Improving Road Worker Safety on the M1

iMOVE Project 1-055

Final Report

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EXECUTIVE SUMMARY

Background and context

The M1 Pacific Motorway connects northern Sydney with the regional city of Newcastle on Australia's east coast, carrying up to three lanes of traffic in each direction over a length of approximately 129km. The M1 is subject to a range of activities that place workers at risk in a live traffic environment, including, maintenance, repairs, incident response, and road and roadside inspections. To improve worker safety, Transport for New South Wales (TfNSW) sought to investigate crash and injury reduction measures, including alternative and innovative methods for the M1 section. In partnerships with TfNSW and iMOVE, Deakin University undertook research activities aimed at achieving the objectives of TfNSW.

Aims, Objectives and Scope

Primary aims of the project were to (1) identify current technologies and innovative work methods for reducing risk associated with M1 operations, and (2) recommend technologies and practices targeting safety improvement for potential future trials.

The recommendations were targeted to achieve three outcomes: (1) remove or reduce the need for workers to be on the road, (2) reduce worker exposure to incidents and minimise incident severity, and (3) ensure control measure effectiveness and ease of use.

Methodology

The project methodology includes five phases:

- Phase 1: Inception, planning, and methodology development
- Phase 2: Understanding work practices and current risks
- Phase 3: Identification of best practices and technologies
- Phase 4: Options analysis and recommendations
- Phase 5: Reporting

At a high level, the project involved a review of the literature and the background materials provided by TfNSW, interviews with workers, consultations with international experts and industry representatives, and options analysis to develop recommendations for future trial. In addition to regularly working with representatives of TfNSW, feedback from TfNSW on an interim report (Deliverable 3 of this project) was obtained which are incorporated in this Final report.

Key findings

The M1 is a high risk workplace for which a wide range of rigorous guidelines, protocols, procedures, administrative and other controls have been developed. 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. Interviews with workers including traffic controllers, maintenance crews, incident

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responders and works managers revealed numerous problems, many of which can be addressed at the technical and/or management level to achieve safety improvement.

Findings from the literature review and the expert and industry consultations identified many innovative and promising safety and alternative work approaches. Some of these are demonstrably effective, while others are yet to be rigorously evaluated or are still in a development stage. These approaches are largely (though not entirely) underpinned and driven by new and emerging technologies and related systems. Smart motorway systems emerge as a basis for many of these improvements. Specific measures were included in the options analysis based on projected outcomes to inform recommendations as follows.

Recommendations

Recommendations are provided for future considerations and trials separately for three application areas: (1) temporary traffic management, (2) alternative work methods, and (3) asset inspection. The recommendations are identified as applicable to planned works (PW), incident response (IR), or both. Note that the recommendations are provided as general recommendations for the M1 section, without making considerations for specific work or site setup, including the location, timing, and context of setting up the solutions noted in the recommendations. In future trials and use, it is strongly suggested that risk assessments, traffic guidance scheme developments, and other relevant approvals are considered before implementing the recommendations on site.

Traffic management solutions	**Planned works**	**Incident response**
Increase variable message signs (VMS) use	Yes	Yes
Variable speed limits	Yes	Yes
Speed feedback and vehicle-activated warning signs	Yes	-
Speed cameras	Yes	-
Increase police presence	Yes	Yes
Automated cone truck	Yes	-
Mobile barrier truck (MBT-1)	Yes	-
Queue warning systems	-	Yes
Errant vehicle warnings	Yes	-
Sequential lighting (traffic guidance)	Yes	Yes
Increase CCTV monitoring (incident monitoring)	-	Yes
Work methods solutions		
Automatic pavement repair truck	Yes	-
Debris removal vehicles & accessories (vacuum & sweeper truck)	Yes	Yes
Increase crossovers/turnarounds	Yes	-
Planning and coordination (e.g., clumping)	Yes	-
Provision of sufficient shoulder width	Yes	Yes
Incident Response Vehicle design and configuration	-	Yes
Remove redundant assets (e.g., shutters)	Yes	-
Asset inspection solutions		
In vehicle Geospatial video, AI (pavement)	NA	NA
In vehicle HD imagery, stills (pavement)	NA	NA
In vehicle Video, sensors (pavement & adjacent assets)	NA	NA
Drone: Video, possible LiDAR 3D models	NA	NA

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LIST OF ABBREVIATIONS

Acronym/Abbreviation	Definition
ATMA	Automated truck-mounted attenuator
CCTV	Closed circuit television
CMS	Changeable message sign
DAS	Driver Aid Services
DOT	Department of Transport
EOQ	End of queue
FHWA	US Federal Highway Administration
IAU	Impact attenuator unit
IM	Incident management
iRAP	International Road Assessment Programme
IRS	Incident response service
IRV	Incident response vehicle
LiDAR	Light detection and ranging
MASH	Manual for Assessing Safety Hardware
MBT-1	Mobile barrier trailer/truck
MUTCD	Manual of Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
NRMA	National Roads and Motorists' Association
PPE	Personal protective equipment
QWS	Queue warning system
SAS	Speed=activated sign
TEP	Traffic emergency patrol
TfNSW	Transport for New South Wales
TGS	Traffic Guidance Scheme
TIM	Traffic incident management
TMA	Truck-mounted attenuator
TMC	Traffic Management Centre
TOC	Transport Operations Centre
TPRS	Temporary portable rumble strip
TRUM	Traffic and Road Use Management manual
TTC	Temporary traffic control
TTD/TTA	Tow Truck Drivers and Attendants
TTM	Temporary traffic management
UAV	Unmanned aerial vehicle
UHF	Ultra-high frequency
US	United States
VAS	Vehicle-activated sign
VMA	Vehicle-mounted attenuator
VMS	Variable message sign

1 INTRODUCTION

1.1 Project context

The M1 Pacific Motorway connects northern Sydney with the regional city of Newcastle on Australia's east coast. This high speed (90-110km/h) dual carriageway carries up to three lanes of traffic in each direction over a length of approximately 129km. The M1 is subject to high traffic volumes, with traffic count averages indicating approximately 90,000 vehicles per day on some sections, and heavy vehicles comprise a relatively large proportion of traffic.

The M1 is subject to a range of works that place workers in close proximity to live traffic, including road and roadside inspections, maintenance, repairs, and incident response. Such works require temporary traffic management to reduce the risk of crashes and related injuries to workers and also road users. Following a number of serious incidents at M1 worksites in recent years, Transport for New South Wales (TfNSW) sought to investigate crash and injury reduction measures with a view to improving worker safety, including alternative and innovative methods. In partnerships with TfNSW and iMOVE, Deakin University undertook research activities aimed at achieving the objectives of TfNSW and prepared this report.

1.2 Background

Roadworks pose significant risks to roadworkers and motorists alike. While the risks are recognised by agencies involved in road construction and maintenance activities, significant work is needed to develop strategies to mitigate these risks at Australian roadwork sites. Although safety issues vary somewhat for different types of roadwork scenarios, there is broad consensus that the risks are greater for high-speed work zones where workers are exposed to live traffic (Debnath et al., 2015).

To address the risks at roadwork sites, researchers and practitioners have developed and tested various controls and technologies, including autonomous and remote-controlled traffic control devices (Finley et al., 2012; Debnath et al., 2017a), innovative enforcement measures (Benekohal et al., 2010), work zone intrusion countermeasures (Brown & Edara, 2022; Gambatese et al., 2022; Ullman et al., 2010), and innovative visibility and lighting configurations (Finley et al., 2013), among others. With the advancement of technologies, innovation in this space is being made continuously.

Controlling the crash and injury risks at high-speed roadworks, including the M1 with its unique geometric and traffic characteristics, requires careful investigation of the relevant and applicable safety issues. While a review of literature provides useful information on the risks and controls, it is important to examine specific risks and hazards by considering local conditions and the experience of roadworkers working on this road. Such context-specific understanding will help to identify the most appropriate controls to mitigate the risks.

1.3 Report purpose and structure

This report presents the project methodology and findings in sections. After this introduction section, Section 2 presents the project objectives and scope, followed by the project methodology in Section 3. Section 4 presents the findings obtained from Phase 3 of this project covering a review of the literature and consultations with experts and industries. Finally, Section 5 includes the solutions and recommendations of this project for future trials and monitoring to be undertaken by TfNSW.

2 PROJECT OBJECTIVES, SCOPE, AND DELIVERABLES

2.1 Objectives

The objectives of the project are to:

- identify current technologies and innovative ways of working in the areas of structural and roadside inspections, temporary traffic control, and alternative ways of conducting temporary roadworks or maintenance activities on the M1, and
- with the overall aim of safety improvement, provide recommendations on technologies and practices for potential future trials to be undertaken by TfNSW.

The objectives are to be achieved three levels of outcomes across three application areas:

- remove or reduce the need for workers to be on the road,
- reduce workers' exposure to the risk of working near traffic and minimise the severity of related incidents, if removal of workers from roadsides is not possible, and
- control measures are to be effective and easy to use.

2.2 Scope

To meet the project objectives, the scope of the research includes investigating:

i. deployment, use and maintenance of temporary traffic control measures, including alternative and innovative practices and products, and
ii. alternative ways of conducting temporary roadworks and related maintenance activities to remove/reduce the exposure of workers to live traffic.

The specific types of work considered to be within scope for the project are those which may require working close to live traffic, on road or roadside, including:

- infrastructure maintenance and repair (e.g., pavement, barriers, markings, signage, signals, shoulders, batters, drainage, bridges, gantries, posts, fences, lighting, communications etc.),
- environmental maintenance (e.g., vegetation, rocks, boulders, cuttings, animals), and
- incident response (e.g., litter and debris removal, dead animals, vehicle crashes and breakdowns, oil spills, flooding, fire).

2.3 Deliverables

This project has four Deliverables:

1. Meeting minutes from the inception meeting (delivered August 2022),
2. Report containing research plan and methodology (delivered August 2022),
3. Interim report containing findings obtained from stakeholder and expert consultations, review of materials provided by TfNSW, worker interviews, and review of the literature, and input from the industry on technology and innovations (delivered November 2022), and
4. Final report, updated from the interim report by addressing feedback obtained from TfNSW, with additional information on project findings and recommendations for future trials (this report).

3 PROJECT METHODOLOGY

This section describes the overall methodology of the project in five phases. The detailed activities of these phases are presented in the following sections.

- Phase 1: Inception, planning, and methodology development
- Phase 2: Understanding work practices and current risks
- Phase 3: Identification of best practices and technologies
- Phase 4: Options analysis and recommendations
- Phase 5: Reporting

3.1 Phase 1: Inception, planning, and methodology development

Phase 1 established the project plan and protocols to ensure the smooth and successful conduct of the project and facilitate communication between the Project team and iMOVE/TfNSW. An initial project inception meeting was held on Teams on 28 July 2022 between the research team, TfNSW Project Manager (PM), and iMOVE representatives for presentation and review of the project plan.

An additional Phase 1 kick-off meeting was held on 3 August between the research team and TfNSW. The purpose of this was to discuss and refine the project objectives, scope, overall plan, and methodology, including aspects related to worker interviews, identification of relevant background materials to be supplied by TfNSW, and potential participants in the industry consultations. The project deliverables were also clarified and confirmed at this stage. Potential project risks were identified, including availability of materials/personnel for interviews/consultation, university ethics approval, and project timeline. The project timeline was revised with minor adjustment to allow for the December-January holiday period prior to project completion.

Phase 1 Deliverable(s):

- Meeting minutes (D1)
- Project plan and methodology (D2)

3.2 Phase 2: Understanding work practices and current risks

To identify the best practices and technologies for reducing the risks to roadworkers, it is first important to understand and document the current work practices and risks at the study area of the M1 section.

3.2.1 Task 2.1 Review of background materials

Background materials (e.g., project documents, research reports, internal reports etc.) related to the study sites on M1, provided by TfNSW to the research team, were reviewed to document the current practices and risks.

TfNSW has done significant work on identification of these practices and risks and in the early stages of the project provided a large quantity of related (deidentified) documents. These documents provided a good base for generating a list of activities/tasks which are typically undertaken on the M1 study section. Attempts were made to document any known hazards associated to the activities/tasks, as well as any known controls or risk mitigation strategies currently in place or planned to be implemented in the near future.

To complement the findings from the document reviews, virtual site visits to M1 sections were conducted using Google Maps and Google Earth. These virtual site visits provided contextual understanding about the road section, in conjunction with the findings obtained from the background documents.

3.2.2 Task 2.2 Worker interviews

General information on research design for interviews and consultations

This project involved interviews and consultation with three distinct groups of participants, including:

i) roadworkers, managers, and traffic control personnel
ii) international experts
iii) industry representatives

Interviews with roadworkers, managers, and traffic control personnel (group 1) were undertaken in Phase 2, with findings used to inform the later consultations/interviews (groups 2 and 3) and targeted literature review undertaken in Phase 3. The current section provides general introductory information on this critical project element.

Using a semi-structured format, interviews and consultations involved open-ended discussion with the researchers of the risks and hazards associated with highway temporary traffic management and related works, and the various control measures to address those risks and hazards. Emphasis was placed on current best practices, as well on emerging and future practices and technologies. To ensure consistency and adequate coverage of topics across interviews, a schedule of guiding questions was used for each group (see Appendices 1-3). Example questions include:

- What are the primary risks and hazards associated with working on or adjacent to highways and motorways that lead to traffic incidents?
- In your experience, what are the common types of incidents occurring at roadwork and/or incident sites where temporary traffic management is installed for short-term and mobile operations?
- In which ways do temporary traffic management and work practices tend to fail?
- Which work methods and aspects of temporary traffic management work best?

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- How can work methods and temporary traffic management be improved in terms of 1) practices and procedures, and 2) technological solutions?

For interviews with roadworkers, managers, and traffic control personnel (group 1), discussion focused on their specific working environment (i.e., the M1 in NSW). For international experts (group 2) as well as industry consultations (group 3), discussion focused to some extent on trials and evaluations, including of new and emerging technologies and practices, and their potential transferability and usefulness in the NSW M1 context. Barriers to the uptake of new or revised practices and technologies were also discussed.

All participants were asked to provide consent to be audio recorded. However, participants who declined to provide such consent could still participate.

Interviews with workers, managers, and traffic control personnel

A series of semi-structured interviews with roadworkers, managers, traffic control personnel and incident response staff were conducted to understand the current risks and practices associated with M1 operations requiring temporary traffic management. Participants were recruited directly by the research partner, Transport for New South Wales, who provided in-person introduction to the researchers on site. Each potential participant was provided the Plain Language Statement and Consent Forms, noting that their participation was voluntary and their data and personal information deidentified, as per the research ethics approval obtained from Deakin University.

A total of twelve interviews was deemed sufficient to provide saturation in terms of the depth and breadth of data collected (comprehensive coverage of issues in relation to different roles). Inclusion criteria were current or recent direct involvement with conducting, managing and/or planning road-related works, as well as unplanned works (such as incident response), on the M1 Motorway in NSW. Ten interviews of approximately 60 minutes duration each were held face-to-face at participants' places of employment, as coordinated by TfNSW. Two additional interviews were held online via Teams.

Interviews were recorded, with participant consent, and transcribed to facilitate an efficient interview process and post-interview data analysis. The data collected at interviews were analysed, with the findings to be combined with those from a review of background materials pertaining to traffic management and related works in the study area (Task 2.1). The overall outcome from this phase is a comprehensive summary of current practices, risks, knowledge, and experiences associated with M1 temporary traffic management and related works.

3.3 Phase 3 Identification of best practices and technologies

This phase aimed to identify best practices, technologies, and innovative ways for working in the areas of structural and roadside inspections, temporary traffic control devices and alternative ways of conducting temporary roadworks or maintenance activities, with the target to reduce/eliminate risks to roadworkers. This involves three separate tasks, as outlined below.

3.3.1 Task 3.1 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. 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 reports, internet publications and any other relevant literature were examined. Special emphasis was given to publications of Australian origin in order to capture any special characteristics and issues related to local roadwork traffic management procedures.

Relevant research findings will be identified by searching the following sources of information:

- Transport Research International Documentation (TRID) database,
- Google Scholar database,
- Science Direct database,
- Government and non-government reports from Australia, New Zealand and internationally,
- Conference proceedings (e.g., Australasian Road Safety Conference, Australasian Transport Research Forum, as well as other national and international road safety related conferences),
- US National Work Zone Safety Information Clearinghouse, and
- Citations from obtained literature.

In addition to the scientific literature, grey literature including industry reports and related materials were also included in the scope of this review. In particular, webpages of key industry bodies related to roadwork safety management, manuals and marketing materials from traffic control and technology companies were reviewed to supplement the findings obtained from the academic literature.

It was expected that the industry literature could provide information on various new and emerging technologies and risk-mitigation procedures. On the other hand, the scientific literature would provide evidence on the effectiveness of various traffic control technologies and procedures tested and trialled across the world. Findings obtained from both sources provide a comprehensive understanding of the best practices and technologies for reducing the risks to workers on the M1.

3.3.2 Task 3.2 Expert consultations

The Deakin research team understands that a large proportion of recent innovations in roadwork safety management have been trialled and implemented in the United States of America (USA). Therefore, researchers of this project consulted with a group of six international roadwork safety experts from the USA regarding their current understanding of 1) work zone risks and hazards in their respective jurisdictions, and 2) best practices and controls used to address the risks and hazards, 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 (i.e., Teams, Zoom). Interviews were recorded, with participant consent, and transcribed to facilitate an efficient interview process and post-interview data analysis. In addition, the experts consulted were invited by the research team to provide any relevant materials (reports, journal articles, technical documents etc.) that they noted during the consultations.

Inclusion criteria for experts is recognised high level expertise and ongoing activity in the field of work zone safety research. International experts were recruited directly through email invitation, with the Plain Language Statement and Consent Forms attached. The experts were offered honorarium for their participation in the consultations to ensure that maximum level of input is obtained from the consultations.

3.3.3 Task 3.3 Industry consultations

To complement the international expert consultations undertaken as part of the current project, consultations were held with representatives of organisations supplying roadwork traffic control and roadway maintenance technologies. These consultations targeted to engage approximately seven industry representatives and were focused on identifying current, new, and emerging technologies and processes for reducing the risks to workers.

Similar to the expert consultations, a semi-structured interview format was used to run these consultations in a virtual platform (Zoom/Teams), for a duration of approximately 45 minutes each. Interviews were recorded where possible, with participant consent, to facilitate an efficient interview process and post-interview data analysis. In addition, the industry representatives consulted were invited by the research team to provide any materials they believe to be relevant to the project, such as technical reports, technology specifications, product approvals and related documents.

Industry representatives were approached by email invitation, with the (group 3) Plain Language Statement and Consent Forms attached. Representatives to be approached were identified through a combination of internet search and/or reference to the representative organisation by the research partner, Transport for New South Wales. Participants were not screened.

3.4 Phase 4 Option analysis and recommendations

Based on the findings obtained in Phase 3, in this phase gaps in knowledge were identified by comparing current practices to the best practices and technological solutions. The gaps were identified using a gap analysis approach where the identified practices and risks (from phase 2) were compared with the best practices identified in phase 3. A qualitative analysis approach was undertaken for this task. The identified gaps, in combination with recommendations from the literature on best practices and consultations with the industry and experts, formed the basis to develop the list of recommendations for the M1.

4 BEST PRACTICES AND TECHNOLOGIES

4.1 Literature review findings

4.1.1 Introduction

This review of research literature was undertaken to identify best practice approaches for improving the safety of workers in highway work zones. The scope of this work encompasses methods and approaches for temporary traffic management, as well as the methods, tools and processes which may be used to complete the relevant work tasks with optimum safety and efficiency. Broadly, for the current project relevant works include road and roadside inspections, maintenance, and incident response. Effective traffic management protects workers (and traffic controllers) for the duration of work activities, while efficient management and completion of work tasks brings inherent safety benefits through reduced exposure of workers to the live traffic environment.

Highway work zone risks and hazards are generally well known to those in industry and are documented comprehensively in the literature and related guidelines and safety manuals. These risks and hazards are summarised in the following section to set the foundation for the current review. Thereafter, the review focuses on controls and mitigation strategies, with emphasis on demonstrated best practice, and innovative and emerging approaches and technologies, including objective assessment and evaluation of such where available.

4.1.2 Highway work zone risks and hazards

Highway work zone risks and hazards have been comprehensively examined in the research literature (e.g., Debnath et al., 2015; Debnath et al., 2017b; Goodsell et. al., 2019; Samareh et al., 2019; Kim et al., 2018; Sze & Song, 2018). While a multitude of hazards have been documented, broadly, those hazards can be grouped into several categories, such as driver behaviour, traffic related (vehicles), traffic control-related, environmental, and work-related hazards. Table 4.1 shows these categories and the common specific hazards they include.

Table 4.1 Overview of hazards in work zones

Category	Hazards
Driver-related (behaviour)	Speeding Distraction Inattention Impairment Following too closely Driver frustration and aggression towards workers
Traffic-related (vehicle)	Heavy vehicles Oversize vehicles Non-motorised traffic
Traffic Control related	Signs – installation and dismantling Tapers and buffers – inadequate and missing Visibility of traffic control devices
Environmental	Atmospheric conditions (working in rain, fog etc.) Temporal factors
Worker and work related	Reversing vehicles Poor communication Working close to traffic stream

4.1.3 Traffic management controls and mitigation strategies

The current project considers two main aspects regarding safety improvement for works on roads and road-related areas: (i) temporary traffic management (TTM) approaches and equipment; and (ii) alternative work processes and technologies for completing work activities. This section addresses TTM, while the alternative work processes and technologies are covered later in Section 4.1.4.

The NSW Traffic Control at Worksites (TCAWS) Manual (TfNSW, 2022, p.32-3) identifies three high-level traffic management methods. These methods are summarised below in Table 4.2, which is adapted from the TCAWS Manual.

Table 4.2 Traffic management methods in Traffic Control at Worksites Manual

TTM method	Description	Example controls
Around (elimination)	Complete separation of work area from traffic. Preferred method where achievable.	Full road closure, detour Sidetrack Contraflow via median
Past (isolate/engineer)	Substitution, isolation and engineering controls; guide traffic on path adjacent to work area.	Contraflow without median Lateral shift taper Temporary barrier system
Through (admin./PPE)	Administrative, training and PPE controls only. No isolation, traffic passes through work area. Least preferred option.	Direct traffic over work area Separation (cones/bollards) Pilot vehicle

Elimination of risks and hazards involves full separation of traffic from the work area, and in terms of a typical hierarchy of controls is the always the preferred method for achieving worker safety. The NSW TCAWS Manual (TfNSW 2022, p.32) identifies this as an **"around (elimination)"** traffic management method, involving full road closure and traffic detour, or "contraflow of traffic via a separated median" (achievable only on divided roads). While fully separating traffic from the work area to maximise safety of those performing the necessary activities, there are still potential risks to traffic controllers in establishing, maintaining and removing the TTM measures and associated guidance (Debnath et al., 2017b). In many cases it is not possible to achieve this degree of isolation.

Exposure reduction methods also seek to isolate workers from traffic, though to a lesser extent than as described above. The TCAWS Manual describes guiding traffic along a path adjacent to the work area as a **"past"** traffic management method, where workers and traffic are completely separated through isolation and engineering methods. However, complete separation is not always maintained, with vehicle intrusion into work areas common and well documented in the literature. In this approach, engineering measures such as temporary barriers (including TMAs) can provide effective physical protection and traffic guidance for lane closure. Additional guidance and speed reduction is required upstream and is typically provided through traffic cone (or bollard) tapers, and static and/or electronic signage.

A **"through"** method as described in the TCAWS Manual provides no isolation of workers from traffic and may permit traffic to pass directly through a work area, or adjacent to it with minimal separation. This is a least preferred option and is not generally applicable for multilane highways and motorways. Such a method may be found on low-speed roads and undivided rural roads, including highways, where (for example) stop/slow signals alternate traffic direction and pilot vehicles may be used for additional guidance.

Internationally, under Worker Safety Considerations (Section 6D.03), the US Manual of Uniform Traffic Control Devices (MUTCD 2009, revised version 2022) identifies five key elements of worker safety and TTM as follows:

- Training for workers
- Temporary barriers
- Speed reduction
- Activity area planning
- Worker safety planning

While the US MUTCD is a comprehensive and detailed manual about the multitude of specific devices and how they should be used, the above information indicates that other aspects beyond the devices themselves are also critical in safety considerations. This is clearly reflected in the research literature which examines the human and other factors which often lead to poor work zone safety performance despite the use of best practice safety devices and related controls. Hence, traffic control methods, processes, and technologies are continuously evolving to seek further safety improvement for both workers and road users. A holistic systems perspective increasingly promoted in general road safety literature and related strategies may also be applied in the work zone context specifically.

For all the high-level approaches summarised above, there are a number of core strategies that are commonly used or promoted to provide safety for workers and also the travelling public. The main controls used can be grouped into six strategies including speed management, directional guidance, positive protection and separation, warning systems, traffic monitoring, and training and education, as summarised in Table 4.3. Specific strategies and controls are identified and discussed in the following sections.

Table 4.3 Key control strategies

Control strategy	Control type	Hazards addressed
Speed management	Speed limit signs – static & electronic Advance warning signs – static & electronic Speed feedback signs – electronic Enforcement – perceived/active/automated Temporary speed humps/rumble strips Reduced lane width Chicanes Pilot/escort vehicles	Excessive speed Driver distraction & inattention Driver confusion
Directional guidance	Tapers & chicanes – cones, bollards, barriers Temporary lines Signage – static & electronic Temporary barriers Human traffic controller	Lack of separation Work zone intrusion Merging conflicts

Control strategy	Control type	Hazards addressed
	Pilot/escort vehicles	Driver awareness & confusion Environmental hazards
Positive protection & separation	Attenuators (TMA) Portable/temporary barriers Lane closure Anti-gawk screens	Work zone intrusion Excessive speed Driver distraction & inattention Driver impairment Merging conflicts
Warning systems	End of queue (EOQ) warning Work zone intrusion alarm Excessive speed warning (radar & VMS) Human spotters Moving work vehicle & plant warnings	Driver distraction & inattention Work zone intrusion Excessive speed Driver impairment Slow vehicle conflicts
Traffic monitoring	Network level Site level Pre-planning	Incidents Congestion Site set-up
Training & education	For workers For road users	Poor awareness & competency

4.1.3.1 Common approaches and effectiveness

Work zone sections

A roadway work zone is typically comprised of four main sections, including an advance warning area, taper/transition area, work/activity area, and termination area (Debnath et al., 2017). An additional section known as a buffer area (prior to the work area) is often identified separately as a fifth section (Austroads, 2012; ITSI, 2011). However, the buffer area may also effectively be considered an extension of the transition area, or an unoccupied precursor to the work area. The sections have previously been defined and described by Austroads (2012, p. 26) as follows:

- ***Advance warning area****: where the advance warning signs are erected to warn and inform of changes to traffic conditions ahead and to give motorists time to adjust their driving patterns.*
- ***Taper area****: where traffic is guided past the work area, usually by means of cones or bollards set out in a taper.*

- ***Safety buffer area:*** *the unoccupied space between the taper and work areas. Safety buffer areas are designed to compensate for driver error and protect workers by allowing errant vehicles to slow down and stop prior to the work area. This area also protects road users from hazards in the work area, such as work vehicles and equipment. The length of the safety buffer area should be based on the speed limit of the road.*
- ***Work area:*** *where the work is being undertaken and is occupied by workers, plant and material.*
- ***Termination area:*** *where traffic has cleared the work area and at the end of which normal traffic conditions resume.*

The advance warning and taper/transition areas are the first encountered by motorists and, according to many studies, are the sections where the vast majority of EOQ and rear-end crashes occur. Motorists can therefore be most vulnerable in these sections. The taper/transition and work/activity areas are where workers may be most vulnerable once a site is established, due to greater exposure, though advance warning area set-up and removal can also be notably hazardous for workers. Note that while the above Austroads (2012) definition of a taper area identifies cones and bollards as the primary means of guidance at that point, electronic signs and truck-mounted attenuators are now also common transition zone features. Work zone sections and typical core components are illustrated below in Figure 4.1.

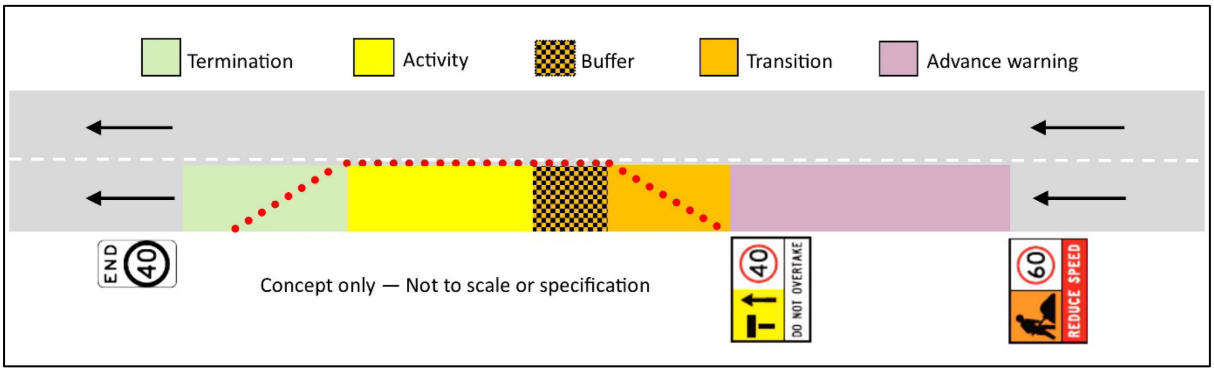

Figure 4.1 Work zone sections and typical core components

Advance warning and speed reduction

Advance warning for motorists approaching a work zone is critical for the safety of workers and motorists alike and is key to the avoidance of work zone intrusions and end-of-queue crashes. Many studies have shown that speed reduction signs in advance warning areas have a desired effect of reducing overall traffic speeds upstream of work zone transition and work areas (Debnath et al., 2017b). However, those studies also show that full compliance is never achieved, with most drivers basing speed choice on perceived hazards and risk of a collision rather than on posted speed limits. In this situation, increased speed variance can be observed in platoons of vehicles, associated partly with different vehicle types, leading to increased conflicts which may result in rear-end crashes (Zhao & Lee, 2018).

Poor compliance is at least partly related to the issue of credibility of work zone speed limits. The need for credible speed limits, and the operational challenges associated with installing, removing, and changing speed limit signs, has long been documented in research (e.g., Finley et al., 2008) and is acknowledged by authorities and industry (Debnath et al., 2017b). Essentially, in Australia as in the US, drivers are reluctant to reduced speeds unless they see workers or other hazards (Finley et al., 2014; Blackman et al., 2014). One solution to addressing the challenge of changing speed limits according to work zone conditions is to use VMS for implementing variable work zone speed limits where possible. This can reduce worker exposure while improving speed limit credibility where work zone activity levels and other conditions change (Finley et al., 2014).

Research also shows that speed compliance in advance warning areas improves generally with the use of VMS as opposed to static signage, though the differences may not necessarily be significant (Debnath et al., 2017b), and the aforementioned potential for speed variance and traffic conflicts remains. In addition to VMS warnings and speed limit display, speed feedback displays have been positively evaluated in numerous studies (e.g., Fontaine et al., 2000; Maze et al., 2000; Savolainen et al., 2022). Most recently, Savolainen et al. (2022) studied effects of a trailer-mounted speed feedback sign deployed on a freeway with single lane closure. A smaller reduction in average speeds (2.4 km/h) was found than in other similar studies (which found up to 16 km/h reductions). The authors tentatively attributed this to the use of temporary rumble strips at the site, as required by authorities, the effects of which could not be discerned. Positioning the feedback sign at the start of the taper resulted in earlier reduction of speed than placing it at the taper end. While this effect might be somewhat expected, importantly, lower speeds were sustained much further into the work zone in the latter scenario. Another recent study reported that speed feedback signs combined with 'presence lighting' may have even stronger effects than speed feedback alone (Sakhare et al., 2021).

As well as speed feedback, VMS display with special messages may also encourage drivers to further reduce speed. Some examples of special massage for VMS displays include messages such as smiley face symbols for compliant motorists, "Slow down", "Thank you for safe driving", and "My dad works here", all of which have been used in different situations (Debnath et al., 2017b). Again, the extent of effectiveness and the temporal and spatial effects vary across these studies, but the overall effects are generally consistent.

It should be noted that countries and jurisdictions apply speed reduction depending on various criteria such as road geometry, work type, pre-work speed limits and traffic volumes, among others. However, jurisdictions also variously specify the amount of reduction that is generally acceptable. For example, FHWA MUTCD recommends speed limit reduction should be 10 mph (16.1 km/h). In the UK, the decrease in speed limit is at least 20 km/h. Similarly, in Australia, the common reduction of speed is at least 20 km/h. In New Zealand, the required reduction of speed is at least 20 km/h below the zoned speed (Debnath et al., 2017b).

Temporary portable rumble strips

Temporary portable rumble strips (TPRS) have been found to be effective for reducing motor vehicle speeds. A review of the literature on TPRS use and effectiveness across 19 US States was reported by Brown et al. (2022). The research shows TPRS to be an effective speed reduction measure, reducing speeds by up to 19 km/h, 'increasing driver braking, and alerting drivers to the presence of the work zone' (p.88). In jurisdictions in which they are used, TPRS are sometimes deployed on divided highways and may be used in conjunction with pilot cars. The US MUTCD specifies that the colour of TPRS should be white, black, or orange unless matched with the pavement colour. European research (Varhelyi, 2019) reports a preference for orange rumble strips which may best address driver awareness and distraction issues. Further information from Brown et al. (2022) is reproduced below (p.71):

> *The statistical significance found with the complete survey data shows that the effect of short-term rumble strips was stronger than long-term rumble strips. However, the two coefficients overlapped each other within the ranges of standard errors, indicating that the more substantial effect of short-term rumble strips might not be conclusive.*

Results of two specific studies included in Brown et al. (2022) are summarised below. In Iowa, for example, effects of two TPRS layouts were examined in a field study by Hawkins and Knickerbocker (2017, cited in Brown et al., 2022). The study compared a layout with two sets of TPRS against one set of TPRS and a sign displaying "Rumble Strips Ahead". The sign was an addition to the standard single TPRS installation to provide a visual alert for drivers and potentially reduce erratic behaviour. Where only 10 percent of vehicles braked upstream of the work zone with no TPRS in place, this increased to 29 and 33 percent of vehicles braking, respectively, when double or single TPRS layouts were present. The TPRS also produced mean speed reductions of 5.9 to 8.8 km/h, compared with no mean speed reduction in the absence of TPRS. Another study in Wisconsin found similar effects for TPRS, with 85th percentile speeds reduced by 7.5 to 8.0 km/h with TPRS, compared to a small 2.4 km/h decrease without TPRS (Sippel & Schoon 2016, cited in Brown et al., 2022). The effects were smaller on the second day of testing, suggesting a temporal halo effect associated with driver unfamiliarity. A notable increase in braking was also found in the Wisconsin study, with 33 to 39 percent of drivers braking with TPRS compared with less than three percent without TPRS. This study also found that a small proportion of drivers (5.5%) engaged in avoidance manoeuvres (e.g., swerving around the TPRS), a behaviour also observed in other studies.

A rural highway evaluation of TPRS was also conducted by TfNSW (Chircop 2017), comparing both grey and yellow TPRS against baseline data. This study found significant reduction in average speeds and a 21 percent reduction in speeding (over limit) during TPRS deployment. Some problems were identified, including that 9 percent of vehicles sought to avoid the TPRS by swerving, which was more prevalent with yellow than grey

TPRS. Additionally, workers identified risks and hazards associated with manual deployment, and movement of the TPRS, but overall benefits were reported to outweigh the risks according to workers.

Police presence and enforcement

Visible police presence, enforcement and perceived enforcement, beyond reduced speed limits and associated warning signs, is one of the most effective measures for encouraging compliance in advance warning areas (Debnath et al., 2015). As reported in Debnath et al. (2017, p.36):

> *The visible presence of police at roadworks as a deterrence strategy is likely to result in substantial increases in speed limit compliance among motorists and is one of the most effective and dependable speed control measures (Arnold Jr, 2003; Benekohal, Resende, et al., 1992; Chen & Tarko, 2012; FHWA, 2007). Overt police presence implies to road users that there is a high likelihood of enforcement, whether or not enforcement is actually carried out. Studying the effects of enforcement in Indiana road worksites, Chen and Tarko (2012) reported that a 41% reduction in crash frequencies was attributable to police enforcement, with no significant difference between enforcement types (overt/covert, active/perceived).*

Benekohal et al. (2010) represents the earliest known formal evaluation of work zone speed enforcement using photo-radar technology (SPE). This study showed significant speed reductions for both cars and trucks in free flow traffic as a result of SPE, comparable to the effects of police presence against which the SPE measure was compared.

More recent research further confirmed the positive effect of police presence, as well as examining the use of two versus three tail (advance warning) vehicles in a night time highway work zone under single lane closure in Queensland (Blackman et al., 2020). This study showed an 8.4 – 12.9 percent reduction in vehicles speeding by at least 5 km/h in the transition area when police were present with flashing lights in the buffer area. The study also showed no benefit in the use of an additional (third) advance warning vehicle in terms of speed limit compliance, with the percentage of vehicles speeding highest under this condition throughout the advance warning area. A greater frequency of late merging was also observed under this condition. Similarly, Ravani et al. (2018) found significant reductions associated with police presence in the proportion of high-speed vehicles (more than 16 km/h above limit) measured at the end of the work zone taper (upstream end of buffer area). Effects of several experimental conditions were compared against a baseline condition (no police) in which up to 11 percent of vehicles were observed travelling at high speed. The test conditions included:

i. trailer-mounted VMS equipped with police lights and radar,
ii. trailer-mounted VMS equipped with police lights, radar, and passive police vehicle
iii. single passive police vehicle only
iv. multiple police vehicles actively stopping speeding drivers

Generally, these measures were all found to result in lower average speeds, with statistically significant results in most cases, and reductions in high speed vehicle observations. However, differences were found according to urban versus rural environments, not all results were statistically significant, and the use of active police was reported to bring only limited benefits. Passive police presence was found to potentially increase speed variance in urban settings, while decreasing variance in rural environments. These effects are important to consider in addition to overall speed reductions, as increased variance is typically associated with higher crash risk.

Average speed control, or Point-to-Point camera-based enforcement (P2P), has been shown to be effective in some European countries in a work zone context, though is yet to be applied in practice at Australian or US work zones to the knowledge of the authors. Depending on the equipment used and the regulatory and deployment requirements, this measure is likely not feasible for short term work sites and mobile operations and is likely best suited to advanced warning areas at long term sites. However, where it can be implemented, it may have better effects on speed variance as well as general compliance than fixed point enforcement according to the European IRIS project (Incursion Reduction to Increase Safety in road work zones) (Strnad et al. 2019: 29):

> *Average speed control in work zones is already used in the UK, Flanders and in Austria. Slovenia is preparing the use of average speed control. In the interviews with Austrian experts it was stated that the use of average speed control leads to a homogenisation of traffic flow, thus enhancing safety within the work zones.*

Previous research by the current authors (Debnath et al., 2017b) included consultation with an expert based in the United Kingdom, who also spoke favourably of P2P work zone enforcement. It is also understood that a trial of work zone P2P enforcement was conducted in New Zealand more than a decade ago, as reported in Soole et al. (2012, cited in Debnath et al., 2017b). Although the collective information gathered in the current study is somewhat informative, published reports and formal evaluations appear still to be lacking.

Stop/go traffic control

Stop/go traffic control methods generally include human flaggers, portable traffic lights, and Automatic Flagger Assistance Devices (AFADs) (Debnath et al., 2017a). Due to the high risk to human flaggers in stop/go operations, recognised and documented over decades (e.g., Antonucci et al., 2005), human flaggers are clearly discouraged and are avoided where possible on high speed roads and elsewhere. To reduce the exposure of human traffic controllers, remotely controlled portable traffic lights are now the commonly preferred option. Less commonly used, at least in Australia, AFADs have also been found to be effective. Reported advantages include that AFADs are more visible from a distance than a human flagger as they are larger and therefore allow drivers more time to react, while also removing human flaggers from the roadway (Gambatese, 2022). However, while achieving the effect of exposure reduction to a large extent, AFADs in various forms are not without some problems (Debnath et al., 2017a; Finley, 2013). Issues encountered in trials of different devices have included poor understanding and perception of the controls among some drivers, and some cases of non-compliance with the stop/go instructions. It must be appreciated that the various devices evaluated have had different characteristics and configurations (lights, symbols, boom gates etc.), and have been trialled in different environments. While work on such devices is ongoing, trailer-mounted portable traffic lights have been largely successful relative to human flaggers in terms of overall risk reduction.

Traditional guidance, delineation and positive protection

Traditional guidance, delineation and positive protection devices still in common use at short-term work zones include traffic cones, bollards, barrels, signs depicting arrows and chevrons, temporary linemarking, amber warning lights, and in some cases temporary barriers. In addition to providing traffic path guidance, temporary barriers may also provide positive protection if of suitable density and construction such as water-filled or concrete types. According to Bolling and Sörensen (2008, cited in Varhelyi 2019), water filled barriers are low cost, quick to install, easily handled and provide clear guidance for drivers. However, the use of such devices may rarely be feasible for short term or progressively moving operations.

Temporary yellow (or orange) line markings can be found in European but generally not in US work zones (Burghardt et al., 2021), although a US trial found some positive effects on driver behaviour and response if not crash rates (DuPont & DeDEne, 2017). While literature is limited on the use and effectiveness of yellow lines in work zones, examples can be seen in Varhelyi et al. (2019). An instrumented vehicle study on the Pacific Highway in northern NSW (Imants et al., 2018) identified that, according to participants, yellow line marking was more visible compared to white line marking and increases driver awareness in work zones. Results also indicated that driver performance was not adversely affected by yellow markings in terms of lane keeping and speed choice. However, as the study involved only 12 participants constituting a small and unrepresentative sample, these findings are not conclusive.

The traditional guidance and delineation devices mentioned above are complemented and in the case of static signs often replaced by trailer- or vehicle-mounted VMS. Compared with static signs and arrow boards, electronic VMS offer greater flexibility in messaging and guidance, and greater visibility from long range and in dark or gloomy conditions (Debnath et al., 2017b). In particular, VMS mounted on truck-mounted attenuators (TMAs) can provide highly visible large format guidance for lane closure in advance of work areas. Additionally, a study by Bushe (2020) evaluating robotic safety systems reported that more than 63 percent of survey participants responded that moving electronic signs are more eye-catching than non-moving ones.

Truck-Mounted Attenuators (TMAs)

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 practical but one or more lanes need to be closed for a short duration due to roadwork or incidents (Birenbaum et al., 2009; Pourfalatoun & Miller, 2021). Their effectiveness in preventing work zone intrusions and reducing incident severity is well demonstrated in the research literature, amid ongoing debate around optimal deployment and design considerations. Those considerations include the number of TMAs to be used, their positioning in the work zone, and the lighting, markings and VMS messaging requirements, among others. There are many studies and guideline documents regarding TMA use, which differ somewhat according to their place of origin and publication date. While those documents are not included in this review, a recent review of countermeasures to reduce TMA crashes provides a useful synthesis of current US practices and recommendations (Aroke et al., 2022):

> *To support worker and driver safety, this study conducted a comprehensive literature review to identify methods of enhancing TMA visibility, improving work zone configurations, and ensuring worker safety. To increase TMA recognition, this study observed that the use of a 6-to-8-inch wide yellow and black inverted 'V' pattern of retroreflective chevron markings, sloped at a 45-degree angle downward in both directions from the upper center of a rear panel is effective in alerting drivers to work zones. This study also recommends applying amber and white warning LEDs, which flash in an asynchronous pattern at a 1 Hz frequency and are mounted against a solid-colored background for a 360-degree view visible at least 1500 feet from the work zone. In addition, a work zone vehicle configuration consisting of a lead, buffer, and advance warning truck with a buffer space between 100 and 150 ft is suggested to reduce the risk of lateral intrusions and TMA roll-ahead. In parallel, workers should wear high-visibility vests noticeable at a minimum distance of 1000 feet and headwear with at least 10 square inches of retroreflective material. Some intelligent transport systems are also suggested to enhance TMA recognition and potentially minimize work zone fatalities. Application of the recommended guidelines will potentially improve current practices and significantly reduce the occurrence of TMA crashes in construction and maintenance work zones.*

Pilot vehicles

Pilot (or escort) vehicles are sometimes used to provide guidance through or past a work area, where warranted and resources and site conditions permit. In addition to guiding traffic along the correct pathway, pilot vehicles also provide one of the most effective means of controlling traffic speeds (Debnath et al., 2017b). However, opportunities to use pilot vehicles are limited and they are not generally appropriate for lane closure on divided multi-lane highways or short term mobile operations as pilot vehicles are required to take U-turns at the end of a work zone to guide traffic from each direction of travel.

4.1.3.2 Innovative and emerging approaches

Smart Work Zone Technologies (SWZT)

A recent NCHRP report (Synthesis 587) documents current practices and use of smart work zone technologies for the (US) National Cooperative Highway Research Program (NCHRP) (Brown & Edara 2022). Eight main types of technologies are identified, including (p.6):

- *Traveler information systems*
- *Queue warning systems*
- *Dynamic lane-merge systems*
- *Dynamic speed limit systems, also known as variable speed limit systems*
- *Work zone data collection technologies*
- *Work zone location technologies*
- *Work zone intrusion alarms*
- *Notification of construction equipment entering/exiting systems*

In terms of performance, of these SWZT types, traveller information, queue warning, and dynamic lane merge systems received the highest ratings according to a survey of US state transport departments. Construction equipment notification systems and work zone intrusion alarms were the lowest rated. Importantly, the research found a 'great deal of variability in the DOT performance ratings for smart work zone technologies, suggesting a wide range of DOT experiences' (Brown & Edara, 2022, p.105). Although not highly rated relative to some other SWZT, work zone intrusion technologies are explored further below due to their potential applicability to the M1 environment.

Work Zone Intrusion Technologies (WZITs)

Another recent NCHRP report (Research Report 1003) (Gambatese, 2022) describes Work Zone Intrusion Technologies (WZITs) in three categories, including (1) positive protection devices, (2) networked systems for workers, and (3) driver warning systems. This report represents something of a recent (US) compendium of relevant technologies and is thus summarised here as an introduction to the current section. The research informing the report identified 15 types of WZITs classified as matured and ready to use on roadways (see Figure 4.2). Of these, nine types were reported to be available (in the United States), with the remaining six types in the research and development stage at the time of publication.

Functionality	Technology	Status
Positive protection devices	1. Automated equipment with truck-mounted attenuators	Research and development
	2. Mobile barrier	Available
	3. Automated flagger with intrusion alert	Available
Worker warning systems	4. Intrusion alert systems with equipment-mounted sensors	Research and development / some applications available
	5. Intrusion alert systems with cone/barrel-mounted sensors	Available
	6. Intrusion alert systems with networked cone/barrel system with sensors	Available
	7. Intrusion alert systems with pneumatic tubes	Available
	8. Intrusion alert systems with Bluetooth	Research and development
	9. Intrusion detection with computer vision and ranging	Research and development
	10. Smartwatches and bracelets	Research and development
Driver warning systems	11. Dynamic message signage	Available
	12. Queue warning systems	Available
	13. Unmanned aerial systems for signage	Research and development
	14. Connected and autonomous vehicles	Research and development
	15. Wearable lighting	Available

Figure 4.2 Work zone intrusion technologies (source: Gambatese, 2022)

Some assessments regarding effectiveness and reliability are included in the NCHRP report (Gambatese, 2022), though these are not based on rigorous evaluations as such. While the technologies discussed aim specifically to address work zone intrusions, some can likely address other types of incidents such as end-of-queue crashes in advance warning and transition areas. It should also be noted that some of the technology in Figure 4.2 may be used as stand-alone products.

TMA outriggers

New Zealand has adopted the use of TMAs with 'outriggers' (Figure 4.3), 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. The outriggers extend from either side of the rear of the host vehicle across adjacent lanes. 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. However, there is apparent potential to extend the utility of TMA resources and achieve greater efficiency through the use of these devices. Safety effects and evaluations of these TMA attachments should be monitored and their future use considered for incident response and potentially other applications.

Figure 4.3 TMA host vehicle with outriggers deployed (source: Waka Kotahi NZ Transport Agency, 2021)

Alternative warning light colours

As mentioned in the findings from worker interviews, concerns about the limited influence of amber warning lights are documented in the literature and were raised by workers in the current research. Alternative warning light colours for traffic control vehicles have been examined in the research literature, including the use of green lights on TMAs used as shadow vehicles for mobile work zones (Brown et al., 2018). This research used simulator and field studies to compare four lighting configurations, including amber/white, green/white, green/amber, and green only. Of these, the most visible configuration, amber/white, also produced the most glare according to simulator results. Green alone produced the lowest glare but also lower visibility. The green/amber configuration found some middle ground between these results and was best regarded by survey participants, while green alone appeared to be associated with lower vehicle speeds in the field study. In conclusion, all four configurations were reportedly viable according to the authors and overall results did not suggest a clearly preferred option.

4.1.4 Approaches to asset maintenance, inspection, and repair

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 section discusses some activities that are amenable to innovation and alternative approaches, specifically pavement surface maintenance and repair, and road asset inspection. Efficient and timely detection and repair of defects can reduce maintenance costs, minimise network disruption, reduce exposure of workers to hazards, and provide a safer environment for the travelling public (Torbaghan et al., 2020).

4.1.4.1 Maintenance activities

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. Further research is required in this area to determine the viability, efficacy and availability of specific systems and products.

Debris removal

Highway debris comes in numerous forms and presents an unexpected and often serious hazard to road users. Timely identification and removal of such debris is essential for road user safety and for maintaining network performance. This must also be achieved with worker safety as a priority. All of these points are noted by Valdez-Vasquez et al., (2014), who identified relevant innovative equipment including promising high speed debris removal systems for US highways. This research also identified a lack of independent research examining traffic and safety impacts and recommended the development of appropriate guidelines and further research in this area.

Surface repair

For pavement surface repair, according to Torbaghan et al. (2020), with use of robotic technology 'sealing small cracks by using 3D printing techniques has shown promising results by achieving superior mechanical properties' (p.83). This is part of a broader conclusion from the study which recommends a proactive approach to roadway maintenance, following a review of current practices and Robotic and Automatic Systems (RASs) for road condition assessment and repair. Further research and development in this area is required.

4.1.4.2 Asset inspection

There is considerable research literature on new and emerging technologies for road asset inspection, including Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGVs), radar, LiDAR and other sensor types, cameras, data logging, Artificial Intelligence (AI) and machine learning, among others. With the rapid advancement of technology and their applications in these areas, various products and services are regularly made available and updated in the market. While a detailed review and examination of the validity/accuracy of these systems and services is beyond the scope of the current project, key points regarding the availability of general features of the technologies are presented in this section.

Remote survey techniques for proactive monitoring of geotechnical assets, identified as embankments, cuttings, and natural slopes, are discussed in Pritchard et al. (2018). This research 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 benefits of the approach may be substantial. Produced for Highways England, the report assesses different applications to provide a guide for selection of the most appropriate solution.

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. A key advantage of the system is reportedly its low power consumption.

A comprehensive description and analysis of relevant technology is provided in *Robots, Drones, UAVs and UGVs for Operation and Maintenance* (Galar et al., 2020), a book of some 400 pages. While it is not possible to thoroughly examine and describe this book in its entirety for the current project, it appears to be a highly valuable and recent resource for future reference on the topic of automated asset inspection. Following introductory and background sections, subsequent chapters of particular relevance to the current project cover inspection methods, sensor types, data acquisition and processing, visualisation, communications, autonomous vehicles, and autonomous inspection with AI.

A range of relatively new road-based services and tools are currently available to facilitate more efficient and safer inspection of road-related assets than afforded by traditional methods of manual inspection. Some example tools and services known to be available in Australia is provided below in Table 4.4 (note that this is not a complete and exhaustive list of tools and services available in Australia, rather this list notes those which appeared and general internet search and consultation with the industry).

Table 4.4 Examples of infrastructure inspection services and tools

Service	Provider	Technology	Application	Claimed benefits/advantage	Link/reference
Pavement analysis only	Vaisala	Geospatial video, AI	>20 surface defect categories, 10m sections	Cost, accuracy, efficiency	https://www.vaisala.com/en/products/road-asset-management
Pavement analysis only	Shepherd	HD imagery, stills 10-15m intervals, GIS	Surface roughness	Cost, efficiency, ease of use	https://www.shepherdservices.com.au/services/road-asset-condition-assessment-system-racas/
Asset analysis – pavement +	ARRB	Video, sensors	Surface defects, friction & texture analysis	Accuracy, integration	https://www.arrb.com.au/asset-management
Asset analysis – pavement +	Retina Visions	Video, AI	20 defect types	Accuracy, 3 lanes per pass, autonomous logging	https://www.retinavisions.com/
Asset analysis – pavement +	Black Moth	Geospatial video	Surface defects Rubbish Graffiti	Cost, accuracy, efficiency, safety	https://blackmoth.com/industries/#section-road-defect-inspection
Asset inspection	In house, other	Drone/UAV	Limited to off roadway	Safety, accuracy, detail, integration	NA

4.2 Expert and industry consultation findings

The project team consulted six international TTM experts between November 2022 and January 2023. This included five experts based in the US and one expert based in Sweden. Consultants collectively provided or identified a total of 29 research reports related to their own work or that of others with which they were familiar. Some of these documents, including internal reports, were previously unknown to the research team and were subsequently incorporated in final updates of the literature review.

Consultation with industry stakeholders took place concurrently with the international expert consultations. These stakeholders included a major transport infrastructure provider (Fulton Hogan), a manufacturer/supplier of innovative TTM devices (Arrowes), manufacturer/suppliers of LED work zone lighting (Pi Variables/OzLED), and an asset inspection services provider (Retina Visions). Two additional manufacturers and suppliers of TTM devices were also approached, but did not respond to invitations to participate in consultation.

In addition to the industry stakeholders above, the TfNSW Director of Infrastructure Technology Services was consulted on the use of drones for asset inspection and incident response services. Several employees of Queensland Transport and Main Roads were also consulted to understand how the roadwork camera enforcement program works in Queensland.

4.2.1 Work zone speeds

Introducing the current section, it should be noted that work zone speed limits in Australia are generally substantially lower than in the US for comparable roadways. Discussion of this point with expert consultants revealed a common reluctance of US authorities to reduce speed limits by significant amounts, if at all, due to traffic flow priorities (including less speed variance) and resistance among some drivers to comply. Nonetheless, various speed reduction measures are used and many published evaluations are available with findings relevant for Australia. Across Europe, work zone speed reduction guidelines and requirements differ by country, but decrements of 20km/h are common according to Varhelyi et al. (2019), as in Australia (e.g., from 100 to 80 then 60km/h, or a straight reduction from 100 to 60 km/h with advance warning signs).

Discussing policy regarding work zone speed limits across US states, and whether there is any comparative analysis to gauge the safety impacts of policy variation, it was noted that decisions tend to be made in a 'fragmented' manner. Comparative evaluation was also said to be too difficult due to the large number of confounding factors that would need to be controlled for.

4.2.1.1 Compliance and enforcement

The prevalence of speeding in work zones and its contribution to crash causation and incident severity is thoroughly documented in the literature and acknowledged by expert and industry consultants. Enforcement of work zone speed limits was thus a key topic in consultations. In the US, Illinois was noted as the first state to do photo-radar WZ speed enforcement and a report on the associated trial and evaluation was provided by a (non-author) consultant. Key findings of the study by Benekohal et al. (2010) are summarised above in the literature review (Section 4.1). Some other states are now doing work zone speed enforcement on high volume roads and it is found to be effective for longer-term work zones. However, one consultant noted that, overall, the US lags somewhat compared to other countries in automated enforcement of work zone speeds. Texas, the second largest US state by area and population, is among the states *not* doing automated enforcement. Reasons for such practices were not made clear in the consultations.

4.2.1.2 Variable speed limit (VSL) signs

Some US jurisdictions employ VSL while others do not, and one consultant noted that this is not currently found on most US highways. Similarly, European jurisdictions were noted to vary in this regard. For example, Netherlands was said to have a lot of VSL and supporting 'smart motorway' infrastructure, while nearby Sweden does not.

A trailer-based and advisory only VSL was found to have limited effect according to one expert, who also reported that fixed VSL had generally not been well-received and showed inconclusive findings. However, there is considerable literature on VSL demonstrating generally positive effects. These mixed findings could be due to a range of factors that influence the effectiveness of VSL, including site, geometric, traffic, and other operational characteristics. Future research is recommended to better understand the effectiveness of this important measure using local 'contextual' conditions for worksites and driver behaviour.

4.2.1.3 Other speed controls

Temporary Portable Rumble Strips (TPRSs) were said by consultants to be generally effective for alerting drivers and reducing speeds. However, rumble strips bring limited speed reduction in one consultant's (4) experience. One expert (2) identified that some TPRS are better than others in terms of performance, stability, durability and/or ease of use. As with other TTM devices, one important factor to consider when using TPRS is installation and removal time, which can potentially be minimised with the aid of vehicle-mounted mechanical devices. The report by Brown et al. (2022) contains some relevant information from TPRS manufacturers.

It was also noted that TPRS are sometimes used in combination with speed feedback signs and related Queue Warning Systems (QWSs). Research in the US found good effects of the rumble strips at night without QWS, somewhat similar to the effect of QWS alone. According to one expert, use of TPRS is considered feasible on smaller roads, but less so on large multi-lane motorways. Additionally, further research was recommended on spatial and temporal effects of rumble strips to help determine optimum deployment specifications and conditions. A maximum spacing of ~400m between TPRS groups was suggested.

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Speed feedback signs have generally been found to have a positive effect, although this may diminish over time and appears most effective in short term deployment. Additionally, this measure may have more positive effects when accompanied by flashing lights ('presence lighting') on top of the speed feedback sign. The research team was alerted to a report on this topic (Sakhare et al., 2021), which is summarised above in Section 4.1.

4.2.2 Other driver behaviour

Consistent with the literature, experts agreed that driver distraction and inattention remains a major issue and one of the most difficult one to address. One expert reported that the known difficulties of changing driver behaviour has at least partly motivated an increased focus on engineering measures. Nonetheless, the use of traditional measures such as flashing lights and signage remains a standard work zone feature.

Discussing the common problem of tailgating with one expert, it was noted that Israel was one country with a dedicated program of enforcement on tailgating. While this did not target work zones specifically, end-of-queue crashes can potentially be reduced to some extent through a general reduction in tailgating. It is likely that few other countries have an ongoing program of this type, and instead rely on only random and sporadic enforcement to reduce this behaviour. Other measures mentioned to address tailgating include chevrons on the pavement surface, but the extent to which these are effective (including for work zones) was not known.

4.2.3 Signs and information provision

According to one expert, the US faces similar credibility issues to Australia concerning signage and related control, such as warnings provided too early and/or at inactive sites. Traffic control providers may be excessive with controls as don't want to be liable in event of an incident. He also suggested that, generally, multiple CMS/VMS spaced at 1-2km intervals represents best practice for EOQ management, while also noting the problems with identifying and predicting queue length and EOQ position.

Drones for traffic monitoring and displaying signs, including speed signage were proposed in Europe according to expert consultation. This was not approved by the relevant authority so was apparently never trialled. Discussion with a relevant consultant in Australia who conducts drone-based asset inspection revealed that approval for this would be unlikely in Australia as well, as drones are not permitted to fly directly over highways. Nonetheless, Gambatese (2022) notes huge potential for unmanned aerial systems in provision of signage, queue monitoring, intrusion alerts and errant vehicle warnings, despite the lack of trials and evaluations.

An European work zone safety expert identified an innovative mobile gantry system developed in the Netherlands. The researchers were directed to a recent report containing a brief summary of this device (Varhelyi et al., (2019), which is able to extend across two lanes if positioned on the shoulder, as described below (p.28):

> *Use of mobile gantry cranes with variable message signs improve visibility of the road signs. They can be deployed from the hard shoulder, but possible space constraints must be considered. Mobile gantry cranes, being a roadside obstacle themselves should be put behind a barrier. This, however, would limit their possible application (signing above the lanes would not be possible). In this respect, the mounting of crash cushions on the mobile gantry cranes is highly recommended if they are not placed behind a barrier.*

Subsequent searches by the authors of this report did not find any research or other information on the abovementioned mobile gantry crane.

4.2.4 Visibility, markings and delineation

As might be expected, high visibility and specifically high contrast is very important according to experts consulted. For warning lights and beacons, alternative colours (other than amber) have potential to improve safety in some situations.

Alternative colours for temporary lines (pavement markings) brings potential for confusion among drivers according to one expert. Nonetheless, orange temporary markings have been used in some European countries with no adverse effects identified (Strnad et al. 2019). Problems with confusing guidance are noted, however, where pre-existing lines are not removed when work zone markings are placed to identify the correct path for motorists.

Sequential lighting was reported to be beneficial by experts in the US and Europe where they are widely used. However, sequential lighting systems come in various forms and configurations, and while there are numerous evaluations of specific systems, it is difficult to determine which of these are most effective and practical in terms of deployment.

An evaluation of green lights on TMAs was referred to the researchers during the consultations. This report (Brown et al., 2018) was located and subsequently included the above literature review. In summary, the study examined effects of four lighting configurations, three of which included a green light. Concluding remarks stated that 'all four configurations appear to be viable although none is clearly superior' (p.56).

4.2.5 Positive protection and exposure reduction

4.2.5.1 Portable barriers

Use of portable barriers was discussed with expert consultants, with water-filled barriers being the type most commonly used at short- and medium-term sites. These provide some positive protection while also providing clear guidance for drivers. While one US consultant expressed that barrier deployment by truck is expensive, an European expert described a system which may lower costs as well as risk after initial outlay. The task of shifting longitudinal barriers laterally across lanes can be completed with a specialised vehicle (truck) and connected barrier system according to one consultant. 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 (see Figure 4.4).

Figure 4.4 Quick moveable barrier (source: Varhelyi, 2019)

4.2.5.2 Attenuators

Recent US trials involving autonomous TMAs (ATMAs) were discussed with multiple consultants. A trial was currently in progress at the time of consultation and involved a driver on board the host vehicle. 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), with the following reproduced from that report (p.ii)

> *The ATMA pilot demonstration testing in Tennessee concluded primarily that the ATMA system is better suited for work zone operations that require continuous movement for longer periods of time. Retracing or installation of pavement markings and roadway sweeping are examples of such operations. Based on the pilot results, the tested ATMA system warrants further development and testing for work zones requiring stop-and-go applications. Pothole patching, weed spraying and trash pick-up on the roadway shoulder are examples of such operations. The ATMA system presents technological advancements that increase safety in work zones. It can be further enhanced by future refinement and implementation of additional system functionalities.*

Regarding another innovation, expert consultants were asked whether they were aware of the TMA 'outrigger' or similar devices as used in New Zealand. No consultant expressed awareness of such devices. In the absence of any published literature or expert knowledge, further information was sought directly from industry stakeholders. With the assistance of the Waka Kotahi NZ Transport Agency, the research team consulted with the relevant industry partner who developed the concept and device. The outrigger was said to be developed to address the issue of vehicles passing the TMA when they should not be (overtaking and undertaking). Such violations were said to often involve 'hostile' drivers who become frustrated at lane closures. While the consultant was not aware of any vehicle impacts with the outrigger devices, their frangibility was noted as a design feature. The consultant noted some initial resistance against outriggers by the road authority due to lack of formal approval but noted that a 'practice note' was currently being developed to address this concern. Safety effects and evaluations of these TMA attachments should be monitored, and their future use considered for incident response and potentially other applications.

4.2.5.3 Mobile barrier truck

Mobile barrier trucks (specifically MBT-1) are a relatively new control in US work zones for positive protection. It was noted that some crews or individual workers may be reluctant at first to use or work with the MBT-1, and this was thought to be largely due to unfamiliarity with the device. It was said that this reluctance can be overcome with persistence, as acceptance was expected to increase with familiarity. This was supported as a general observation by industry consultants also.

Discussion of the MBT-1 with the European expert revealed that while he was aware of the device, it had not been approved for use on European roadways. This was said to be due to the difficulty of manoeuvring the large trailer and the associated transportation issues.

4.2.5.4 Automated cone and other deployment trucks

Vehicles with systems for automated deployment of traffic cones and other devices were discussed with the European expert consulted, who also referred to reports with relevant information. First, an automated cone deployment truck was trialled in Ireland, but was found to 'not suit the Irish scenario' through testing, so its use was discontinued (year unknown).

One expert has reportedly seen trucks for automatically deploying the large channelising drums which are used for guidance and taper demarcation on US highways. These drums are widely used in the US in preference to smaller cones, with the observation during consultation that drivers don't want to hit them. No information was given on the extent of use of the automatic deployment truck in the US. However, for Australian work zones, it may be worth considering the large drums for greater visibility and possibly greater compliance (although they may be rejected due to risk to workers on foot of being hit by dislodged drums).

In Australia, a new Automated Cone Truck (ACT) has recently been developed and has received a Victorian award for innovation. The development of this ACT was discussed with the industry consultant who is directly involved and has engaged multiple state transport departments in consultation and promotion of the product. Key features of the ACT are single driver operation, automated deployment and retrieval and 400 cone capacity.

4.2.6 Smart work zones

At the time of consultation, numerous US companies were reportedly supplying 'smart work zone' technologies in response to increasing concerns to address congestion issues. There was said to be strong competition between these companies, with technologies and related systems gradually evolving to improve reliability and ease of use.

Industry consultants spoke of the increased use of technology in TTM devices as well as in management of operations. Specific devices mentioned included speed activated signs, remote controlled stop/go devices and networked VMS. Such developments are generally understood to be beneficial from safety and economic perspectives, although formal evaluations are often lacking.

4.2.6.1 Warning systems

The use of QWS is reportedly now common in the US, with several vendors providing QWS of similar types. The research team was referred to two studies on crash reduction attributable to QWS, conducted in Texas (TTI), and Wisconsin. Both studies were said to have found similar results, including significant reductions in crash occurrence and crash severity (Ullman et al., 2016). These studies are described in greater detail in the literature review.

Correct installation of QWS components was said by experts to be critical, where incorrect placement will result in errors and diminish credibility of the systems with motorists. Maintaining credibility was noted as an important factor for the systems to be effective. Additionally, first-time users of the systems could struggle with set-up, and provision of training with an experienced technician was recommended. Asked about key features of a best practice QWS, one expert mentioned multiple VMS at spacings of 1-2km.

The need for a low-cost and easily deployable QWS for short term work zones, and development of such, is discussed in a recent report from the University of Wisconsin (Chitturi et al., 2020). This research notes the requirement for testing and approvals of equipment according to MASH standards as a barrier to implementation of a more versatile QWS system. Where QWS are used, it was noted that one specific jurisdiction (DoT) wants queue detection and warning issued within 1 minute of queue formation.

One consultant stated that an extended trial was currently underway of automated warning systems for workers and warning system for drivers, with these to conclude 1-2 years from the time of consultation. While noting no direct experience with QWS specifically, this expert mentioned that current trials and evaluations were expected to demonstrate QWS crash reduction potential.

An industry consultant identified vehicle activated signs which can be networked to provide tailored messages and warnings according to traffic behaviour at different traffic control points (i.e., vehicle speeds). These locally produced devices can also be linked with remotely controlled portable traffic lights for stop/slow operations, and can potentially be employed in a QWS.

4.2.7 Information, education and awareness

Use of technology for in-vehicle driver warning of work zone presence was discussed with multiple experts.

Several US states (e.g., Alabama, Arizona, Kentucky, Georgia, Michigan, New Jersey, North Carolina, Ohio, and Texas) are currently experimenting with or planning to develop capabilities to send real-time work zone information to commercial motor vehicle (CMV) drivers via in-cab alerts through navigational apps or telematics systems to reduce the risk of CMV crashes in work zones. In-cab safety messages could include warnings about slowdowns, reduced speed limits, lane closures, lane shifts, or detours. Navigational apps (e.g., WAZE, HERE, those developed by state departments of transportation, etc.) that provide visual and auditory alerts to drivers about work zones on their travel routes are widely available. The US Federal Motor Carrier Safety Administration (FMCSA) has provided grants to multiple agencies to help get work zone information to CMV drivers via such apps (FMCSA, 2020; Luna et al., 2020). However, the work zone information provided by such apps often does not accurately reflect actual work zone conditions, thus these could reduce the credibility of work zone signage and systems further to motorists.

The development and ongoing enhancement of the Work Zone Data Exchange (WZDx) Specification has helped agencies and various private-sector entities improve accessibility to, and sharing of, real-time work zone event information in a standardized format (WZDx, 2022). The Georgia DOT is working to develop CMV safety alerts using the WZDx specification. Similarly, Michigan consortiums have received multiple FMCSA grants to improve CMV driver access to traffic condition information around static work zones as well as awareness of mobile, short-duration, and short-term work zones via connected work zone devices (Brookes, 2022). As another example, the North Carolina DOT contracted with Drivewyze® and INRIX© to provide real-time in-cab alerts through an Electronic Logging Device (ELD) already included in most CMVs. On certain travel corridors, CMV drivers are alerted when the system detects significant slowdowns in the next two miles ahead or if delays greater than three minutes are detected over the next three miles (Clark, 2022). As part of the pilot program, the consortium also tested the use of the in-cab technology to warn CMV drivers of possible delays at a work zone 40 miles away to encourage diversion to an alternate route. Similar efforts to utilize existing ELD technology to communicate with CMV drivers are being pursued in New Jersey, Ohio, Texas, and Virginia.

On the topic of driver education in the US, one expert noted that driver training programs do not address driving safely in work zones and as such could be improved. In Australia, this issue was raised by workers interviewed for the current study and has also been reported previously in a study of worker perceptions in Queensland (Debnath et al., 2015).

4.2.8 Incident response

The international experts consulted were largely involved in work zone safety research for planned works and had little direct experience with examining incident response. Some relevant information was gathered, however, including that organisational hierarchy at incident response is well-observed in the US according to one consultant. Additionally, some US emergency services are reportedly using drones for incident response with some success, as well as for accident reconstruction and investigation, though details were not able to be provided. Work was reportedly also underway in Australia on the use of drones for incident response.

A range of issues and potential solutions that are relevant for both incident response and planned works were discussed. Among these is VSL, which has been discussed above in Sections 4.1 and 4.2.1. The 'loop around' times and opportunities to get from one point to another was discussed and identified as important for timely incident response and efficient TTM. Consultation suggested that the longest distance between interchange points on US highways is approximately 14km, with at least one turnaround point midway on such sections, so roughly every 7-8km. Public use of such turnarounds is a noted concern due to the potential for this to disrupt traffic flows and generate traffic conflicts.

Some research has been conducted on audible alarms and alert systems for incident response in the US state of Michigan. It is understood that some systems capable of triggering such alerts may also be used to trigger speed limits. Industry consultation identified sequential lighting systems that may be rapidly deployed within or on top of traffic cones, or as stand alone devices to provide traffic guidance at lane and/or shoulder closures. This consultant also identified small magnetic flashing beacons which may be easily attached to PPE such as hard hats and steel capped boots.

TMA outriggers are discussed above in Section 4.2.5.2 as a promising innovative measure. As mentioned, these have potential to improve both safety and efficiency in incident response, though formal evaluations are currently lacking. According to the consultations undertaken, these are increasingly used in rolling blockades for debris removal, and short term lane closures. Related to this, the use of automated debris and litter removal devices is reportedly common in the US, though detailed knowledge of the various types was not available.

4.2.9 Research, collaboration and management

Good collaboration between researchers, industry and government could help to develop large scale research and evaluation programs. One consultant noted that, generally, work zone traffic data is not as good as desired for research purposes. Work zone event data for public access and use is also lacking in most jurisdictions. Consultation alerted the researchers to the development of the Work Zone Data Exchange (WZDx) Specification, which 'aims to make harmonized work zone data provided by infrastructure owners and operators available for third party use, making travel on public roads safer and more efficient through ubiquitous access to data on work zone activity' (WZDx, 2022). More specifically for research, work zone incident data can be improved through linkage of police and hospital records, which is occurring in some European jurisdictions according to one consultant. The need for data linkage for Australian work zones was also identified in the literature review (see Blackman et al., 2020 for a detailed comparison of different types of crash and incident databases in Queensland, Australia as well as McClure et al., 2023 the use of crash data comparison of safety levels at different stages of roadworks).

In discussion concerning work zone management and guidelines, Ireland was noted as exemplary among European countries for work zone safety auditing and inspections. A Standards document for temporary safety measures inspection from Transport Infrastructure Ireland was provided directly by the expert consultant.

An industry consultant noted that temporary traffic management does not work as well as it could, due at least in part to contractor issues and priorities. Similar thoughts were expressed by M1 workers interviewed for the current project.

4.2.10 Asset inspection, specialist works vehicles and related technology

An asset inspection industry representative was consulted about road-based asset inspection using AI and video recordings captured by vehicle-integrated mobile phone. The system discussed is 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. It was also said that accuracy is not affected by vehicle speed, although was reportedly limited during night time conditions. It is important to note that formal independent evaluations of such systems were not found in the literature.

Use of drones was said 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 inspection of bridges and related infrastructure discussed in consultation with a relevant 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.

One international expert noted that the University of California was currently working on automated vehicles/systems for surface repair and (potentially) other works, but detail on these developments was not available at the time of the 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. It seems possible that this is one aspect being considered or addressed in the work by University of California, however this cannot be confirmed at the time of writing this report.

Overall, it appeared that significant research and development works are being undertaken in the use of technologies for automated and unmanned inspection of assets. It is recommended that specific products and systems, upon formal and independent evaluation, should be considered for future trials and use in the context of M1, as such technologies have significant potential to reduce the exposure of workers to traffic and incidents.

5 SOLUTIONS AND RECOMMENDATIONS

5.1 Background

The current section presents possible solutions and estimated outcomes separately for the three application areas:

i. temporary traffic management,
ii. work methods, and
iii. asset inspection.

Note that for each application area, the solutions are identified as applicable to planned works (PW), incident response (IR), or both.

The availability and practical feasibility of solutions can be confirmed for those measures which are already in use and/or have been subject to trial(s) and evaluation in Australia with positive results. These measures can potentially begin to be implemented without delay, although specific trials in the context of M1 is recommended to confirm the suitability in the M1 environment and to quantify the benefits provided by the measures.

Other measures are identified as potential future solutions for which the availability, feasibility and/or effectiveness requires further investigation, as reliable information on these aspects were not available at the time of writing this report. Some solutions are not currently available in Australia and/or are likely to require further research and development, followed by formal trials. Solutions which are not likely to be considered suitable for use on the M1, such as stop/slow traffic control devices, have not been included in the recommendations.

Matrices of the potential solutions and outcomes for each application area presented below in Tables 5.1-5.4, forming the basis for subsequent recommendations. The recommendations are based only on the estimated outcomes, with consideration of costs, regulations and other factors such as specialised skills and training being beyond the scope of the current project. The crash worthiness of many potential solutions is currently unknown, particularly for those that are not currently in common use, and may also depend on implementation factors. However, for those solutions that are in common use or are thoroughly trialled and evaluated, crash worthiness is generally deemed to be acceptable if appropriately implemented.

The Tables 5.2-5.4 provide lists of different solutions considered for recommendations and their impacts on different outcomes. Among these lists, a selection of recommendations is discussed in Sections 5.2-5.4 as priority considerations for trial and/or implementation on the study section of M1.

Note that the recommendations are provided as general recommendations for the M1 section, without making considerations for specific work or site setup, including the location, timing, and context of setting up the solutions noted in the recommendations. In future trials and use, it is strongly suggested that risk assessments, traffic guidance scheme developments, and other relevant approvals are considered before implementing the recommendations on site.

Table 5.1 Legends and background information for Tables 5.2-5.4

Key to ratings/estimations based on current knowledge:
Yes = Almost certain to have some positive effect
Likely = Positive effect considered likely in most cases
Potential = Potential for positive effect – more information needed
Conditional = Effects dependent on site characteristics, implementation and other factors
No = Unlikely to have positive effect
NA = Solution not applicable to outcome measure
TBC = To be confirmed – more information needed (reliable information not available at the time of writing this report)

Other abbreviations and symbols	**Work type**
IV = in-vehicle	PW = Planned works
IRV = incident response vehicle	IR = Incident response
TMA = truck-mounted attenuator	Both = Planned works & incident response
VMS = variable message sign (electronic)	
VSL = variable speed limit	
TC = traffic controller	

Table 5.2 Temporary traffic management solutions

Solution	Reduce Traffic exposure	Reduce Incident exposure	Reduce Incident severity	Improve driver compliance	Ease of use	Work type
VMS (increased use, portable/fixed)	Conditional	Likely	Potential	Yes	High	Both
VSL (portable/fixed)	Conditional	Likely	Likely	Yes	High	Both
Speed feedback sign	No	Potential	Likely	Yes	High	PW
Vehicle-activated warning sign	No	Potential	Likely	Yes	High	PW
Speed cameras (including P2P)	No	Potential	Likely	Yes	High	PW
Police presence (increased)	No	Yes	Yes	Yes	Conditional	Both
Automated cone truck	Yes	Yes	Yes	No	Conditional	PW
Manual cone truck (increased use)	Potential	Potential	Yes	No	Conditional	PW
Mobile barrier truck (MBT-1)	Yes	Yes	Yes	No	Conditional	PW
TMA outrigger	Yes	Potential	Potential	Potential	High	Both
Queue warning system (QWS)	No	Likely	Likely	Yes	Conditional	IR
TPRS (manual install/removal)	No	Likely	Likely	Yes	Conditional	PW
TPRS (auto install/removal)	No	Likely	Likely	Yes	High	PW
Errant vehicle warnings	No	Likely	Likely	Potential	Conditional	PW
Radio messages/alerts	No	Potential	Potential	Potential	Conditional	Both
GPS info (e.g., Waze, Google maps)	No	Potential	Potential	Potential	Conditional	Both
Awareness campaigns/driver ed.	No	Potential	Potential	Potential	High	Both
Sequential lighting (guidance)	No	Likely	Likely	Potential	Conditional	Both
Alternative light colours	No	Potential	Potential	Potential	High	PW
CCTV monitoring	Likely	Potential	No	Potential	High	IR
Drone surveillance/inspection	Potential	Potential	No	No	Conditional	IR
Mobile gantry	No	Potential	Potential	Potential	Conditional	PW
Barrier shifting truck	Yes	Yes	TBC	No	TBC	PW
Improve TC training/competency	No	Potential	Potential	No	NA	Both

Table 5.3 Work methods solutions

Solution	Reduce Traffic exposure	Reduce Incident exposure	Reduce Incident severity	Improve driver compliance	Ease of use	Work type
Pothole/pavement truck – automatic	Yes	Yes	Yes	No	TBC	PW
Vacuum truck	Yes	Yes	Yes	No	TBC	PW
Sweeper truck/accessory	Yes	Yes	Yes	No	Conditional	Both
Other tools (e.g., sign straightener)	Potential	Potential	No	No	Conditional	Both
Crossovers/turnarounds (increase)	Yes	Potential	No	No	Conditional	PW
Communications technology (improve)	Potential	Yes	Potential	Potential	Conditional	PW
Planning & coordination (e.g., clumping)	Yes	Potential	No	No	NA	PW
Remove redundant assets (e.g., shutters)	Potential	Potential	No	No	NA	PW
IRV design/configuration (improve)	No	Potential	Potential	No	Conditional	IR
Ensure sufficient shoulder width	Potential	Yes	Yes	No	NA	Both
Training and competency (improve)	Potential	Potential	Potential	No	NA	Both

Table 5.4 Examples of asset inspection solutions

Solution	Reduce Traffic exposure	Reduce Incident exposure	Reduce Incident severity	Improve driver compliance	Ease of use	Product
IV Geospatial video, AI (pavement)	Yes	Yes	Yes	NA	TBC	1, 2
IV HD imagery, stills (pavement)	Yes	Yes	Yes	NA	TBC	3
IV Video, sensors (pavement)	Yes	Yes	Yes	NA	TBC	4
IV Video (pavement & adjacent assets)	Yes	Yes	Yes	NA	TBC	5, 6
Drone: Video, possible LiDAR 3D models	Yes	Yes	Yes	NA	TBC	7

1: Vaisala, 2: Black Moth, 3: Shepherd, 4: ARRB, 5: Retina Visions, 6: RoadBotics (Michelin), 7: Various/in-house

5.2 Temporary traffic management (TTM)

5.2.1 TTM Recommendations

The following measures are recommended as priority considerations for trial and/or implementation on the study section of M1. Several of these measures support the realisation of a smart motorway, which should be an ultimate medium- to long-term objective of this road section. Where a control or measure is already in use, the recommendation is that its use be increased where feasible. Trials of new measures should be accompanied by rigorous formal evaluation where possible.

5.2.1.1 Variable message sign (VMS) and related information provision

Findings of the current research suggest that increased use of VMS is likely to improve compliance, reduce exposure to incidents and potentially reduce incident severity. VMS can also be expected to reduce exposure to traffic, particularly where it can be provided as permanent fixtures and remotely operated. Whether fixed or portable, message content and symbols must be appropriate for conditions and easy for all drivers to understand.

5.2.1.2 Variable speed limit (VSL) sign

The infrastructure needed for permanent VMS, including overhead gantries, can also accommodate VSL signs which, if linked to appropriate sensors and information technology, may respond automatically to different levels of traffic congestion and incidents (e.g., broken down vehicle, presence of hazards such as debris on road). When installed at appropriate spacings for a speed environment (e.g., in a smart motorway setting), VMS and VSL could potentially better inform drivers of road/traffic conditions and regulate traffic flow than using static signs or either of these electronic signs alone.

5.2.1.3 Speed feedback and vehicle-activated warning signs

Speed feedback signs should be used at work sites wherever possible as a reminder to drivers to check their speeds and adjust if needed. Consideration should also be given to trials incorporating flashing beacons on top of speed feedback signs as research has found this to be an effective addition for drawing drivers' attention. The technology for speed feedback also supports delivery of other vehicle-activated messages which can be tailored according to need. These measures should improve compliance, reduce exposure to incidents and potentially reduce incident severity by lowering vehicle speeds.

5.2.1.4 Traffic monitoring and congestion warning systems

Increased CCTV monitoring is recommended to assist with incident assessment and response. This is expected to be incorporated in smart motorway infrastructure, which should also accommodate a congestion warning system. Future advancements in AI and image processing technologies could provide a reliable platform for automated detection of incidents, congestion, and other road hazards such as presence of debris on road.

5.2.1.5 Errant vehicle warning systems

A wide range of technologies are identified in the literature for warning drivers of errant behaviour and alerting workers to impending work zone intrusions. Although development, refinement and evaluation of such technologies is ongoing, some are available and should be strongly considered for trial due to the high potential to reduce incident exposure and severity. Through early detection of errant vehicles and potential intrusion to work/incident sites, future systems could consider the use of different warning mediums for workers, such as auditory alerts, haptic-based alerts, wearable technologies for workers. It is noted that future research and development is needed for these different types of alert mediums.

5.2.1.6 Speed cameras

Mobile speed cameras are recommended to be trialled and used at work sites. TfNSW should liaise with Queensland Transport and Main Roads on its development and trial of the current Queensland work zone speed enforcement program. While the current Queensland program has focus on enforcement on the fast lane, considerations should be given on enforcement on all lanes of the M1 section. Following trials, Point-to-point (P2P) speed enforcement should also be introduced as a general measure on sections where it can be implemented to improve overall speed limit compliance.

5.2.1.7 Increased police presence

Increased visible presence of police at work sites is highly likely to improve work zone speed compliance and is therefore recommended. Police cars should be located safely within work zones and protected by appropriate traffic controls suitable for conditions.

5.2.1.8 Automated cone truck

Trial of new commercially available automated cone trucks is recommended for trial to reduce worker exposure to traffic and incidents. 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.

5.2.1.9 Mobile barrier truck (MBT-1)

Further trial of the MBT-1 mobile barrier truck is recommended for applicable operations to reduce worker exposure to traffic and incidents. Consideration should be given to ways in which use of the MBT-1 can be made more practical and feasible, such as increasing turnaround options for example.

5.2.1.10 Improve driver awareness

Although the impacts and safety benefits of public awareness campaigns can be difficult to measure, it is recommended to continue to inform road users of work zone safety

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issues and related driver behaviour through appropriate media. Novel approaches to messaging may be worth considering, however, their novelty effects should be monitored through rigorous evaluation. Driver education, training and licensing programs should incorporate and/or strengthen content on safe driving in and on approach to work zones and incident sites.

5.2.1.11 Sequential lighting

Formal trial and evaluation of sequential lighting system/s for guidance at tapers and channelisation is recommended. Such technology has potential to reduce worker exposure to incidents. With a range of systems available (e.g., within or on top of traffic cones or posts, vehicle activated or otherwise), consideration needs to be given to which may be most appropriate for relevant M1 operations.

5.2.2 TTM solutions for monitoring and future consideration

The following solutions should be monitored in terms of development, availability, refinement, and evaluation, and considered for future trial and implementation.

- TMA outrigger – further consultation needed with New Zealand stakeholders
- TPRS (automated install/removal) – confirm M1 suitability before trial
- Radio messages/alerts – more information needed
- GPS info (e.g., Waze, Google maps) – already in some use but effects are unclear
- Alternative light colours – wide range of options but research is inconclusive
- Drone surveillance/inspection – subject to restrictions on use above roadways
- Mobile gantry – not available in Australia and more information needed
- Barrier shifting truck – not available in Australia and more information needed

5.3 Work methods

5.3.1 Work method recommendations

5.3.1.1 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. While further investigation is needed to identify and confirm the availability of relevant products, trial and evaluation of the most promising options is recommended to reduce worker exposure to traffic and related incidents.

5.3.1.2 Debris removal vehicles and accessories

Trial of new vehicle-based tools and technologies for debris removal and drainage maintenance is recommended. This may include vacuum trucks for clearing drains and scuppers, and sweeper trucks and related accessories.

5.3.1.3 Crossovers/turnarounds (increase)

Increased provision of and access to crossovers and turnaround points is recommended to reduce travel times to, from and between sites, for incident response and planned works 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.

5.3.1.4 Communications technology (improve)

Some sections of the M1 are known to be compromised in terms of telecommunications and signal transmission. Efforts should be made to ensure that communication networks are as reliable as possible in all locations and that workers are provided with (and competent in the use of) the most appropriate technology. This may result in reduced exposure to traffic and related incidents and allow more efficient completion of works.

5.3.1.5 Planning & coordination

Improved planning and coordination of operations is recommended to allow some works to be completed with greater efficiency, particularly for very short duration and mobile works. M1 workers indicated that such 'clumping' of different activities could be achieved more regularly, thereby reducing exposure to traffic and related incidents. Similarly, planning and coordination between TfNSW teams and contractors could also be improved, although it is acknowledged that TfNSW has limited control over contractor practices and priorities.

5.3.1.6 Remove redundant assets

The removal of redundant assets is recommended where possible 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 recommended to identify all of those which are no longer needed or in use.

5.3.1.7 Ensure sufficient shoulder width

Some sections of the M1 do not provide sufficient shoulder width for safe storage of traffic management vehicles, work vehicles and public vehicle breakdowns. It is recommended that this be addressed as a priority, to allow occupants to exit vehicles safely and provide sufficient distance from fog lines for stationary vehicles.

5.3.1.8 IRV design/configuration

A review of IRV design and configuration is recommended to ensure that vehicles are fit for purpose. While it is not suggested that this is not currently the case, new Austroads guidelines for IRV design have been developed and are due for 2023 publication.

5.3.1.9 Other tools

A range of other tools for completing works on and adjacent to the M1 may be subject to review and considered for potential upgrade. While a thorough identification and review of such tools was not undertaken as part of the current research, M1 workers identified room for potential improvement in this area. Relevant tools include but are not limited to sign straighteners, post hole diggers, woodchippers, mowers and slashers, among others.

5.3.1.10 Training and competency

Interviews with workers suggested that in some cases their colleagues showed limited competency in performing tasks assigned to them. While this was not reportedly a frequent concern, addressing the issue by ensuring sufficient competency and training, as well appropriate task allocation, is likely to result in safer and more efficient completion of some activities. As such, a review of relevant programs and processes is recommended.

5.4 Asset inspection

A range of asset inspection services and technologies was identified as part of this project, as summarised above in the relevant sections. While this is not an exhaustive list, these can be categorised in the following groupings according to the different technologies used:

- IV Geospatial video, AI (pavement)
- IV HD imagery, stills (pavement)
- IV Video, sensors (pavement)
- IV Video (pavement & adjacent assets)
- Drone: Video, possible LiDAR 3D models

Some such asset inspection services and technologies are currently being used and/or trialled in NSW and other jurisdictions. All can achieve the key objective of substantially reducing worker exposure to traffic to some degree and an appropriate solution should be pursued. However, which is the most appropriate solution for the M1 and comparable roadways must depend also on the broader objectives of TfNSW in terms of data collection and processing requirements, efficiency, reliability, cost, and other factors. Specific service or system recommendations are not made in the current project, however, it is recommended that the above considerations are made in selection of services and systems for trials. The current project recommends harnessing specific expertise for further exploration, with detailed objectives specified for asset inspection and management outcomes.

5.5 Other considerations

While TfNSW provides extensive induction and training materials specific to the M1 environment in addition to general training, periodic review of traffic controller, incident responder, and worker competency and training is recommended. Strengthening of processes for identification and reporting of deficiencies and problems should support such review to target specific issues in need of attention.

General health of workers should be supported through appropriate health and wellbeing programs and activities.

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