tan et al., 2019; Wada et al., 2007; Xu & Qu, 2014; Yang et al., 2017
Roadside external features	24	13 (54.2)	Al-Ghamdi, 2007; Ambros & Kyselý, 2016; Derbel et al., 2012; Ding et al., 2017; Figueira & Larocca, 2020; Fu et al., 2013; Horrey et al., 2006; Hourdos et al., 1968; Kusano et al., 2015; Leong & Muhammad, 2019; Lewis-Evans et al., 2010; Li & Chen, 2017; Li et al., 2015; Li et al., 2017; Michael et al., 2000; Moher et al., 2009; Mollu et al., 2018; Postans & Wilson, 1983*; Rosenbloom & Eldror, 2014; Schoemig et al., 2018; Stylianou & Dimitriou, 2016; Tscharn et al., 2018; Wang et al., 2011; Yan et al., 2018; Zhang et al., 2016
On-road features	20	14 (70.0)	Aron et al., 2015; Brackstone et al., 1999; Ding et al., 2017, 2019; Hajbabaie et al., 2011; Huang, 2019; Jeong & Liu, 2017; Jiang et al., 2018; Li et al., 2018, 2020; Limited, 2012; Mitra & Utsav, 2011; Moher et al., 2009; Radwan & Kalevela, 1985; Silvano et al., 2020; Taieb-Maimon & Shinar, 2001; Vogel, 2003
On-vehicle features	26	13 (50)	Aswad Mohammed et al., 2019; Bondallaz et al., 2016; Chen et al., 2010; Dimitriou et al., 2018; Dubart, Kassaagi, & Poppicul, 2008; Feenstra et al., 2008; Hainen et al., 2013; Horrey et al., 2006; Ivanco, 2017; Jehn & Turochy, 2019; Jung et al., 2011; Khaisongkram et al., 2011; Leong & Muhammad, 2019; McGehee et al., 1994; Risto & Martens, 2014; Shariff et al., 2016; Simons-Morton et al., 2005; Song & Wang, 2010; Tan et al., 2019; Tivesten & Dozza, 2015; Van Winsum & Heino, 1996; Veldstra et al., 2015; Von Buseck et al., 1980; Wu et al., 2011; Zhu et al., 2016
Total	113**	56 (49.6)	

* Measured headways manually using a stopwatch by an observer watching from a road bridge crossing (Postans & Wilson, 1983).
** These include studies (e.g., reviews and comparisons) that used multiple measurement techniques (in bold (Mitra & Utsav, 2011; Bella et al., 2014; Ding et al., 2018; Risto & Martens, 2014; Xie et al., 2018; Rosenbloom & Eldror, 2014; Luo et al., 2015) and excludes reviews (Brackstone & McDonald, 2007; Caird et al., 2014, 2018; Hutchinson, 2008).

surements inaccurate. Furthermore, even when adjustments for vehicle length are made, accuracy will continue to suffer when a 'typical' length correction value is used.

4.2. Headway terminology and reference points

This systematic review identified at least 7 non-equivalent terms used for headway in the research literature. Without a precise definition of headway, relative terms such as 'large/longer headway' (Pampel, Jamson, Hibberd, & Barnard, 2015), 'safe headway' (Horrey, Simons, Buschmann, & Zinter, 2006) and 'shortest headway' (Horrey & Simons, 2007) add to the confusion. For example, Summala (Summala, 1980) used 'short headway' to denote time headways of 1 s or less, whereas Mitra and Utsav (Mitra & Utsav, 2011) and Maltz et al. (Maltz, Sun, Wu, & Mourant, 1899) considered less than 2 s of headway as 'safe/short'. Similarly, definitions such as the 'elapsed time it takes for the following vehicle to reach the position of the lead vehicle' can be unclear if the vehicle reference points (e.g., front bumper/axle/rear bumper) are not indicated (Michael et al., 2000; Rosey et al., 2017).

4.3. Measuring devices

Device accuracy is important while estimating headway. Devices that rely on roadside features, such as video cameras, have inherent measurement errors, due to their position next to the road, manual headway calculation (e.g., from videos) or technical limitations (e.g., low frame rate in videos) (Ding et al., 2019; Jeong & Liu, 2017). Loop detectors, on the other hand, can be used to detect headways applying multiple reference points (e.g., front bumper/axle/bumper rear), which might create a different source of bias. That is, different reference points could lead to different headway measurements if any component of the vehicle length is not excluded from the headway measure. These accuracy errors are expected to reduce over device versions or models as new research emerges and more sophisticated products are released (Bertolazzi, Biral, Da Lio, Saroldi, & Tango, 2010). Nevertheless, this review found that very few studies reported the accuracy of measurement devices.

All 13 studies utilising on-vehicle features defined reference points for headways as the rear of the preceding vehicle to the front of the instrumented vehicle, which is an accurate headway definition, although terminologies varied (e.g., time gap or time headway) (Brackstone, Waterson, & McDonald, 2009; Leblanc et al., 2013; Li et al., 2011; Zhang et al., 2016). However, such devices have measurement error which needs to be clearly identified and details on reference points and technical design issues should be provided before a device can be considered reproducible, consistent and reliable (Limited, 2012). It is also unreasonable to expect readers to explore headway measuring methods from technical guides of these devices separately for each study.

4.4. Recommendations for headway reproducible definitions

The findings of this systematic review suggest that in driver behaviour studies, headway measured between the rear end of the lead vehicle and front end of the following vehicle (generally the front bumper) is the most accurate representation of headway. Both time and distance could be used as a measure provided the speeds of the vehicles are recorded, which will allow the transformation between time headway and distance headway and, if necessary, conversion to TTC using the equations discussed.

Mathematical statements and pictorial depictions that include all necessary components to clearly define headway should be used in future studies for reproducibility. From the reviewed articles and the results above, four recommendations are proposed. Firstly, vehicle length should not be included as part of headway measures. Devices that include vehicle or parts of vehicle lengths without adjusting for them are incorrect and introduce systematic bias. Secondly, when the vehicle length is included, the definition of headway should specify the reference points (e.g., front bumper/axle/rear bumper) of measurement, which could be presented as equations and/or diagrams. Thirdly, a consistent terminology for headway is crucial for reproducibility and comparisons across studies. Fourthly, the accuracy of headway measuring devices should be reported alongside the device type and version number to inform the precision of a study's findings.

5. Conclusions

This systematic review identified 110 studies of driver behaviour that report on measuring vehicle headway. Despite the existence of standard definitions from traffic engineering, the definition and terminology for headway were largely inconsistent across all studies. Less than half of the included studies did not clearly define headway, contextualise reference points (e.g., bumper/axle/rear) for headway quantification, or report on the accuracy of measuring devices. To improve our understanding of vehicle headways and their role as a causal factor of crashes, it is recommended that future driver behaviour studies use standard methodology and terminology for headway and be transparent in reporting to improve reproducibility and comparisons across studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethical standards

No primary data were used in this study. All information was extracted from published material.

Author contribution

RK Biswas conceptualised the study, reviewed literature, synthesised the analysis plan, compiled data and drafted the manuscript. R Friswell reviewed literature, compiled data and edited the manuscript. J Olivier and A Williamson critically reviewed and revised the manuscript. T Senserrick conceptualised the study and critically reviewed the manuscript. All authors read and approved the final manuscript.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2020.12.011.

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