Australasian Transport Research Forum 2023 Proceedings
29 November – 1 December, Perth, Australia
Publication website: http://www.atrf.info

Best practice exposure reduction measures for working in high-speed traffic environments

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Abstract

Live traffic places workers at risk on roads and roadsides during maintenance, repairs, incident response, and road and roadside inspections. The risks associated with such work are generally greater on roads with high traffic speeds and volumes. Despite many research studies on understanding work zone risks, some significant gaps remain in the literature, including a lack of attention to different work activities when identifying best practice, and a focus on traffic management and positive protection which overlooks other exposure reduction strategies. To address these gaps, this paper aims to identify the best practices to reduce exposure of workers to traffic and traffic-related incidents in high-speed road environments by considering different application or activity areas, including temporary traffic management, work methods, and asset inspection activities. This aim was achieved by undertaking a review of the literature, consultations with international experts and industry personnel, and interviews with workers for a case study on one of Australia's busiest motorways, the M1, on the NSW Central Coast. Results showed that, from a risk reduction perspective, the best solutions reduce exposure by removing the need for workers to be on the road. As this is often unachievable, best practice measures to reduce workers' exposure to traffic and related incidents include a range of technological and traffic control solutions, some of which represent recent industry innovations (e.g., smart motorway systems, automated cone trucks, mobile vehicle-based asset inspection). These results provide useful insights for responsible agencies managing worker risk at high-speed roads and roadsides.

1. Introduction

Works on roads and roadsides, including maintenance, incident response and asset inspection, pose significant risks to workers and motorists alike. Although safety issues vary somewhat for different types of works and road environments, there is broad consensus that risks to workers are greatest where they are exposed to live traffic on high-speed, high-volume roads. Research to identify these risks and potential countermeasures has been conducted in Australia (e.g., Debnath et al., 2015) and the United States (e.g., Theiss and Ullman, 2019) using surveys, consultations, and analysis of incident data. Previous research has highlighted the difficulty of obtaining accurate data on work zone crashes and traffic-related injuries in Australia (Blackman et al., 2020), however, recent research (McClure et al., 2023) showed that crash rates during roadworks on high speed roads could be around 30 crashes per 100 million vehicle kilometres travelled for some roads.

A wide range of measures are used to reduce or eliminate these risks, including static and electronic signage, physical traffic control devices, and enforcement and educational measures. Despite having such measures, the need for reduction in exposure of workers remains a critical

issue for many jurisdictions, and therefore, many measures are being developed for this purpose across the world (see Debnath et al., 2012 and Nnaji et al., 2020 for review of the relevant safety measures). While the impacts of these developments on improving the safety at work zones have been the subject of considerable amount of research across many jurisdictions, there is limited understanding available in the literature on the best practices to reduce exposure of roadworkers.

A review of the literature also revealed some other important gaps in highway work zone safety research. One such gap is a lack of attention to different work activities when examining and identifying best practice controls and strategies for work zones. Another is a general focus on temporary traffic management and positive protection which overlooks other means by which traffic and incident exposure reduction might be achieved to protect workers. Further, some new and innovative measures have not yet been formally trialled or evaluated so are absent from the published literature.

To address these gaps, this paper aims to identify the best practices to reduce exposure of workers to traffic and traffic-related incidents in high-speed road environments by considering different application or activity areas, including temporary traffic management, work methods, and asset inspection activities. The paper draws on a broad and diverse range of data and information sources for the holistic identification of best practice for reducing worker exposure to live traffic. The M1 Motorway section connecting Sydney and Newcastle on the NSW Central Coast, carrying up to three lanes of traffic on dual carriageway at up to 110km/h for approximately 129km, was used as a case study to achieve the aims.

2. Methods and approach

To identify the best practices, a multi-step methodology was developed and included the following elements:

i. Review of the literature
ii. Consultations with experts from international jurisdictions
iii. Consultations with industry
iv. Interviews with workers
v. Review of background materials for the case study road section

Deakin University Ethics Approval was obtained for all three consultation and interview stages (reference number SEBE-2022-48).

2.1. Literature review

A comprehensive review of the literature was undertaken to identify the best practices and technological solutions for reducing or eliminating the risks to workers, including but not limited to exposure reduction measures. The scope of the review included works in the areas of structural and roadside inspections, temporary traffic control measures and alternative ways of conducting short-term roadworks or maintenance activities.

The review was international in scope to ensure capture of all relevant materials. Studies were assessed based on their methodological rigour, and relevance to the study area, to ensure empirically sound conclusions. Academic journal publications (peer reviewed), conference papers, government, and non-government (e.g., industry) reports were examined, and findings documented.

2.2. International expert consultations

The researchers consulted international work zone safety experts from the USA (n=5) and Europe (n=1) regarding (a) their understanding of work zone risks and hazards in their respective jurisdictions, and (b) best practices and controls, including emerging and innovative measures. Six individual semi-structured interviews of approximately 45-60 minutes duration each were held via a mutually agreed online platform. International experts were recruited directly through email invitation, on inclusion criteria of recognised high-level expertise and ongoing activity in the field of work zone safety research. Participant selection focused predominantly on the USA due to the relatively large amount of work zone safety research there and the predominance of published trials and evaluations in the country.

2.3. Industry consultations

To complement the international expert consultations, representatives of organisations supplying roadwork traffic control and roadway maintenance technologies were also consulted (n=5). Participants were identified through a combination of internet search and/or reference to the representative organisation by the industry partner of this study, TfNSW. Similar to the expert consultations, a semi-structured interview format was used to run these consultations in a virtual platform, for a duration of approximately 45 minutes each. The industry representatives were invited to share their knowledge, perceptions and experiences and provide any materials they believe to be relevant to the project, such as technical reports, technology specifications, product approvals and related documents.

2.4. Interviews with workers

Twelve semi-structured group interviews of around one hour duration were held with roadworkers, managers, traffic controllers, and incident response staff to understand the current risks and practices associated with temporary traffic management and related activities. Participants were recruited directly by the industry partner of this study, TfNSW, who provided in-person introduction to the researchers on site at maintenance depots. Two interviews were held online. Across the 12 interviews conducted, the 44 participants were asked to share their experiences, knowledge and perceptions regarding the M1 work environment and related hazards and controls.

Interview transcripts were processed in NVivo software and information from all groups was coded into four main categories including: M1 Environment, Incidents, Hazards, and Controls. These categories were developed through a deductive reasoning process to provide the overarching structure for thematic analysis.

2.5. Review of background materials

To identify best practices and technologies, it was important to understand and document activities, risks and work practices in the context of the case study location. This was enabled through the provision by TfNSW of background materials relating to M1 environmental characteristics, work activities, and controls and risk mitigation strategies currently in place or planned for future implementation. Complementing the review of background materials, virtual site visits to M1 sections were conducted using Google Maps and Google Earth to enhance contextual understanding of the road section.

3. Results

Outcomes of the 5 phases of the research methodology provided insights on measures to reduce the exposure of workers to traffic and incidents. Findings obtained on these measures, as well as those relevant for the case study of M1, are presented in the subsequent sections.

3.1. Reducing exposure to traffic

Exposure to the risks of working near traffic can be reduced if work activities are able to be performed more efficiently, less frequently and/or with a greater level of automation. This includes exposure reduction through measures that allow individual tasks and activities to be completed faster, and through planning and coordination whereby multiple tasks can be completed together in more instances (sometimes referred to as 'clustering'). Both strategies were supported by workers interviewed for the current project.

Increased crossovers and turnaround points were generally supported by incident responders and maintenance crews during worker interviews as a means to reduce exposure to traffic and related risks by allowing tasks to be completed in shorter timeframes. This was not identified in the search of literature on work zone exposure reduction measures but was discussed with international experts as a relevant issue. Consultation with one expert suggested that the longest distance between interchange points on highways in the USA is approximately 14km, with at least one turnaround point midway on such sections, so roughly every 7-8km. Crossover and turnaround opportunities are currently fewer and further between on the M1 according to the current research. Acknowledging the utility of turnaround facilities and the potential safety benefits, international expert consultation suggested that public use of such turnarounds is also concern due to the potential for this to disrupt traffic flows and generate traffic conflicts. As such, consideration needs to be given to balancing improved worker mobility with appropriate restriction of public access.

Relevant tools were mentioned that could allow works to be completed faster, reduce personnel and/or reduce the need for workers to leave a vehicle, such as vacuum trucks for clearing pits and drains, sweeper trucks, pothole trucks, and other more efficient machinery. Searches conducted for the current project on roadway maintenance methods and technologies identified a range of commercial products but relatively little in terms of research covering formal assessment and evaluation of safety effects. One exception is Valdez-Vasquez et al. (2014), which identifies relevant innovative equipment including high-speed debris removal systems for US highways. This research also identified a lack of independent traffic and safety impact evaluations and recommended the development of appropriate guidelines and further research in this area. Similarly for pavement surface repair, Torbaghan et al. (2020) reported promising results regarding robotic technology for pavement crack sealing with 3D printing techniques, but the broader conclusion from the study recommended a review of current practices and further research and development. One international expert noted current work in California on automated vehicles and systems for surface repair and (potentially) other works, but detail on these developments was not available at the time of consultation. Another expert also noted that automated works vehicles (e.g., pothole repair truck) may not do as good a job as completing this work manually, but this could not be confirmed.

Vehicles with systems for automated deployment of traffic cones and other devices were discussed with the international experts consulted, and the use of automated cone trucks had been observed in Ireland as well as on some highways in the USA. However, no published literature or evaluations of those automated cone trucks were found in the current research. In Australia, a new commercially available automated cone truck has recently received a Victorian State award for innovation (MTIA Director General's Health and Safety Innovation

Award, 2022). Development and capabilities of this truck were discussed during industry consultation with the supplier who has engaged multiple state transport departments in promotion of the product. Key features of the product are single driver operation, automated deployment and retrieval, and 400 cone capacity, suggesting substantial exposure reduction potential. An earlier version of an automated cone truck which had been briefly trialled in the case study location was discussed during worker interviews. This was reportedly associated with technical problems, to the extent that no net benefit was perceived to result from its use. Conversely, a more traditional pod truck as used by some contractors was perceived to be useful for laying out cones in relatively quick time. However, relying on a person harnessed at the rear of the pod truck was also noted as risky due to potential for rear-end impacts in which a worker may be severely injured.

There is considerable research literature on new and emerging technologies for road asset inspection which can reduce or in some cases eliminate exposure to traffic. These include Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGVs), radar, LiDAR (light detection and ranging) and other sensor types, cameras, data logging, Artificial Intelligence (AI) and machine learning, among others. Research by Pritchard et al. (2018) suggests that a combination of visual and sensor-based techniques, including the use of UAVs, is suitable for geotechnical asset management. While such techniques are generally costly, and some are limited in terms of capability, safety, efficiency, and resilience, exposure reduction benefits of the approach may be substantial. The range of relatively new road-based services and tools currently available can facilitate more efficient and safer inspection of road-related assets than afforded by traditional methods of manual inspection.

Some example asset inspection tools and services were found to be available in Australia, where an industry representative was consulted about road-based asset inspection using AI and video recordings captured by vehicle-integrated mobile phone. The system discussed was reportedly able to capture up to 20 different road and road-adjacent defect types across three traffic lanes in a single pass. The claimed accuracy of approximately 80 percent of defects captured was said to be constantly improving. Accuracy is reportedly not affected by vehicle speed, although was apparently limited during night time conditions. It is important to note that formal independent evaluations of such systems and their potential safety benefits were not found in the literature. However, pending formal trials and evaluations, these technologies have significant potential to reduce the exposure of workers to traffic and incidents.

Use of drones was said by international experts to be increasingly common in the US for inspection of some road-related assets, as well as for accident reconstruction and investigation. This is also occurring in Australia, with bridge and related infrastructure inspection discussed in consultation with a local industry expert. There is future potential to complement currently used video data with LiDAR technology and associated data. Through 3D modelling facilitated by LiDAR data, the potential for virtual inspections using 360-degree imaging may be realised in the foreseeable future. Use of a drone-mounted AI framework for road asset inspection is examined in Mohan et al. (2021). This is an experimental study tested accuracy of the system regarding 14 asset classes, which were reduced to 12 classes following initial tests and analysis. Asset classes included guardrails and delineators, pavement markers, paved shoulders, vegetation, debris, drains, signs, ditches, and rigid and flexible pavements, among others. Test results demonstrated 81 percent overall accuracy, with specific accuracy differing according to asset class.

3.2. Reducing exposure to incidents

Truck-mounted attenuators (TMAs) have become a standard work zone feature in high-speed traffic environments over recent decades. TMAs are typically used in situations where full road

closure is not feasible but lane closure with positive protection is required (Birenbaum et al., 2009; Pourfalatoun and Miller, 2021). Their effectiveness in preventing work zone intrusions and reducing incident severity is well demonstrated in the research literature. Discussing TMAs with traffic controllers, maintenance workers, and incident responders, views were varied on the appropriate number of TMAs to use and the ways in which to best use them (depending somewhat on operational requirements). The limited availability of skilled and qualified TMA operators was also noted as problematic in some instances.

Mobile barrier trucks (Figure 1) are a relatively new control used in work zones for positive protection, initial trials of which were being undertaken in the case study location during the current research period. These devices were discussed with international experts and in worker interviews (participants did not have direct experience with the new barrier truck). An expert based in Sweden revealed that while he was aware of the devices, they had not been approved for use on European roadways due to the difficulty of manoeuvring the large trailer (which constitutes the barrier itself) and the associated transportation issues. These and other deployment issues are discussed in Kamga and Washington (2009). Among experts based in the USA, it was noted that some crews or individual workers may be reluctant at first to use or work with the barrier truck, and this was thought to be largely due to unfamiliarity with the device. Reportedly this reluctance can be overcome with persistence, as acceptance was expected to increase with familiarity, and this view was also supported as a general observation by industry consultants. Among workers, the mobile barrier truck was seen to have both positive and negative aspects, including limited scope for use.

Figure 1: MBT-1 mobile barrier truck (source: Mobile Barriers, 2023)

Recent trials involving autonomous TMAs (ATMAs) were discussed with international experts based in the USA where trials were currently in progress. Findings of a trial in Colorado and California were reported in Porfalatoun and Miller (2021). While the ATMA was accepted positively overall, issues around trust in the technology were identified. Higher levels of trust appeared to result from greater familiarity and experience with the technology. A trial was also conducted and completed in Tennessee, as reported in Khols (2021). While positive safety effects were acknowledged, the need for further research, development and refinement was also reported.

New Zealand has adopted the use of TMAs with ‘outriggers’, which consist of retractable devices to facilitate multiple lane closure with a single TMA (up to 3 lanes). Attached to either side of a TMA host vehicle, the outrigger devices consist of high visibility panels with

markings, warning lights and signage (Figure 2). The outriggers extend from either side of the rear of the host vehicle across adjacent lanes, and may be used for incident response as well as planned short term and mobile operations. Aside from description in New Zealand's Road Incident Management (RIM) Guide (Waka Kotahi NZ Transport Agency 2021) and Code of Practice for Temporary Traffic Management (CoPTTM) (Waka Kotahi NZ Transport Agency, 2018), the use of outriggers in conjunction with TMAs has not been identified in the literature and no published evaluations have been found to date. International experts also expressed no knowledge of this innovation. However, consultation with a New Zealand industry representative revealed apparent potential to extend the utility of TMA resources and achieve greater efficiency using these devices.

Figure 2: TMA host vehicle with outriggers deployed (source: Waka Kotahi NZ Transport Agency, 2021)

The task of shifting longitudinal barriers laterally across lanes can be completed with a specialised barrier shifting truck and connected barrier system according to international expert consultation. This technology avoids the need for workers to be on the roadway unprotected and allows the task of moving barriers to be completed relatively quickly. While one expert expressed that barrier deployment by truck is generally expensive, another referenced the specific barrier shifting system which may lower costs as well as risk after initial outlay (Figure 3). Although this innovation shows substantial exposure reduction potential, no published literature or product information was found in the current research.

Figure 3: Barrier shifting truck on European motorway (source: Varhelyi, 2019)

3.3. Case study environment and characteristics

The current section provides a summary of the findings in relation to the M1 case study area, obtained through a review of background materials sourced from TfNSW, including documents related to operations, traffic management, risk assessment, incident investigation, and training and induction processes. At a high level, the Draft Central Coast Regional Transport Plan 2041 (TfNSW, 2022a) covers the M1 as the primary road link in the Central Coast Region. Among the key Objectives of the Plan, seven have direct relevance to M1 safety and performance for workers and motorists alike, including:

- Provide efficient, reliable, comfortable and safe connectivity between Central Coast, Greater Sydney and Newcastle
- Proactively address road safety deficiencies and high-risk sections on the road network and address crash clusters across the Central Coast
- Improve safety outcomes with the use of technology
- Enable and support successful places to live, work, and visit
- Improve travel information and legibility
- Build greater resilience into the transport network
- Utilise technology to communicate and respond to network disruptions

The objective to *Improve safety outcomes with the use of technology* specifically references the M1 Smart Motorway project and the delivery of 'smart infrastructure to reduce the impact of human error' (p.40). This is expected and provide for efficient, timely and safer speed limit reductions when needed, and to improve incident response, as demonstrated on existing smart motorways. Variable speed limits (VSL) are an integral part of smart motorway systems and can be applied to planned works as well as incident response to achieve overall safety improvements. As such, the use of information technology and related systems can be considered vital for maximising worker safety improvement. While arguably having limited impact in terms of reducing exposure to traffic, this can nevertheless reduce worker exposure to traffic-related incidents.

The identified work tasks and activities generally reflect those undertaken on other major motorways and highways in Australia. However, due to some specific environmental and transport-related characteristics, the frequency and challenges associated with some of the activities may differ somewhat from those on otherwise comparable roadways. A list of approximately 100 specific activities undertaken in six different work categories was provided to the researchers by TfNSW. These activities have been condensed into 27 groups for presentation in Table 1.

According to interview with workers, the M1 presents numerous specific hazards associated with the natural environment, such as steep hills, large river crossings, deep cuttings, blind corners, as well as weather and drainage issues. In the background materials provided to the researchers, hazards related specifically to traffic and work activities were documented for the period July 2018 – September 2021. These included observation of excessive queue lengths at worksites, traffic control irregularities (e.g., missing or fallen signs) and traffic guidance scheme departures, site and facility access problems, slips, trips and falls, errant vehicles and pedestrians, work zone intrusions, and manual handling accidents, among others. Reported incident occurrences included a similarly diverse range of incidents, but also included a considerable number of vehicle and plant collisions and near misses.

Table 1: M1 tasks and activities

Activity group	Traffic proximity
Abandoned vehicles	On-road and shoulder
Advertising removal	Shoulder and adjacent land
Asset inspection	On-road, shoulder and adjacent land
Animals (dead)	On-road, shoulder and adjacent land
Animals (live, herding)	On-road, shoulder and adjacent land
Batters	Shoulder and adjacent land
Bridges and gantries	On-road, shoulder and adjacent land
Cameras (speed)	Shoulder and adjacent land
Drainage, culverts and pits	Shoulder and adjacent land
Fences	Shoulder and adjacent land
Flooding	On-road, shoulder and adjacent land
Graffiti removal	On-road, shoulder and adjacent land
Guardrails/barriers	Shoulder and adjacent land
Guideposts	Shoulder and adjacent land
Incident response	On-road, shoulder and adjacent land
Linemarking and delineation	On-road and shoulder
Litter, rubbish, debris	On-road, shoulder and adjacent land
Pavement and surface	On-road and shoulder
Phones (emergency)	Shoulder
Rest area maintenance	Shoulder and adjacent land
Rocks (removal and secure)	Shoulder and adjacent land
Signs, VMS and lighting	Shoulder and adjacent land
Shutters	Shoulder and adjacent land
Spills and slips (oil, rocks etc.)	On-road and shoulder
Surveying	Shoulder and adjacent land
Traffic control	On-road, shoulder and adjacent land
Vegetation management	Shoulder and adjacent land

The review of background materials confirmed that the M1 is a high-risk workplace for which a wide range of rigorous guidelines, protocols, procedures, administrative and other controls have been developed, demonstrating a proactive approach on the part of the relevant road authority. Training and induction materials appear to comprehensively address all common highway work zone hazards, and specifically highlight those requiring emphasis or focus in the M1 context. The Traffic Control at Worksites (TCAWS) Manual 6.1 was released in 2022, following previous update in 2020, and includes amendments reflecting the most recent applicable changes to temporary traffic management practice in NSW (TfNSW, 2022b).

3.4. Best practices for application areas

Findings from the literature review and expert and industry consultations identified many innovative and promising approaches to temporary traffic management (TTM) and related work activities, as well as effective traditional measures. As recognised in the TCAWS Manual (TfNSW, 2022a) and comparable guidelines, from a risk reduction perspective, the most promising solutions reduce exposure by separating traffic from the work area and/or removing the need for workers to be on the road, including for road asset inspections. As complete separation of traffic from the work area through diversion to alternative routes is often not feasible for motorway operations, the current paper focused on measures to remove workers from the road and/or provide appropriate positive protection to reduce exposure to incidents.

The identification of best practice and selection of potential solutions was based on three key criteria (*need*, *effectiveness*, and *feasibility*) referencing the various data sources identified at the beginning of Section 2. The anticipated *effectiveness* of specific measures was informed mostly by (i) the review of literature and (ii) international expert consultations, with additional input from (iii) industry consultations and (iv) worker interviews. The *need* for specific measures, and their *feasibility*, to address identified problem areas was drawn from (v) the review of background materials and (iv) worker interviews. The inclusion of some measures for which objective and rigorous evaluations were lacking was based on all data sources, but drew most heavily on (ii) international expert consultations and (iii) industry consultations. The measures were not ranked, as such, due to each targeting different specific risk factors and activity areas.

Solutions identified as representing best practice and/or for future consideration in the context of the case study area are summarised below in Table 2 and described in further detail thereafter. Note that these are presented in order of Application area and are not prioritised in terms of importance, estimated effects, feasibility, availability, cost or other criteria. According to the current project, some of the solutions identified are demonstrably effective in providing positive protection and reducing worker exposure to traffic if appropriately implemented. However, their effectiveness and feasibility for implementation will inevitably depend on a range of specific operational requirements, costs, environmental characteristics, and design and construction features, among other factors. These measures include increased crossovers and turnaround points, removal of redundant assets, coordinating works to improve efficiency, vehicle-based positive protection, automated vehicle systems, and vehicle-based asset inspection services.

Other potential solutions appear promising but are either yet to be rigorously evaluated, are still in a development stage, or are not currently available or approved in Australia. These measures include TMA outriggers, barrier shifting trucks, and drones for road asset inspection and incident assessment (current restrictions limit application).

Table 2: Solutions to reduce exposure by application area

Exposure reduction and positive protection measures	Application area		
	TTM	Work methods	Asset inspection
Automated cone truck	✓		
Mobile barrier truck	✓		
TMA outrigger	✓		
Barrier shifting truck	✓		
Increased crossovers and turnaround points	✓	✓	
Planning and coordination (e.g., clustering)	✓	✓	
Automated pavement repair trucks		✓	
Debris removal vehicles (vacuum and sweeper truck)		✓	
Removal of redundant assets		✓	✓
In vehicle Geospatial video, AI (pavement)			✓
In vehicle HD imagery, stills (pavement)			✓
In vehicle Video, sensors (pavement and adjacent assets)			✓
Drone: Video, possible LiDAR 3D models			✓
Smart motorway systems	✓	✓	✓

Smart motorway systems

Some innovative approaches which may generate worker safety improvement are aimed more broadly at general traffic safety and are largely underpinned and driven by new and emerging technologies and related systems. Smart motorway systems emerge as a basis for many of these improvements and may reduce the occurrence of incidents and therefore incident exposure through improved driver compliance and awareness. According to experts consulted, such systems are currently realised sporadically across traffic networks in the USA and Europe but are clearly increasing in coverage and are well supported. The Draft Central Coast Regional Transport Plan 2041 (TfNSW, 2022a) indicates the current direction in terms of technological enhancement, from which workers and motorists alike will benefit on the M1 and comparable roadways. This is a broad and multifaceted approach which can impact positively on all application areas and differs conceptually from the specific measures identified in the current paper.

Automated cone truck

For temporary traffic management, trial of new commercially available automated cone trucks is supported to potentially reduce worker exposure to traffic and incidents by reducing the need for them to be on the road. The current research identified that automated cone trucks have previously been developed and trialled, but their effectiveness has been limited by technical and operational problems. A new commercially available product may provide improved outcomes, having recently received a Victorian award for innovation, and should be considered for trial and evaluation. While worker resistance to new technologies and systems such as automated cone trucks can be a potential issue, such resistance can be overcome with sufficient training and experience with the use of the systems.

Mobile barrier truck

There is recognised potential for mobile barrier trucks to reduce worker exposure to traffic and incidents in some planned works through provision of a protective steel barrier, supported by an approved impact attenuation device (these are not considered suitable for incident response due to limited manoeuvrability). Consideration should be given to ways in which use of the barrier truck can be made more practical and feasible, such as increasing turnaround options for example. Acknowledging the high cost, additional burdens on traffic control contractors, and potential risks identified through feedback, the barrier truck is likely suited to a limited range of scenarios and activities. Opportunities should be further examined through rigorous cost-benefit analyses for specific applications.

TMA outrigger

With the ability to quickly close multiple lanes with a single attenuator vehicle and without workers on foot, the TMA outrigger has incident exposure reduction potential and warrants strong consideration and further consultation pursued with New Zealand stakeholders. For some tasks, the need for multiple TMAs may be reduced to one through use of the outrigger device. This represents a relatively accessible and affordable innovation which can be retrofitted to existing host vehicles and may be suitable for planned works as well as incident response.

Barrier shifting truck

The potential of barrier shifting trucks identified as being used in Europe for exposure reduction should be further explored as the shifting of heavy barriers is a traditionally intensive exercise. The technology has potential to remove multiple workers from the roadway and to enable more efficient barrier movement and relocation. This is not currently available in

Australia and more information is needed in the absence of published evaluations. It is expected that this exposure reduction solution would only be appropriate for medium- to long-term planned works.

Increased crossovers and turnaround points

Increased provision of and access to crossovers and turnaround points is likely to reduce travel times to, from and between work sites, for incident response, planned works and asset inspection alike. This would reduce exposure to traffic and allow works to be completed with greater efficiency, while potentially allowing more timely incident response in some cases. Worker fatigue may also be reduced as a result of less time on road.

Planning and coordination (e.g., clustering)

Appropriate planning and coordination of operations can allow some works to be completed with greater efficiency, particularly for very short duration and mobile works. Workers themselves may need to spend less time on the roadway and adjacent areas, while traffic control requirements and activities can also expect to be reduced. M1 workers indicated that such 'clustering' of different activities could be achieved more regularly, thereby reducing exposure to traffic and related incidents.

Automated pavement repair trucks

A range of technologies, including 3D printing, are available for automated minor pavement repair such as pothole and crack filling, allowing such works to be completed more efficiently and quickly without requiring workers to exit the vehicle in many instances. While further investigation is needed to identify and confirm the availability of relevant products, the current research supports trial and evaluation of the most promising options to reduce worker exposure to traffic and related incidents.

Debris removal vehicles (vacuum and sweeper truck)

Trial of new vehicle-based tools and technologies for debris removal and drainage maintenance is supported and may include vacuum trucks for clearing drains and scuppers, and sweeper trucks and related accessories. Further exploration is required as sufficient evaluations of relevant equipment and products were not discovered in the review of literature. Depending on the type of vehicle and its capabilities, this is applicable to planned maintenance as well as incident response, and can substantially reduce the need for workers to be on the road unprotected.

Removal of redundant assets

The removal of redundant assets can be supported to reduce maintenance requirements and, subsequently, worker exposure to risks and hazards. Roadside shutters were mentioned by workers as one such example of a redundant asset, but a review of relevant assets is necessary to identify all of those which are no longer needed or in use. Reduced maintenance requirements can be expected to result in workers having to spend less time on the road, both inside and outside of vehicles.

Asset inspection services

A range of asset inspection services and technologies was identified as part of this project, as listed above in Table 2. Some such asset inspection services and technologies are currently being used and/or trialled in Australian jurisdictions. All show potential to achieve the objective of reducing worker exposure to traffic to some degree. Specific expertise can and should be harnessed for further exploration, with detailed objectives specified for asset inspection and management outcomes.

4. Conclusions

This research examined best practice measures for reducing worker exposure to traffic and traffic-related incidents on high-speed roads. The M1 Motorway in NSW provided a valuable case study and contextual foundation for framing the research and highlighted the importance of understanding local conditions and related needs. It was broadly conveyed in background materials and worker interviews that the M1 is a somewhat unique environment from a traffic management and incident response perspective, differing from other motorways in terms of geographic and topographic characteristics, roadway infrastructure, road user mix, and associated challenges. Nonetheless, the research findings can in many ways be considered transferrable to other high-speed work zone environments. This transferability is supported by findings from the international expert and industry consultations undertaken as part of the project, which crucially helped to identify best practice including new and emerging technologies and approaches which are in some cases absent from the existing literature.

While research examining work zone safety measures to reduce worker exposure is plentiful, the current paper extended identification of best practice measures to different work and activity types, including temporary traffic management, work methods, and asset inspection. Although different solutions were in some cases identified for different types of activity, it is broadly concluded that substantial safety improvement potential can be realised by harnessing technologically innovative products and systems. Enhanced management practices in terms of planning, coordination, and support for trial and evaluation of promising alternative approaches, can also assist in reducing the exposure of workers to traffic and traffic-related hazards.

Acknowledgements

This research was funded by iMOVE CRC, Transport for New South Wales (TfNSW), and Deakin University, and supported by the Cooperative Research Centres program, an Australian Government initiative.

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