Inventory of best practices to prevent incursions into work zones - Literature review.

Varhelyi, Andras

2018

Document Version:
Other version

Link to publication

Citation for published version (APA):
Varhelyi, A. (2018). *Inventory of best practices to prevent incursions into work zones - Literature review.* (Version 5.0 ed.)

Total number of authors:
1

CEDR Transnational Road Research Programme
Call Safety

Funded by Belgium-Flanders, Ireland,
Netherlands, Slovenia, Sweden, United Kingdom

Incursion Reduction to Increase Safety in road work zones

Task 1.3

Inventory of best practices to prevent incursions into work zones

Literature review

Internal report

Date (28/04/2018)

Partners

KFV Kuratorium für Verkehrssicherheit, Austria

Lund University, Sweden

Vias institute, Belgium

CEDR Call 2016: Safety

Incursion Reduction to Increase Safety in road work zones.

Inventory of best practices to prevent incursions into work zones

Literature review

Start date of project: 01/09 2017 End date of project: 30/06/2019

Author(s) of this deliverable:

András Várhelyi (Lund University)

Version: 5.0

Table of contents

List of abbreviations

AWIS - Automated Work zone Information System
CMS - Changeable Message Sign
CB - Citizen Band
DLM - Dynamic Lane Merging
ESL - Electronic Speed Limit
HAR - Highway Advisory Radio
IAS - Intrusion Alert System
ITS - Intelligent Transport System
LED - Light Emitting Diode
PPRS - Portable Plastic Rumble Strips
SPE - Speed Photo-radar Enforcement
SMD - Speed Monitoring Display
TIPS - Travel time Prediction System
TMA - Truck Mounted Attenuator
TM - Traffic Management
VMS - Variable Message Sign
VSL - Variable Speed Limit

Executive summary

The aim of this report was to review the literature to identify existing best practices used to prevent incursions into work zones and improve safety of road users and road workers. A systematic literature search was conducted and various available sources referred to by knowledgeable experts in the field were considered. Best practices found in the literature review comprise both regulatory/management issues and technical issues.

Regulatory/management issues

- Legislation and regulation should emphasize the severity of speeding at work places and stricter penalties for speeding should be applied there.
- Involve work place protection agents in the development of traffic plans and risk analysis. Road workers should not be on the road until it is secured.
- Lift the temporary traffic management plan out of the tender, by splitting the offer in a safety part and a road work part.
- Use safety related performance goals.
- Ensure safety measures through contractual obligations and budget; part of the money to be paid for the work should depend on safety results during the project.
- Formalise supervision of contractors around safety and quality to ensure they are fully complying with the contract.
- Conduct regular performance monitoring by standardized work zone safety reviews.
- Arrange regular meetings with contractors.
- Require contractors to pass courses on how to handle roadworks and to produce regular reports and face penalties if they overrun

Technical issues

Establishment of a road work zone

- During the short period of time when the work zone signs are deployed all traffic can be stopped by three-to-four vehicles blocking all lanes.
- Deployment and dismantling of road signs and traffic devices can be automated where a robot arm deploys and picks up traffic devices.
- To sign the newly established road work zone a mobile gantry crane with the relevant signs mounted on it can be quickly deployed.

Informing, warning and guiding road users

- Where a diversion route has been set up drivers should be informed by road side signs not to rely on their navigation system, and service providers should be encouraged to update the navigation system.
- A trailer mounted portable Highway Advisory Radio (HAR) broadcasting system combined with a Variable Message Sign (VMS) informing when a real-time message on road work related information was available was found to be successful in the USA.
- A congestion warning VMS can contribute to more homogenous speed distribution. Displaying queue lengths was found better than displaying delay times.
- A Dynamic Lane Merging (DLM) system, consisting of a series of trailer-mounted traffic signs with the message “LEFT LANE - DO NOT PASS WHEN FLASHING”, combined with flashing beacons was found beneficial.
- The alternating merging technique, encouraging drivers to take turns when merging in motorway lanes, makes drivers more cautious in their merging manoeuvres.

Speed management

- Temporary speed limit or advisory speed signs should only be left in place after the work shift is over if roadway restrictions still present hazard to road users.
- VMSs governed by a speed-flow-density algorithm contribute to increased speed compliance, reduced speed variance and improved traffic throughput and safety.
- Complementary signage with a VMS "Recommended Highest Speed" on road paint vehicles results in lower speeds of passing vehicles.
- Speed feedback on portable VMSs reduces speed of passing vehicles. Innovative use of fonts and content, e.g. ‘‘YOU ARE SPEEDING’’ followed by ‘‘MINIMUM FINE …” may achieve greater speed reduction.
- A VMS on a Truck Mounted Attenuator (TMA) with the message “You drive too fast" (if speeding) was found effective at a motorway work zone and the message indicating “MY SPEED XX” and “YOUR SPEED” was found effective at intermittent road-works.
- Portable plastic rumble strips provide results similar to those of permanent rumble strips. Orange rumble strips have an additional effect due to their provision of visual alertness.
- Section speed control with automated speed cameras increases compliance with the work zone speed limit along the entire enforced road section.
- A drone radar, triggering the drivers’ radar detectors on purpose, affects the speed of the cars equipped with radar detectors so its effectiveness depends on the number of radar detectors in the vehicle flow.

Protecting road workers and road users

- At chicanes, anti-glare screens of heights from 60 to 120 cm above the road surface, and preferable even higher should be used.
- Flashing strobe lights on TMAs improve driver reactions. Wide retro-reflective tape around the edges of the arrow board improved drivers’ recognition distance.
- Longitudinal, water filled barriers used at temporary road workplaces or filling gaps in zone guard barriers are quick to install and involve low costs.
- Mobile barriers, integrating a rigid wall on a semi-trailer and standard semi-tractors, offers safe work environments for road workers in temporary work zones.
- At complete carriageway closures the “Airlock” system reduces the likelihood of incursions. An electronic gate allows to control access and stop unauthorised breaches.
- Traffic management operatives placed at entry points should be issued with video recording equipment.
- Incursion detection, based on various types of sensors (pneumatic tube, microwave or infrared) can trigger sounds an alarm the workers.
- Transponders on road workers and receivers on a road side screen that lights up can inform drivers when there are road workers nearby.
- A temporary bridge to roof over road work creating safe conditions for the workers and reducing the need for diversions is worthwhile to develop/use.

1 Introduction

Road work is often carried out with passing traffic in close vicinity creating a potential risk for both road workers and road users (see e.g. Trafikverket, 2016). An important contributory factor to accidents at work zones is incursion. Incursion is defined by Highways England (2016) as “an intentional or unintentional unauthorised entry into temporary traffic management, by all or part of a vehicle being driven by members of the public or emergency services”. Incursions can be: a) Intentional, where the road user seeks to gain a benefit, where the road user is seeking information or refuge; b) Unintentional, where a road user follows a works vehicle into the works area in error, as a result of confusion or as a result of a collision or to avoid a collision.

To prevent incursion and/or mitigate its effect there is a need for well-designed temporary traffic management plans considering well documented best practice measures. Best practices can be of regulatory/management or technical kind. Incorporating them into the regular activities of road authorities and contractors can contribute to making work zones safe for both road workers and road users.

2 Aim

The aim of the task this report concerns was to review the literature to identify existing best practices used to prevent incursions into work zones and improve safety of road users and road workers.

3 Method

A literature search was conducted in the Swedish National Library Catalogue - TRANSGUIDE at the Road and Transport Research Institute in Linköping. The database contains over 140,000 references to Nordic and English-language publications in the areas of traffic, road users, vehicles, transport and infrastructure.

The search string was the following: work zone* AND (safety OR incursion). Publication years were limited to the period of 2007-2017.

The search gave 106 hits of which - after a screening process - 32 were included in this report. Besides the systematic literature search in the transport database, other available sources referred to by knowledgeable experts in the field were considered.

.

4 Findings

4.1 Principles of safe work zones

PIARC (2012) put forward a 4 C's principle, i.e. conspicuous, clear, consistent and credible, for safe and efficient management of work zone design, operation and maintenance:

- Conspicuous implies that the driver must be physically able to see what is coming up. The work zone must be obvious, noticeable and eye-catching to draw the attention of the drivers and encourage them to act in the desired way with regard to increased attention, speed adaptation and position of vehicle.
- Clear means that all signing, guiding and other instructions through road works must be clear in order for drivers be absolutely certain about what is required in terms of correct decisions about how to safely approach and pass the site.
- Consistent implies that drivers should encounter uniform standards, layouts and arrangements at all work zone sites of the same kind so they are conditioned to act in a certain expected way.
- Credible means that the instructions are 'believable' so the drivers can rely on what they are told (e.g. the need to slow down) and that the messages they are given are a true representation of what will occur ahead.

There should be no surprise for the driver at any site, hence uniformity and harmonization not only throughout a country but across boundaries should be aimed at letting the road users to encounter similar layouts and situations (PIARC, 2012).

In order to prevent accidents at work zones, priority should always be given to diversion of traffic. If diversion is not possible, traffic should be directed so that the vehicles pass at a safe distance and as last option, traffic should be separated from the workplace by traffic devices. There must be protective devices that effectively prevent traffic from entering the workplace (Trafikverket, 2012, 2013).

As a general rule, according to the main principles prescribed by the Swedish Transport Administration, temporary traffic management should **inform/warn road users**, **guide road users** and **protect road workers and road users**. When road users approach a road work, they should be warned so that they know what's ahead and can adjust their speed. When they arrive at road work they should be guided in a sufficiently clear and safe way past the workplace. When traffic passes the road workplace, road works must be protected so that road work can be carried out safely (Trafikverket, 2013).

Time constraints should be used to carry out road work at times with lower traffic intensities, so that risks are reduced and traffic disturbances can also be minimized (Trafikverket, 2013).

4.2 Regulatory / management issues

4.2.1 Legislation

The example of Dutch legislation and road safety model, which requires that road workers should not be on the road until it is secured, was accentuated by the Swedish Service and Communication trade union, who in cooperation with the Work Environment Managers and Chief Protection Officer carried out workshops and interviews with road workers as well as workplace visits to highlight good examples of safety measures at road works (SEKO, 2012). Something that has emerged in the discussions is that the work place protection agents rarely participate in the development of traffic plans and risk analysis which means that the Work Environment Act is overlooked.

4.2.2 Procurement

Contracting rules and tender procedures tend to give the contract to the company who does the work at the lowest costs. Safety does not seem to be an important issue in these procedures (ETSC, 2011). Bolling & Sörensen (2008) concluded in their review report that lifting the temporary traffic management plan out of the tender, by splitting the offer in a safety part and a road work part would make it easier to implement new methods to increase safety at road works. Both the client and the contactor should consider the use of safety related performance goals. Safety measures should be ensured through contractual obligations and budget. Part of the money to be paid for the work should depend on safety results during the project (ETSC, 2011).

4.2.3 Monitoring and Safety Inspections

To make sure that work zone standards are maintained regular inspections should be carried out. It is recommended that immediately after the installation, dated photos of the various areas including all the recommended signing and marking are made (PIARC, 2012).

Consistent reviews of work zones by construction inspectors and district work zone safety personnel, improved documentation of work zone conditions, and improved response time to work zone deficiencies by contractors are beneficial for assuring safety at road works. Standardized work zone safety reviews can provide contractors, in writing, a list of work zone deficiencies to improve the appearance and function of work zone traffic control. The Virginia Department of Transportation (VDOT, 2018) introduced a two page work zone safety checklist form for reviewing and documenting the status/condition of work zones. The form must be completed weekly by construction inspectors. VDOT provides the completed form to the contractor for correcting work zone deficiencies, and a copy is filed with the project records. Another checklist is provided by PIARC (PIARC, 2012).

VicRoads (Australia) has a formalised supervision of contractors. It has a surveillance officer to supervise contractors, particularly around safety and quality, ensuring they are fully complying with the contract. VicRoads also has regular meetings with contractors (at least monthly), attended by a senior project director and senior contractor. Contractors are required to produce regular reports and face penalties if they overrun. (CREDO, 2017).

The Danish Road Directorate arranges audits to ensure effective ongoing performance monitoring. Spot checks of roadworks are conducted to determine contractor performance, particularly around safety. The Danish Road Directorate also legally requires contractors to

pass courses on how to handle roadworks. The different courses are adapted to the job each individual will perform and the responsibilities associated with it. (CREDO, 2017).

4.2.4 Road user communication and incentives

The Netherlands applies a holistic approach and prioritises communicating the broader 'story' of the roadworks, as well as using particular incentives to drive positive change in road user behaviour around roadworks. The customer communication puts emphasis upon communicating the facts around the scheme but also upon telling the details of what is going on within the roadworks and what the benefit will be. If congestion is likely to be significant, a "rush hour" scheme is set up: Commuters can enrol by an app and they receive a financial reward of between 2-7 Euros for each time rush hour is avoided. The economic benefits were found to outweigh the costs accounting for the time value of reduced congestion.

4.3 Establishment of a road work zone

The most dangerous activities carried out in connection with road work are the establishment and de-establishment of road work places (Trafikverket, 2013).

Bolling & Sörensen (2008) in their review describe a method used for deployment of traffic signs in Sweden. Three-to-four vehicles block all lanes, thus stopping all traffic during the short period of time when the signs are deployed.

To sign the road workplace a mobile gantry crane can be used, see Figure 1. The signs are mounted on a crane which can be quickly deployed. The port cranes, borrowed from the Netherlands, were tested in Stockholm with good results (Bolling & Sörensen, 2008).

Figure 1. A mobile gantry crane for quick setup of signs at newly established road work zone (Bolling & Sörensen, 2008).

SVEVIA (2014) conducted a comparative analysis of existing technical solutions used for automation of the deployment and pick-up of traffic devices. The study concluded that “Autocone”, see Figure 2, was the most interesting solution. Autocone can be mounted on a flat truck or a large trailer and it has a robot arm and a storage device that can be adapted to handle side-mark screens without the need for extensive changes. The storage unit is a rotating cylinder with space for cones in several rows. With the help of the robot arm, cones can be put out and taken up on both sides of the machine and in two directions.

Figure 2. Autocone trailer with magazine for 130 cones and truck with magazine for 500 cones. (SVEVIA, 2014).

A new prototype for deployment of road signs at a work zone was developed and tested in Sweden (Lidström, Odermatt, 2010). The systems consists of a Truck with a crane with an advanced control system that on command automatically deploys/picks up temporary road signs, see Figure 3. The road signs are provided with a RFID-tag and each of them has an electronic ID. The crane uses the RFID to identify the actual road sign to be picked. The driver operates the system via a mobile hand terminal.

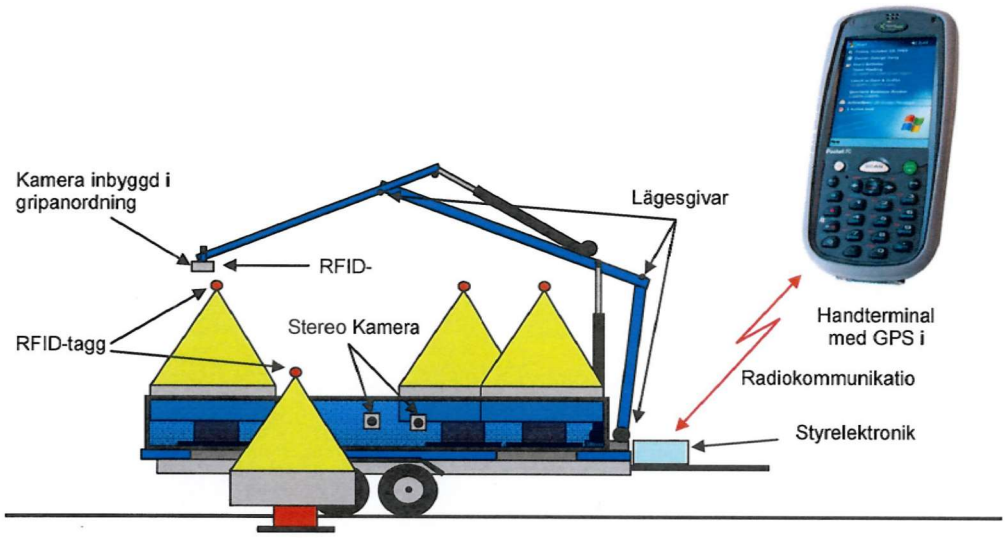

Figure 3. A prototype principle for deployment/pick up of road signs at work zones (Lidström & Odermatt, 2010).

4.4 Informing, warning, guiding road users

4.4.1 Re-routing information

In the case of long-term road works, it is suitable to inform road users about alternative routes in order to avoid long queues at times of high traffic flows.

Drivers who rely on satellite navigation systems for directions and traffic information may make poor decisions if no updated information is available. Where a diversion route has been set up or a road layout has been significantly altered, then navigation instructions may be inappropriate to the new layout and cause major congestion or serious incident. Drivers should then be informed by road side signs not to rely on their navigation system, see e.g. Figure 4. Service providers should undertake a route survey with SATNAV to identify where this is the case and update their system.

Figure 4. Drivers should be reminded not to blindly trust their navigation system (Highways England, 2016).

Smart work zones using sensors to detect traffic flow conditions on the approaches of work zones and based on the collected data alerting drivers of congestion were tested in the USA. I a driver survey more than 70% of those who frequently travelled on the route replied that they sometimes or often had taken a different route. Of those who travelled rarely on the route 50% used the information to take another route (Fontaine & Edara, 2007).

4.4.2 Work zone information/alert systems

An automated work zone information system (AWIS) alerts travellers to work zone conditions before they enter the work zone so they can take appropriate actions. Fitzsimmons et al. (2009) in their review refer to evaluation studies reporting that an automated portable real-time traffic control system consisting of a dynamic message sign, portable electronically linked traffic sensors and portable closed circuit video cameras providing real-time traveller information about delays and lane closures and displaying the number of citations issued resulted in a downward trend in violations, as well as a decrease in congestion and rear end crashes.

Highway Advisory Radio (HAR) is a broadcasting system used by the road agency in The USA to disseminate real-time traffic information to motorists, see Figure 5. Most commonly these transmitters are located at major highway intersections or near major transportation attractions, such that motorists could take alternate routes in case of congestion or emergencies. (Wang et al., 2013). Wang et al. (2013) in their literature review refer to research findings by Washington State Department of Transportation, telling that trailer mounted portable HAR units enjoyed great success when integrated into construction projects with high driver interest due to traffic impacts. Motorists were satisfied with the quality of the broadcasts and supportive of this innovative approach to traffic management in work zones. Extinguishable signs turn on and off depending on when the HAR has a message available (FHWA, 2005).

Figure 5. Highway Advisory Radio System (HAR). (https://www.google.se/search?q=Highway+Advisory+Radio+Systems&dcr=0&tbm=isch&source=iu&ictx=1&fir=NztKHIMwMMnP3M%253A%252CSUucky9z00Io6M%252C_&usg=__gqBMM_hZZrfKAxZKFSTe8hPjPhA%3D&sa=X&ved=0ahUKEwi43tOi7pPZAhUBZCwKHUQhCBsQ9QEIQjAG#imgrc=P9Pl4uXo6EfWnM:)

A similar to HAR system is the Wizard citizen band (CB) Alert System for traditional motorist information dissemination. It is designed to give drivers monitoring the CB radio advanced warning of upcoming delays at construction sites or incidents. The advanced warning allows drivers the opportunity to moderate their speed and become observant of the need to slow, stop, or manoeuvre before they reach the work zone or encounter queues of halted vehicles. Since truck operators most commonly monitor CB radios, it was assumed that the CB Wizard would have the most impact on truck drivers. A Case Study in Iowa, USA, where large trucks are a significant portion of the traffic volume, evaluated the effect of the system. The CB Wizard was set to broadcast a warning message on the most commonly used frequency by truck drivers. The system was found effective in warning truck operators of approaching mobile work zones. Sixty- three percent of the truck operators that had their CB radio tuned to the indicated channel as they passed the paint crew heard the Wizard CB Alert message and 41 percent stated that the CB message was their first indication that they were approaching the paint crew. Many truck operators showed their support for the system. (FHWA, 2005). Such a system was introduced in Nordrhein-Westfalen (Germany) as well with good results (Höhne and Overberg, 2018).

4.4.3 Congestion warning

It is of interest to increase driver attention, make them adapt their vehicle's speed and position to the upcoming situation.

A congestion warning dynamic message sign, see Figure 6, was evaluated in before/after field trials in Sweden (Sörensen & Wiklund, 2010). The system consisted of a trigger (ca. 400 metres upstream from the point where the two lanes merged to one lane just before the road work zone) activating two dynamic message signs (ca. 800 metres and ca. 1900 metres upstream before the trigger) when vehicle speeds were lower than the pre-set 50 km/h speed, indicating a congestion. The speed distribution became more homogenous during rush hours when the system was in use. It was concluded that the most suitable distances from the sign and the trigger to the work zone have to be investigated further as well as the triggering speed level. Also, an alternative design, where the icon used for road work warning is shown together with the distance to the work zone, is proposed whenever the congestion warning is not in action.

Figure 6. A congestion warning dynamic message sign. (Sörensen & Wiklund, 2010).

A real-time Travel time Prediction System (TIPS), which includes mobile changeable message signs (CMSs) displaying the travel time and distance to the end of the work zone, was evaluated in the USA (Zwahlen, 2001). The travel times displayed to the motorists were computed by an algorithm and travel-time estimation model, which took input from microwave radar sensors that detected the vehicle traffic on each lane of the motorway. The system also included 220 MHz radios for transmitting data from the sensors to and from the computer and to the CMSs. The estimated travel times were shown to the drivers at three places before the road work zone. Survey responses from passing car drivers indicated that they noticed a certain inaccuracy in the travel times, but is was perceived as helpful addition by almost 97% of surveyed motorists.

A literature review by Ukkusuri et al. (2016) in the USA concluded that displaying queue lengths is better than displaying delay times.

A number of Intelligent Transport Systems (ITS) solutions for work zone traffic management were studied in the USA (Luttrell et al., 2008). These ITS systems included, among others, mobile, portable traffic monitoring and management to provide information to motorists to help with route choice, provide advance warning of slowed or stopped traffic. Some key lessons learned from the studies were:

- Significant traffic diversion rates and lower observed mainline volumes in response to appropriate messages displayed during congested conditions and an enhanced ability to manage traffic and incidents during construction.
- Improved ability to react to stopped or slow traffic – 82% of surveyed drivers felt that the ITS system improved their ability to react to stopped or slow traffic.
- Driver perception of improved work zone safety – 49% of surveyed drivers indicated that that the electronic messages made them feel safer.

4.4.4 Guiding and lane shift information

A lane separation system can provide efficient channelization of traffic, see Figure 7.

Figure 7. Curb system (http://www.pexco.com/markets/industrial/traffic/lane-separator-curb-systems/fg-300-interstate-grade-curb-system/)

Ullman et al. (2008) identified a number of issues regarding temporary traffic control at urban motorway interchanges and concluded the following:

- Continued usage of existing guide signs in coexistence with removed or covered lane assignment arrows that no longer correspond to lane positions (due to lane shifts or other temporary changes in alignment) do significantly degrade the abilities of drivers approaching a motorway interchange to quickly determine the appropriate lane to be in.
- The provision of temporary diagrammatic guide signs and/or the use of pavement marking symbols designating the lanes assigned to the various routes approaching the interchange significantly improve the drivers' lane choice abilities.
- The use of descriptors of the route and direction complementing pavement arrows to indicate through and exiting lanes provides better driver comprehension and lane choice decisions.
- The provision of pavement symbols in all lanes approaching the interchange does not significantly improve driver comprehension and lane choice decisions over simply providing the symbols in the exiting lanes only. However, if heavy traffic volumes are likely to obscure the pavement symbols for a large portion of the traffic stream, providing symbols in all lanes may be necessary to ensure that all drivers receive at least some indication whether they are in their desired lane.
- Lane closures on through lanes immediately downstream of exit lane drops are difficult to effectively convey to drivers with current advance warning signs without closing both the through and the exiting lanes upstream of the interchange. Such upstream closures will often create significant queues, leading to incidents and crashes. If a significant amount of approaching traffic is destined for the exit, waiting to close the through lane(s) until after the exit can sometimes reduce or eliminate such queuing.
- When lane shifts are required on multi-lane facilities, the use of reverse curve signs that have multiple arrows (the number of arrows corresponding to the number of lanes) may slightly improve driver comprehension of the required driving manoeuvre (i.e. to stay in a lane) than the standard reverse curve sign with a single thick arrow. The multiple-arrow sign format is strongly preferred by drivers over the single-arrow format.

Running light in combination with a solid luminous arrow to mark lane change was tested in the USA (Finley et al., 2001). The system consists of a series of interconnected, synchronized individual flashing warning lights attached to drums that form the lane closure taper, see Figure 8. The flash of light was seemingly "moving" from the beginning to the end of the lane closure taper. Four alternatives were studied: 1) no warning light, 2) only solid shine, 3) solid shine combined with stronger shine in running light, 4) only running light. Interview with drivers showed that 62% preferred the alternatives with running light and most of these alternatives featured with solid backlight. The most preferred alternative was compared with traditional guidance in a field trial. In one try, no differences were found. In another attempt in urban environment, differences were found. Just over 300 meters before the lane ceased, 30% of the cars and 19% of the lorries remained in that lane in the before situation. With the system tested, these figures dropped to 23 % and 7 % respectively.

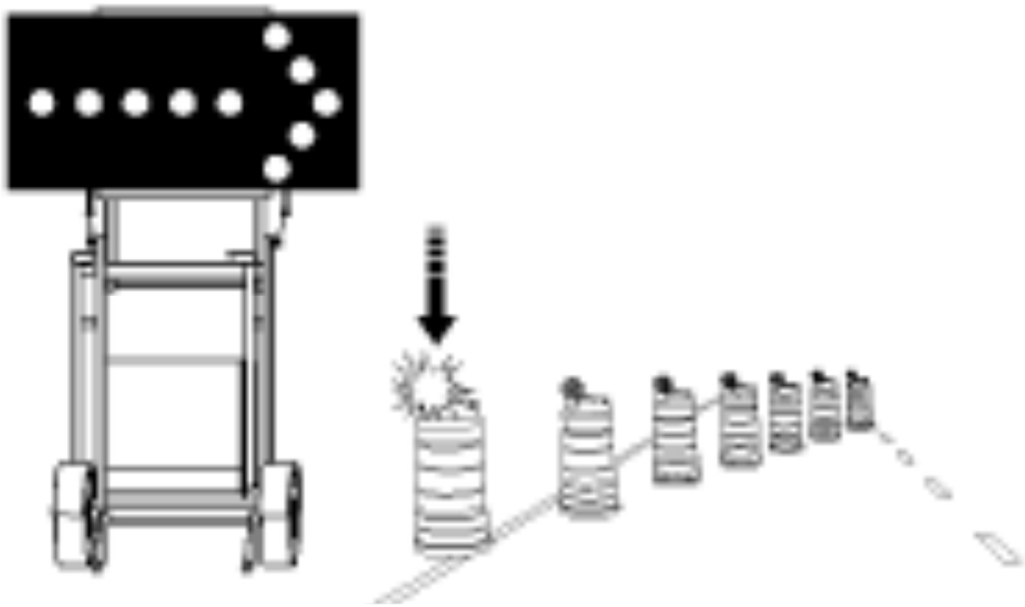

Figure 8. Running light in combination with a solid luminous arrow to mark lane change (Finley et al., 2001)

A Dynamic Lane Merging (DLM) system creating a dynamic “No Passing” zone in advance of the work zone area is designed to automatically react to the changing queue length and flow conditions and adjust the length of the no passing zone and advise motorists to merge early. As congestion occurs at a specific point, the no passing zone is moved upstream of this point to provide vehicles with time and space to merge while traffic is still moving and there are sufficient openings. The system communicates to drivers with help of a series of trailer-mounted traffic signs with the message “LEFT LANE - DO NOT PASS WHEN FLASHING”, combined with flashing beacons, see Figure 9. The trailer closest to the merge is always flashing. Each trailer is also equipped with a microwave sensor to detect vehicle volume and speed. The information from the sensor is processed to determine the congestion level at that particular point. If congestion is detected a signal is relayed to the next upstream station. The sign at the upstream station is then activated to extend the no passing zone. An evaluation study (Bushman et al., 2003) showed that the system was beneficial in reducing aggressive driving, reducing travel time delay, decreasing traffic stops and their duration. Another evaluation of the DLM system on a motorway section in the USA (Luttrell, et al., 2008) showed reductions in aggressive manoeuvres at work zone lane drops – forced merges were seven times less frequent and dangerous merges were three times less frequent when the system was on (flashers on).

Figure 9. Dynamic lane merger sign (Bushman et al., 2003).

To increase the efficiency and safety of traffic flow in the vicinity of lane reduction transition areas, an innovative technique is alternating merging, which encourages drivers to take turns when merging in motorway lanes and ramps. This kind of design i.e. a two-sided taper in which both approach lanes are reduced simultaneously into a single lane, thereby eliminating an assigned lane priority. To evaluate its effect on traffic, a field study was conducted in a live, work intensity-controlled work zone in Louisiana, USA. Lane-specific volume and vehicle speeds in the joint merge were compared with those observed in a conventional merge design at the same site. Overall, merging speeds were found to be relatively similar at volumes ranging from 600 to 1,200 vehicles per hour and did not affect the discharge rate at the merge outflow point. However, the experimental results did suggest that drivers were more cautious in their merging manoeuvres. This was thought to be attributable to the joint merge, which produced a more evenly balanced lane volume at the transition zone entrance (Idewu & Wolshon, 2010).

4.4.5 Work zone posting

Providing appropriate information about the upcoming road conditions and the appropriate action to be taken in these conditions can help avoiding potential hazards. However, too much or overly complex information can also lead to driver confusion/overload

The fact that road work signs and signs with reduced speed limit are too often left along the road when they are not needed leads to their reduced credibility, decreased compliance and negative public opinion about work zones. When drivers pass a work zone sign and they cannot see any activity ongoing but they still are required to lower their speed they lose confidence in road work zone information. In order to maintain the credibility of temporary speed limit signs at work zones they should be covered or removed when no work is

occurring or no hazards are present. To address this problem, a legislature Act 229, requiring work zone signs complemented with flashing light when road workers present at the site was introduced in Pennsylvania, USA, see Figure 10, and its effects were evaluated (Sesny, Lentz and Rensel, 2007). A white flashing light attached to the "Active Work Zone When Flashing" sign indicated an active work zone. The findings showed that the measure had a minimal impact on motorist speed and safety. Both motorists and contractors felt the signs were ineffective in deterring speeding and increasing driver awareness of workers' presence in active work zones. A number of respondents from the public survey suggested that several changes should be implemented to the measure. Some of the suggestions were to improve visibility of the flashing white light and if workers are no longer present then the flashing beacon should be turned off.

Figure 10. Work zone sign complemented with flashing light when road workers present at the site (Sesny, Lentz and Rensel, 2007).

A literature review (TRB, 2009) concluded that colours added to the basic yellow light used on work vehicles resulted in increase in motorists' appropriate response frequency. The presence of law enforcement vehicles gave a further increase in this response frequency. The presence of more than one work vehicle was effective in informing motorists that they were approaching a larger work zone operation.

4.4.6 Traffic Pilots

A demonstration study with pilots was carried out at a repair work of the cable rails on a 2+1 road in 2004 and 2005 in Sweden (Bolling & Sörensen, 2008). The pilot, a driver on a 4-wheeled motorcycle with radio contact with the site manager lead the row of vehicles passing the work zone at about 20 km/h. When the last car in the queue passed, the pilot turned and led the row of vehicles from the opposite direction past the workplace. A pilot round back and forth took about 3 minutes for traffic volumes between 300 and 400 vehicles per hour. The trial showed that this kind of traffic pilot solution works well at shorter road work areas at these vehicle flows. In order to investigate how well the traffic pilot method works with larger traffic volumes and how large road work areas the pilot can handle, computer simulation was carried out. The results show that the queuing times increase significantly already at flows of 700-800 vehicles/hour when the road work zone is 200 m long. For longer road work zones, capacity is further reduced for the traffic pilot method. For 400 m long work zones, the method works up to 600 vehicles/hour (Bolling & Sörensen, 2008).

4.5 Speed management

4.5.1 Speed information/feed-back

When road workers are exposed to moving traffic or road work operations present increased risks to road users, appropriate speed reduction is needed. However, it is very important to remove or cover the regulatory speed limit signs or advisory speed signs when they are in conflict with the temporary work zone speed limits or advisory speeds. Temporary speed limit or advisory speed signs should only be left in place after the work shift is over if roadway restrictions still present hazard to road users. Failure to remove speed limit or speed advisory signs when they are not needed leads to reduced credibility of speed limits and decreased compliance and negative public opinion of work zones.

Variable message signs

Variable speed limit signs (VSLs) provide the flexibility to vary the speed limit dynamically and they can be used at work zones to increase speed compliance so that traffic throughput and safety are improved. The simplest type of a temporary speed limit sign is a static speed limit sign with flashing beacons when reduced speed limit is in effect. A more dynamic version of a changeable sign is an electronic sign allowing an effective change in the prevailing speed limit and its recording, see Figure 11. (ARTBA, 2017)

Figure 11. A static speed limit sign with flashing beacons when reduced speed limit is in effect and a variable speed limit sign at road work zone. (https://www.google.se/search?q=speed+limit+sign+work+zone&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwiine2MsdfXAhWna5oKHYSdB8oQ7AkIOA&biw=1050&bih=1507#imgrc=_).

A literature review by Ukkusuri et al. (2016) in the USA concluded that deployment of variable speed limit (VSL) governed by a speed-flow-density algorithm determining the appropriate speed limit resulted in increased speed compliance, reduced speed variance and improved traffic throughput and safety.

A test of a VSL system on a congested portion of the Washington D.C., Beltway at a major work zone (Fudala & Fontaine, 2010) showed that VSL can delay the onset of congestion and help produce more rapid recovery from congestion, provided that demand volumes are not too far above the work zone capacity. When demand volumes are extremely high, VSLs offer no appreciable benefit over static speed limits. The simulation also showed that VSL sign location is extremely important, and signs must be positioned so that drivers will accelerate back to a reasonable speed once they pass through a bottleneck. Algorithm design also proved to play an important role in system effectiveness.

Trout et al. (2010) report on a laptop-based laboratory survey to determine a) motorists' understanding and opinions of alternative short-term signs for speed limits in work zones, b) the success of the orange or white light-emitting diode (LED) colour used on electronic speed limit (ESL) signs, and c) motorists' preference for short-term speed limit displays. The signs included in the survey were: 1) static work zone signs; 2) electronic speed limit (ESL) signs; and 3) "Your Speed…" signs. Based on the findings, the use of ESL signs and flexible roll-up signs for displaying speed limits were recommended in static work zones. To ensure that the speed limit displayed on ESL signs is considered a regulatory speed limit, the changeable display should be composed of white LEDs.

Complementary signage with a Variable Message Sign "Recommended Highest Speed" on road paint vehicles, see Figure 12, resulted in lower speeds for passing vehicles in Sweden (Persson, 2011). The speed cuts varied considerably between different road distances. The speed reducing effect had greater effect on wider roads (at least 10 meters) than on narrow roads, a particularly clear reduction of the highest speeds.

Figure 12. Complementary signage with a Variable Message Sign "Recommended Highest Speed" on road paint vehicles (Persson, 2011).

Speed feedback signs on portable variable message signs (VMS) are ideal for short-term and mobile work zones. A literature review by Ukkusuri et al. (2016) in the USA found that radar equipped VMSs were effective in reducing mean speed, 85th percentile speed, and percentage of vehicles exceeding the speed limit. Graphic-aided VMSs were more legible and recognizable compared with text-message VMSs and innovative use of fonts and content may achieve greater speed reduction. The message ‘‘YOU ARE SPEEDING’’ followed by ‘‘SLOW DOWN,’’ was proven effective, likewise ‘‘YOUR SPEED IS __’’ followed by ‘‘SLOW DOWN” in reducing speeds in work zone areas. The Message ‘‘YOUR SPEED IS __’’ followed by either ‘‘THANKS FOR NOT SPEEDING’’ or ‘‘SLOW DOWN,’’ performed similarly and did not significantly differ from the previously mentioned messages, despite the belief that positive feedback for compliant drivers would be useful in addressing the tendency of drivers to increase their speeds after passing the VMS. The novel approach with displaying possible consequences for speeding, i.e. the message ‘‘YOU ARE SPEEDING’’ followed by ‘‘MINIMUM FINE $200’’ showed comparable speed reductions to the other messages.

Measuring driver's speed and then presenting it on a VMS sign was found to have good effect on speed behaviour according to studies in the USA (Fontaine, Carlson & Hawkins, 2000). An empirical study on a VMS showing the approaching vehicle’s speed (the Speed Monitoring Display - SMD), see Figure 13, found that speed was reduced on average by 6% (Bowie, 2003). By comparison, it can be mentioned that the presence of the police at the work zone reduced speed by 10%. However, the positive effect of SMD decreased after a few weeks. A questionnaire showed that car drivers were positive to the signs. About 95% responded that they would slow down if SMD showed they drove too fast.

Figure 13. Speed Monitoring Display (Bowie, 2003).

The effect on driving speed of three alternatives of Variable Message Sign (VMS) on Truck Mounted Attenuator (TMA) at a road work zone on a motorway was evaluated in Sweden (Trafikverket, 2012a). The alternative VMS signs used were: 1) recommended 50 km/h fixed sign; 2) Recommended 50 km/h, but blinking if the driver drove above the recommended speed; and 3) A sign with the text "You drive too fast" if the driver drove faster than the recommended speed, see figure 14. The tests showed that the lowest average speed, 38.4 km/h, was achieved with the sign "You drive too fast". The average speed was highest, 45.0 km/h with the 50 sign flashing at higher speeds.

Figure 14. VMS with the text "You drive too fast" (in Swedish) if the driver drove faster than the recommended speed on TMA. ” (Sörensen & Wiklund, 2010).

Two types of VMSs were tested during intermittent road-work conditions. The signs were placed on the vehicle carrying the Truck Mounted Attenuator (TMA) driving directly behind the road work vehicle washing the reflector posts along the road. The upper variable sign displayed either the text “MY SPEED XX” or a digital road work warning sign and the lower sign showed either the text “YOUR SPEED” or “REDUCE SPEED” when a vehicle from behind approached at a speed higher than 50 km/h (or it just was turned off), see Figure 15. The system shifted mode according to a pre-set schedule. Three alternative combinations of two variable message sign combinations, each combination displayed for 1.5 seconds were tested, see Table 1.

Figure 15. TMA with two Variable Message Signs (text in Swedish). Alternative C with the two phases: 1) “MIN FART” (“MY SPEED”) and “DIN FART” (YOUR SPEED”; 2) road work warning sign and “SÄNK FARTEN” (“REDUCE SPEED” (Sörensen & Wiklund, 2010).

Table 1. The three alternative combinations of two variable message sign combinations, each combination displayed for 1.5 seconds (Sörensen & Wiklund, 2010).

Alternative	Sign	Phase	
		1	2
A	Upper	digital road-work warning sign	digital road-work warning sign
	Lower	(off)	REDUCE SPEED
B	Upper	MY SPEED YY	digital road-work warning sign
	Lower	(off)	(off)
C	Upper	MY SPEED YY	digital road-work warning sign
	Lower	YOUR SPEED XX	REDUCE SPEED

All three alternatives gave a mean speed of 30 km/h or lower, however alternative C gave statistically significantly lower mean speed than alternative A. Hence, drivers seem to reduce their speed more when given information about the speed of the road work vehicle as well as their own speed. Positive reactions regarding the tested measures and their effects were received from road workers. (Sörensen & Wiklund, 2010).

Transverse pavement marking bars

Transverse pavement marking bars or even called optical bars are pavement markings placed perpendicular to the flow of traffic, see Figure 16. Fitzsimmons et al. (2009) in their synthesis of traffic calming techniques in work zones refer to evaluation studies reporting small but statistically significant speed reducing effects of the measure.

Figure 16. Transverse pavement marking bars (Fitzsimmons et al., 2009).

Experiments with optical bars before a road work zone were performed in Sweden (Sörensen & Wiklund, 2010). The 30 cm bars were fixed onto the road surface at an angle of 90 degrees to the direction of travel, along both edges of the traffic lane. The longitudinal distance between the bars was reduced from 5.5 to 2.8 meters along the section. By gradually reducing the distance between the bars in the direction of travel, an illusion of increased speed is supposed to be created if the driver keeps to the same speed through the section. The section was 200 meters long and ran from a 70 km/h to a 50 km/h speed limit sign. The results showed small but statistically significant reduction in mean speed (-1 km/h). However, the optical speed bars are not effective during winter. Positive reactions regarding the measure were received from road workers.

Rumble strips

Rumble strips alert drivers by generating sound and vibrations. Schrock et al. (2010) compared the attention-getting characteristics of several temporary rumble strips with permanent rumble strips. The ability to generate steering wheel vibrations and sound of portable plastic rumble strips and adhesive rubberized polymer rumble strips were tested and compared with permanent rumble strips. The portable plastic rumble strips were more effective on cars than on trucks for generating in-vehicle vibration and increasing the in-vehicle sound level. Also, they were generally better than the adhesive rumble strips in matching the characteristics of the tested permanent rumble strip. It was concluded that the portable plastic rumble strips provide results similar to those of permanent rumble strips.

Field tests of Portable Plastic Rumble Strips (PPRS) in the USA, see Figure 17, found that the PPRSs being an effective device in achieving speed reductions (Wang et al., 2013). They were more effective on cars than trucks for generating in-vehicle vibration and increasing the in-vehicle sound level. Properly installed PPRSs could create a 7.6 to 10.6 miles per hour speed reduction for cars compared to the regular flagger traffic control only. The effects of the PPRSs on truck speed reduction were not significant at one of the test sites, but they still created 5.0 to 11.7 miles per hour mean speed reduction for trucks at the other two sites. Nevertheless, the PPRSs gained the attention of truck drivers (indicated by the brake lights set on) even though the effects were not shown in the form of a speed reduction. Two sets of four rumble strips at 36 inches spacing are recommended to be used in short-term work zones in addition to the standard traffic control devices. However, since about five percent of drivers were swerving around the PPRSs during the field test, additional driver information may be needed to assure the public that these devices are meant to be traversed.

Figure 17. Portable Plastic Rumble Strips (PPRS) (Wang et al., 2013)

A literature review by Ukkusuri et al. (2016), on the effectiveness of existing technologies in alerting drivers when approaching work zones in the USA, concluded that studies suggest that 6-inch-wide strips may generate sound 4 dBA higher than 4-inch-wide strips. Eight strips per set may increase the sound up to 5 dBA higher compared with 4 strips per set. Most often two to three sets of rumble strips are used together, with two to three strips in each set and placed in a perpendicular manner rather than at an angle. Orange rumble strips provide visual alertness in addition to vibration and sound. The majority of the studies found reductions in vehicle speeds up to 10 mph. Also Meyer (2003) found that the temporary orange painted rumble strips had the greatest effectiveness, attributable to their high visibility. Portable rumble strips are recommended for short-term work zones. However, the ease of installation and removal are major concerns for using rumble strips.

Chicanes

A chicane, see Figure 18 is a lateral displacement of the trajectory of vehicles forcing them to decrease their speed. It reduces speed efficiently and useful in the transition area of work zones. However it demands an extensive work to establish and dismantle the devices(ASAP, 2015).

Figure 18. A chicane (http://www.buckslocalnews.com/news/yardley_area/engineer-updates-lower-makefield-supervisors-on-sandy-run-road-engineering/article_2c447361-1858-58c5-bb6c-3b252b1bae37.html).

Auditory warning

Auditory warning with loudspeakers produces directional sounds over distances to alert drivers and draw their attention to the upcoming work zone. A literature review by Ukkusuri et al. (2016) concluded that the effectiveness of loudspeakers varies and an array of multiple loudspeakers in an appropriate pattern was found to be the most suitable for long-distance auditory warnings. This technology implemented at a mobile work zone resulted in a speed reduction of 2 mph and increased merging distance of 122 ft. The type of loudspeakers applied is critical to the effectiveness of driver alertness and the array and the timing of the speakers should be adjusted properly to obtain the best effects.

4.5.2 Speed enforcement

If drivers do not comply, to achieve lasting speed reductions at the work zone, active enforcement is necessary.

Police presence

A police car circulating or parked at the work zone are two characteristic ways of police enforcement. A literature review by Ukkusuri et al. (2016) in the USA concluded that the presence of police cars reduced car speeds by 4.4 mph and truck speeds by 5 mph (in a 45 mph speed zone). High speed drivers were most affected by police enforcement. Mobile enforcement during daytime and intensive static enforcement during night time resulted in significant speed reductions. However, despite the effectiveness of police cars presence, the ‘‘halo’’ effect and high costs were pointed out as two main drawbacks of the method.

Automated speed cameras

The use of automated speed cameras allows flexible speed enforcement. However, legislation and regulation should emphasize the severity of speeding at work places by deterrent fines for speeders at work zones, see Figure 19. Applying stricter penalties for speeding at a work zone is applied in the Netherlands and the USA (ETSC, 2011).

Figure 19. A warning sign indicating the elevated risk of penalty in case of speeding. (https://www.google.se/search?q=speed+limit+sign+work+zone&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwiine2MsdfXAhWna5oKHYSdB8oQ7AkIOA&biw=1050&bih=1507#imgrc=_).

The impact of photo radar speed enforcement on speed through an active highway work zone was examined by Joerger (2010) in Portland, USA. During photo radar enforcement periods, speeding was reduced on average by 27% at the traffic sensor site within the work zone. However, the observed speeding reduction was temporary and did not persist beyond the departure of the photo radar enforcement van.

Benekohal et al. (2009) found that automated speed photo-radar enforcement (SPE) in work zones in Illinois, USA was effective in reducing the average speed and increasing compliance with the work zone speed limit. The average free-flowing speed of cars was reduced by 4.2 to 7.9 mph, and that of trucks by 3.4 to 6.9 mph. SPE had a halo effect of 1.8~2.7 mph on free-flowing trucks in one work zone but none in the other work zone.

Medina et al. (2009) found significant speed reducing spatial effects (at a location 1.5 miles downstream of the camera) of automated speed photo-radar enforcement (SPE). Average reductions of downstream speed of free-flowing traffic by 2 to 3.8 mph for cars and by 0.8 to 5.3 mph for trucks were found. SPE also reduced the percentage of cars in the general traffic stream exceeding the speed limit by more than 10 mph in virtually all cases, and eliminated such trucks in all but one case.

SMARTcam by Carbell (2018) provides a visual deterrent discouraging motorists from speeding or taking short-cuts through the cones. Utilising two front and two rear facing cameras, the system is able to capture ‘beginning to end’ evidence of near-miss incidents, including details of the vehicle involved, regardless of the time of day or night, see Figure 20.

Figure 20. Safety cameras (Carnell, 2018).

Section speed control is an efficient speed enforcement method, affecting speed limit compliance along the entire enforced road section and also it leads to crash reductions, see Figure 21 (ETSC, 2009).

Figure 21. Section speed control (Stefan, 2006).

Drone radar

Drone radars alert drivers by triggering radar detectors in vehicles. A drone radar works more as a warning or deterrent for drivers who have installed radar detectors in their vehicles to warn them of the presence of speed radars. A drone radar triggers the drivers' radar detectors on purpose, causing the drivers to believe that speed enforcement is ahead and consequently to lower their speed. Since aggressive drivers are assumed to be more likely to install radar detectors the application of drone radars has the advantage of affecting the extreme group of drivers. Eckenrode et al. (2006) evaluated the effect of drone radar as a speed reduction measure in work zones on interstates and secondary highways during day and evening conditions for both passenger cars and tractor-trailers in the USA. The study involved the use of a specialized radar-detector detector to identify vehicles using radar detectors. The findings showed a 20% speed reduction in vehicles exceeding the speed limit. Mean speed reductions of 2 mph for the entire traffic stream were shown; however, individual vehicles equipped with radar detectors reduced speeds ranging from 5 to 8 mph. However, if there are no legal consequences associated with drone radar, the method is less effective (Eckenrode et al., 2006).

A literature review by Ukkusuri et al. (2016) in the USA concluded that drone radars were reported to be effective in reducing the number of aggressive drivers (up to 33%), but they were ineffective in reducing vehicle speeds in general. The effectiveness of drone radars depends on the number of radar detectors in the vehicle flow.

4.6 Protecting road workers and road users

4.6.1 Glare limitation

To avoid disturbances in dense traffic road works are to an increasing extent carried out during night hours when traffic volumes are lower. Passing the work zone in the dark constitutes considerable difficulty for the drivers due to glare from meeting traffic, yellow flashing lights and work zone illumination. A Nordic project investigated how to provide a good visual environment at road works during night time and how glare can be reduced. The findings showed that to counteract glare effects road work should be illuminated with a luminance level of at least 0.7 cd/m^2. For work zone lighting symmetrical floodlights without glare shield or limiters should only be used if the angle of tilt less than 30°, i.e. when using relatively high lighting masts. Excessive glare can occur at a chicane, where it is suggested to use anti-glare screens of heights from 60 to 120 cm above the road surface, and preferable even higher (Ihs, et al., 2009).

4.6.2 Truck mounted attenuator (TMA)

Truck mounted attenuators (TMAs) consist of an attenuator or crash cushion mounted on the rear of a work zone truck, see Figure 12, in order to dissipate the energy formed by a rear-end collision. A literature review by Ukkusuri et al. (2016) in the USA concluded that flashing strobe lights mounted on trucks improved drivers' reactions. Wide retro-reflective tape around the edges of the arrow board improved drivers' average recognition distance of the TMA by at least 38 meters under daytime or night time conditions. An advance warning system, 400 m upstream from TMAs, was found to perform well.

4.6.3 Safety barriers

In order to separate the work place from traffic, some kind of barrier can be used as protection. At fixed road workplaces, movable concrete barriers or removable steel rails can be used. If they are placed so that the angle of impact becomes small, the rack will be able to avert also heavy vehicles (Bolling & Sörensen, 2008).

At temporary road workplaces, longitudinal water-filled barriers can be used to separate the workplace, see Figure 22. Such devices also provide a good visual guidance for road users, effectively separating them from the road work area. They are easy to handle, quick to install and involve low costs. (Bolling & Sörensen, 2008). Water filled barriers also can be used to fill gaps in zone guard barriers.

Figure 22. Water filled barriers filling the gap in the zone guard (Highway Safety Hub, 2018).

A “Quick moveable barrier” provides separation of the work place at temporary lane closures, see Figure 23.

Figure 23. A “Quick moveable barrier” (http://www.barriersystemsinc.com/stuff/contentmgr/files/0/06bcc8d5b07bf7ded9c026797c585635/files/qmb_const_pi_sheet_international_04_18_13.pdf)

Mobile barriers, integrating a rigid wall on a semi-trailer and standard semi-tractors, can offer safe work environments for road workers in temporary work zones, see Figure 23. It constitutes both a physical and visual wall between passing traffic and workers. MBT-1 provides a protected space of 42 to over 100 ft. The height of the MBT-1 blocks the driver's view towards the work area. A literature review by Ukkusuri et al. (2016) on best practices in work zone safety in the USA concluded that workers felt safer and more efficient behind the mobile barrier trailer MBT-1. Drivers ware also positively affected by the Mobile barrier. Mean vehicle speeds were 45.8 mph and 39.6 mph respectively with and without MBT-1, i.e. higher when the mobile barrier was on site.

Figure 23. Mobile Barrier Trailer MBT-1. http://www.barriersintl.com/mobilebarriers/images/Photos/day/Mobile%20Barriers%20MBT-1%20Capital%20Beltway%20I-495%20Express%20Lanes/vertical/tb-Mobile%20Barriers%20MBT-1%20Capital%20Beltway%20I-495%20Express%20Lanes%20Maintenance%205.JPG

4.6.4 Airlock Gated System

Where a complete carriageway closure is required, the “Airlock” system is recommended by Highways England (2016) as a proven method to reduce the likelihood of vehicle incursions, see Figure 24. Even if the primary reason for using the “Airlock” is to prevent road users from entering the closed carriageway, if a road user manages to enter there he/she must be able to re-join the live carriageway in a safe and controlled manner. The “Airlock” system is recommended to be used at all entry points to the closed carriageway where works vehicles will access the works. To reduce the number of follow-ins it is suggested that the access be from the primary carriageway and not an entry slip road. It is less likely to get intentional incursions from the main carriageway as traffic is gradually being directed down the slip road. The works access on the main carriageway should be located as far away from the point of closure as is possible. This is to discourage motorists from accessing the site and also to allow for a certain amount of stacking for site vehicles whilst waiting to enter the site. The length of the ‘Airlock’ depends on the numbers of works vehicles that must enter the site.

Figure 24. The ‘Airlock’ system at a complete carriageway closure (Highways England, 2016).

The system allows a gateman to control access and stop unauthorised breaches by the public. This is achieved by holding them in the area between the two closures. The system can be used to communicate site specific instructions to authorised vehicles as well as provide emergency services with guidance on how to access, transit and leave site in the event of an emergency. An electronic gate, see Figure 25, can be activated using remote control, which reduces the risk of conflict to the operatives by moving them away from points of conflict. (Highway Safety Hub, 2018).

Figure 25. Automatic Gate to control access to the airlock (Highway Safety Hub, 2018).

When an exit slip road - where the drivers can see their destination and may be aware of a potentially lengthy diversion route - is to be closed, it is more likely that an attempted incursion may take place. It is important that there is a safe 'escape route' back on to the main carriageway for a vehicle who has gained entry into the traffic management zone (Highways England, 2016). The "Airlock" system for an exit slip road closure is seen in Figure 26.

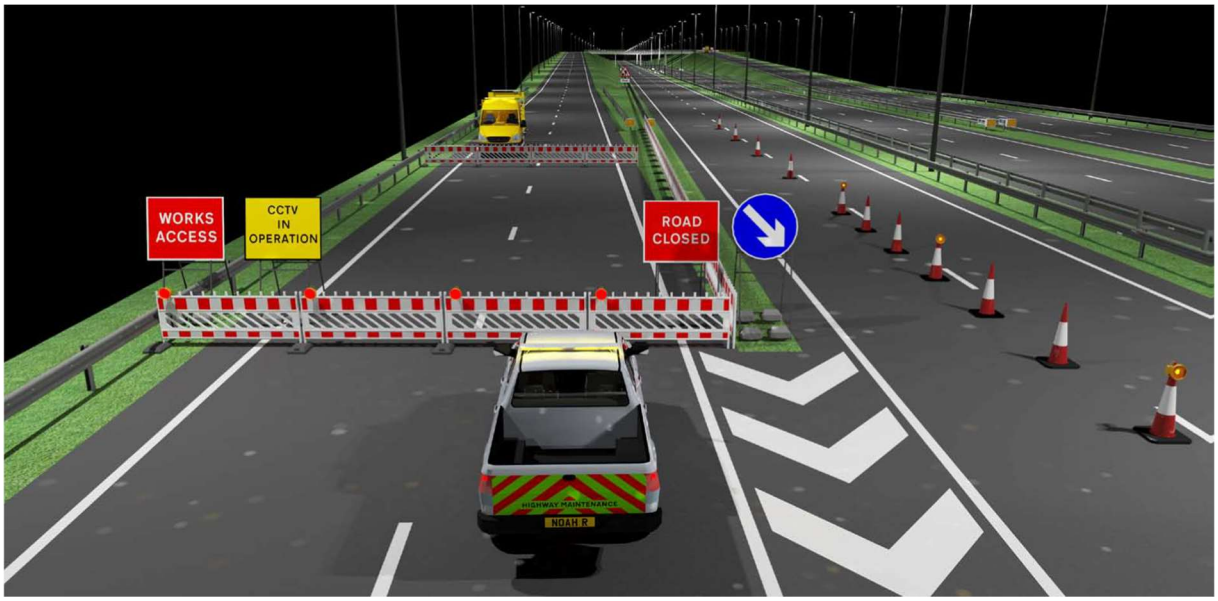

Figure 26. Exit slip road closure (Highways England, 2016).

Where a work access is located at an entry slip road the public are more likely to attempt to gain access to the slip road by force, i.e. moving the cones. Then, it will be difficult to direct the unauthorised vehicle back onto the carriageway in a safe and controlled manner. Hence, a work access should not be deployed at entry slip roads (Highways England, 2016). Where

an entry slip road is to be closed and not used as a work access, a solid line of cones should be detailed showing all possible entry on to the slip road being closed off, see Figure 27. A trained Traffic Management (TM) operative should remain in position at the slip road and the TM vehicle should be situated back from the entry to the slip road. This should deter the public from confrontation with the operative. It is important to keep the operative in the vicinity as they would provide a deterrent to motorists trying to gain access to the closed carriageway. If it is unavoidable to create a work access on the entry slip road, an airlock system should be installed to retain the public from entering there (Highways England, 2016).

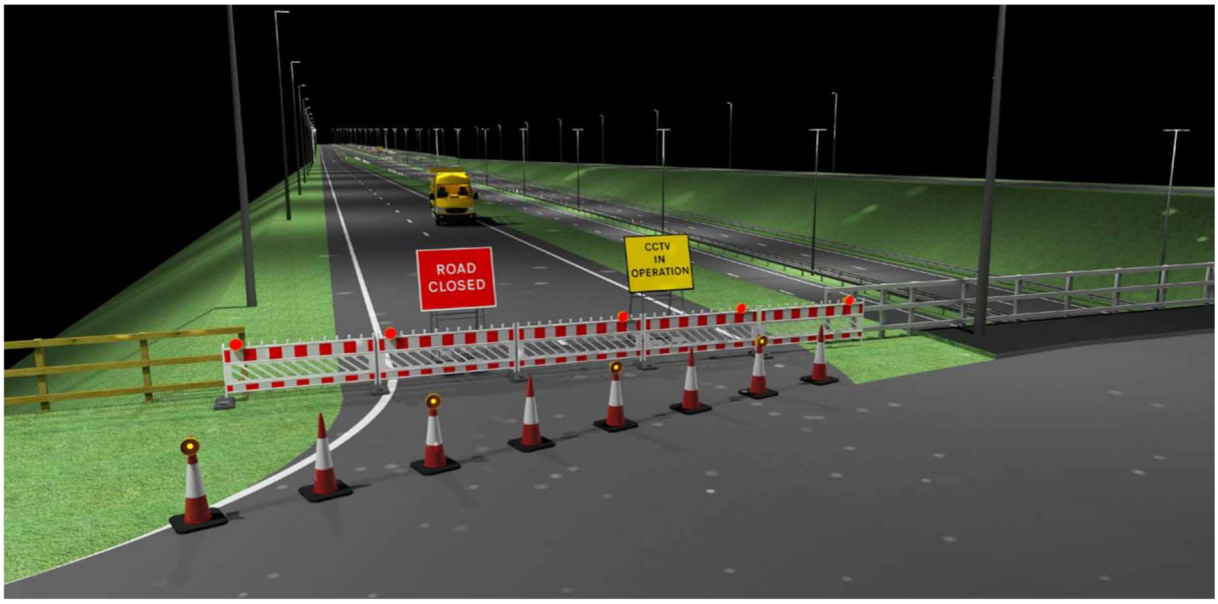

Figure 27. Entry slip road closure (Highways England, 2016).

It is strongly recommended by Highways England (2016) that all Traffic management operatives placed at entry points are issued with working video recording equipment, this will act as a deterrent to members of the public against threatening or abusive behaviour towards the operative. A key part of the use of CCTV of any type is ensuring that road users know that CCTV is in use and their actions are being recorded.

4.6.5 Incursion Warning

To detect incursion into a work zone various types of detection can be used, such as pneumatic tube, see Figure 28, microwave or infrared wireless technology. When a vehicle crosses into the work zone it activates the sensor and a base station sounds an alarm for the workers.

Figure 28. Pneumatic tube incursion alarm (Wang et al., 2013).

A GPS based Incursion Warning System, based on intelligent geo-zones and mobile phone apps, enables traffic management operatives to warn instantly workforce in case of errant vehicle incursion, see Figure 29 (Highway Resource Solutions, 2018).

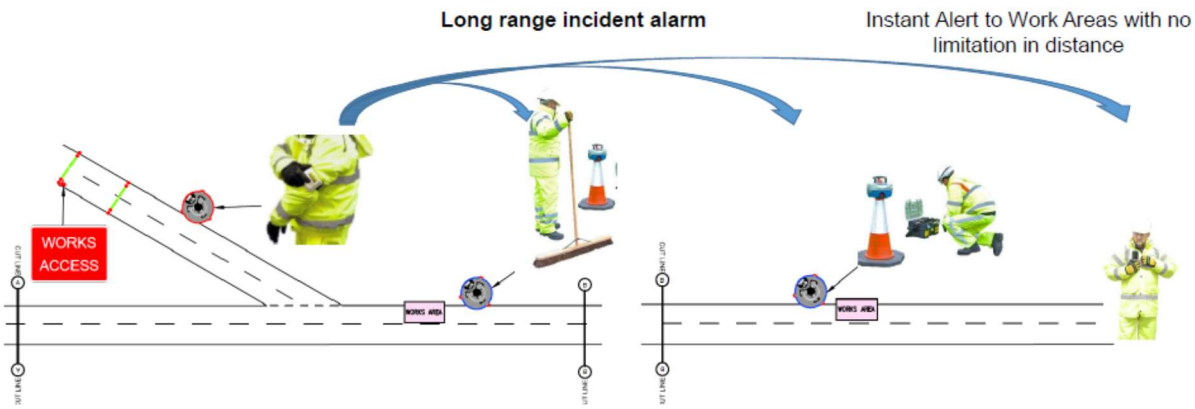

Figure 29. Instant incursion alert (Highway Resource Solutions, 2018).

Movement sensors built into certain TM equipment may provide additional warning to the operative of an incursion attempt. A robust risk assessment is required for all entry slip roads as this has, in the past, been the area at the highest risk of intentional incursion. (Highways England, 2016).

Wang et al. (2013) in a national survey in the USA found that the application and effectiveness of Intrusion Alert Systems (IAS) are limited. The survey showed that 44 % of states with experience in these systems commented that this device was ineffective. The time for installing and removing the units was too long and the alarm sound was not loud enough at noisy work zones. Also, false alarms and maintenance issues contributed to avoiding using these devices. The application of this device at short-term work zones was not recommended until the product is improved.

Another ITS solution is to deploy transponders on road workers and receivers on a road side screen, so when a road worker is close to traffic the screen lights up, informing drivers that there are road workers nearby.

4.6.6 Temporary bridge

A temporary bridge is used to roof over road work creating safe conditions for the workers and reducing the need for diversions, see Figure 30. Such a system has been used in Vienna for maintenance works at bridges (renewal of expansion joints) on urban highways with very high traffic volume (AADTV > 120.000) ASFINAG (2018).

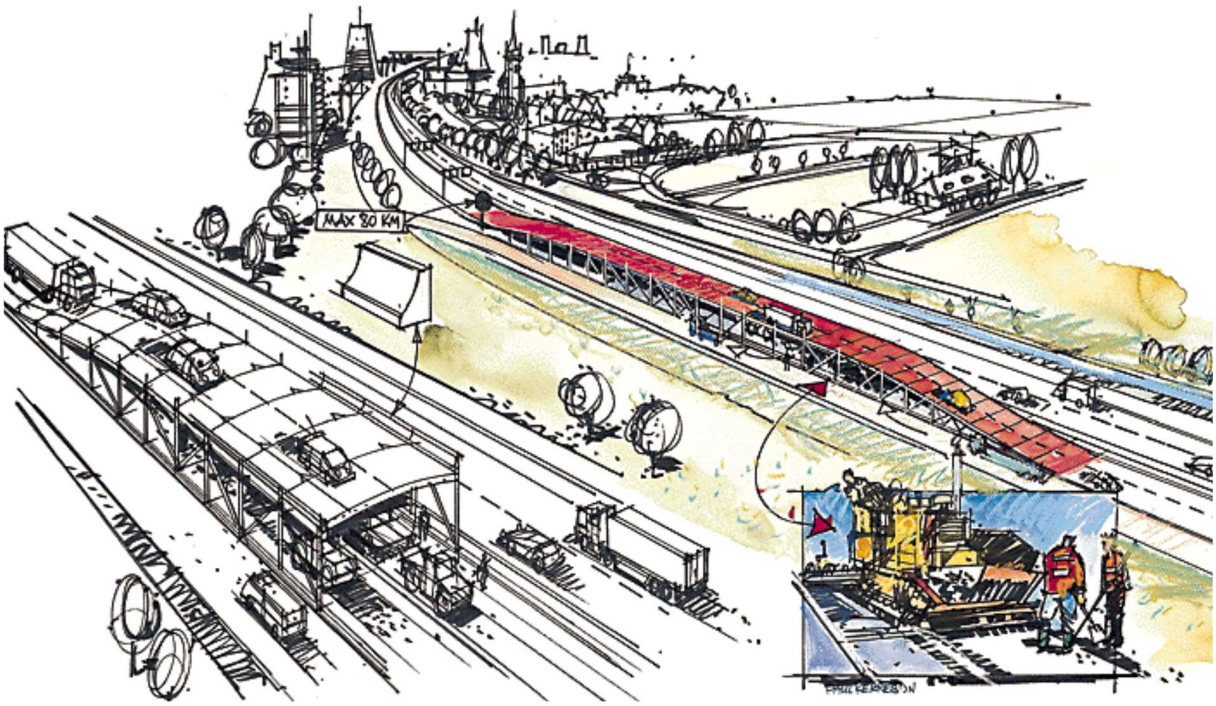

Figure 30. The idea of a temporary bridge to roof over road work (FEHRL, 2008).

5 Conclusions

Best practices found in the literature review comprise both regulatory/management issues and technical issues.

5.1 Regulatory/management issues

- Legislation and regulation should emphasize the severity of speeding at work places and stricter penalties for speeding should be applied there.
- Involve work place protection agents in the development of traffic plans and risk analysis. Road workers should not be on the road until it is secured.
- Lift the temporary traffic management plan out of the tender, by splitting the offer in a safety part and a road work part to make it easier to implement new methods to increase safety at road works.
- Use safety related performance goals.
- Ensure safety measures through contractual obligations and budget; part of the money to be paid for the work should depend on safety results during the project.
- Formalise supervision of contractors around safety and quality to ensure they are fully complying with the contract.
- Conduct regular performance monitoring, spot checks of roadworks. Standardized work zone safety reviews can provide contractors, in writing, a list of work zone deficiencies.
- Arrange regular meetings with contractors (at least monthly), attended by a senior project director and senior contractor.
- Require contractors to produce regular reports and face penalties if they overrun.
- Require contractors to pass courses on how to handle roadworks.
- Use incentives for positive change in road user behaviour around roadworks, by e.g. offering rewards for avoiding rush hours.

5.2 Technical issues

Establishment of a road work zone

- During the short period of time when the work zone signs are deployed all traffic can be stopped by three-to-four vehicles blocking all lanes.
- Deployment and dismantling of road signs and traffic devices can be automated where a robot arm deploys and picks up traffic devices.
- To sign the newly established road work zone a mobile gantry crane with the relevant signs mounted on it can be quickly deployed.

Informing, warning and guiding road users

- In case of long-term road works, road users should be informed about alternative routes.
- Where a diversion route has been set up drivers should be informed by road side signs not to rely on their navigation system, and service providers should be encouraged to update the navigation system.
- A portable real-time automated work zone information system (AWIS), consisting of a dynamic message sign, portable traffic sensors and video cameras providing real-time information about delays and lane closures, alerts drivers to work zone conditions.
- Dissemination of real-time traffic information to motorists via a trailer mounted portable Highway Advisory Radio (HAR) broadcasting system combined with a VMS informing

when a message on road work related information was available was found to be successful in the USA.

- A congestion warning dynamic message sign can contribute to more homogenous speed distribution during rush hours. Displaying queue lengths was found better than displaying delay times.
- Lane separation by a curb system can provide efficient channelization of traffic.
- The provision of temporary diagrammatic guide signs and/or the use of pavement marking symbols designating the lanes assigned to the various routes approaching the interchange significantly improve the drivers' lane choice abilities.
- The use of descriptors of the route and direction complementing pavement arrows to indicate through and exiting lanes provides better lane choice decisions by drivers.
- A Dynamic Lane Merging (DLM) system, consisting of a series of trailer-mounted traffic signs with the message "LEFT LANE - DO NOT PASS WHEN FLASHING", combined with flashing beacons was beneficial in reducing aggressive manoeuvres at work zone lane drops, reducing travel time delay, and decreasing traffic stops and their duration.
- The alternating merging technique, encouraging drivers to take turns when merging in motorway lanes, makes drivers more cautious in their merging manoeuvres.
- The presence of more than one work vehicle is effective in informing motorists that they are approaching a larger work zone operation.

Speed management

- Temporary speed limit or advisory speed signs should only be left in place after the work shift is over if roadway restrictions still present hazard to road users. Failure to remove speed limit or speed advisory signs when they are not needed leads to their reduced credibility and decreased compliance and negative public opinion of work zones.
- Variable speed limit signs (VSLs) governed by a speed-flow-density algorithm determining the appropriate speed limit contribute to increased speed compliance, reduced speed variance and improved traffic throughput and safety.
- VSL can delay the onset of congestion and help produce more rapid recovery from congestion, provided that demand volumes are not too far above capacity at the site.
- Complementary signage with a VMS "Recommended Highest Speed" on road paint vehicles results in lower speeds of passing vehicles.
- Speed feedback on portable VMSs governed by radar reduce mean speed, and percentage of vehicles exceeding the speed limit and is ideal for short-term and mobile work zones. Innovative use of fonts and content, e.g. ''YOU ARE SPEEDING'' followed by ''MINIMUM FINE …" may achieve greater speed reduction.
- A VMS on a TMA with the message "You drive too fast" (if speeding) was found effective at a motorway work zone and indicating "MY SPEED XX" and "YOUR SPEED" was found effective during intermittent road-work conditions.
- Transverse pavement marking bars or even called optical bars can give small speed reducing effects.
- Portable plastic rumble strips provide results similar to those of permanent rumble strips. Orange rumble strips have an additional effect due to their provision of visual alertness.
- The presence of police car(s) at the work zone affects high speed drivers most.
- Automated speed cameras with section speed control affect speed limit compliance along the entire enforced road section.
- A drone radar, triggering the drivers' radar detectors on purpose, affects the speed of the cars equipped with radar detectors so its effectiveness depends on the number of radar detectors in the vehicle flow.

Protecting road workers and road users

- To provide a good visual environment and prevent glare during night time, road works should be illuminated with a luminance level of at least 0.7 cd/m^2. For work zone lighting symmetrical floodlights without glare shield or limiters should only be used if the angle of tilt less than 30°, i.e. when using relatively high lighting masts. At chicanes anti-glare screens of heights from 60 to 120 cm above the road surface, and preferable even higher should be used.
- Flashing strobe lights mounted on TMAs improve driver reactions. Wide retro-reflective tape around the edges of the arrow board improved drivers' recognition distance of the TMA.
- Movable concrete steel barriers with small angle of impact are able to avert also heavy vehicles.
- Longitudinal, water filled barriers used at temporary road workplaces or filling gaps in zone guard barriers are quick to install and involve low costs.
- A "Quick moveable barrier" provides separation of the work place at temporary lane closures.
- Mobile barriers, integrating a rigid wall on a semi-trailer and standard semi-tractors, offers safe work environments for road workers in temporary work zones. It constitutes both a physical and visual wall between passing traffic and workers.
- At complete carriageway closures the "Airlock" system is recommended to reduce the likelihood of vehicle incursions. An electronic gate allows to control access and stop unauthorised breaches and can be activated by remote control, which reduces the risk of conflict to the operatives.
- Traffic management operatives placed at entry points should be issued with video recording equipment. This will act as a deterrent to members of the public against threatening or abusive behaviour towards the operative.
- Incursion detection, based on various types of sensors (pneumatic tube, microwave or infrared) can trigger sounds an alarm the workers. However, further product development is necessary to minimise false alarms and find a way to function in the noisy environment.
- Transponders on road workers and receivers on a road side screen that lights up can inform drivers when there are road workers nearby.
- The idea of a temporary bridge to roof over road work creating safe conditions for the workers and reducing the need for diversions is worthwhile to develop/use.

6 References

ARTBA (2017) Guidelines on managing speeds in work zones. American Road & Transportation Builders Association, USA. https://www.workzonesafety.org/files/documents/training/courses_programs/rsa_program/RSP_Guidance_Documents_Download/RSP_Speed_Guidance_Download.pdf Downloaded 21/11/2017.

ASAP (2015) Towards a European Guideline for Speed Management Measures in Work Zones. Deliverable 5.1 of the CEDR 2012project “Speed Management in Work Zones”.

ASFINAG (2018) Fly Over. https://www.youtube.com/watch?v=ALEC2NI7xuI

Benekohal, R., Wang, M-H., Chitturi, M., Hajbabaie, A., Medina, J. (2009) Speed Photo-Radar Enforcement and Its Effects on Speed in Work Zones Transportation Research Record, V 2096, s 89-97. https://doi.org/10.3141/2096-12

Bolling, A., Sörensen, G. (2008) State-of-the-art för utformning av vägarbetsplatser: förslag till nya lösningar. (State-of-the-art concerning work zone safety – new solutions. In Swedish). VTI notat 6-2008. Swedish National Road and Transport Research Institute, Linköping, Sweden.

Bowie, J.M. (2003) Efficacy of speed monitoring displays in increasing speed limit compliance in highway work zones. Utah: Brigham Young University.

Bushman, R., Berthelot, C., Klashinsky, R. (2003). Deployment and Evaluation of ITS Technology in Work Zones. Paper presented at the Work Zone Safety Session of the 2003 Annual Conference of the Transportation Association of Canada.

Carnell (2018) Safety cameras. https://www.carnellgroup.co.uk/solutions/smartcam/ Downloaded 15/01/2018

CREDO (2017) Highways England – Roadworks Management. Final Report. Credo Business Consulting LLP. London, UK.

Eckenrode, R.T., Sarasua , W.A., Mattox, J.H., Ogle, J.H., Chowdhury, M (2006) Revisiting the Use of Drone Radar to Reduce Speed in Work Zones, South Carolina's Experience. Transportation Research Record, Journal of the Transportation Research Board. https://doi.org/10.3141/2015-03

ETSC (2009) Section Control: towards a more efficient and better accepted enforcement of speed limits? SPEED Fact Sheet N 5, 2009. European Transport Safety Council, Brussels.

ETSC (2011) Road Safety at Work Zones. Thematic Report 6. European Transport Safety Council, Brussels.

FEHRL (2008) NR2C - New Road Construction Concepts. Towards reliable, green, safe & smart and human infrastructure in Europe. The Forum of European National Highway Research Laboratories.

FHWA (2005) Developing and Implementing Transportation Management Plans for Work Zones: Report of the Federal Highway Administration. Department of Transportation, USA.

FHWA (2013) Work Zone Operations Best Practices Guidebook. Report FHWA -HOP-13-012, Federal Highway Administration, USA.

Finley, M.D., Ullman, G.L., Dudek, C.L. (2001) Work Zone Lane Closure Warning Light System. Project Summary report 3983-S.Project Summary Report 3983-S, Texas Transportation Institute, USA.

Fontaine, M.D., Carlson, P.J., Hawkins, Jr., H.G. (2000) Evaluation of traffic control devices for rural high-speed maintenance work zones: Second year activities and final recommendations. Texas Transportation Institute. USA.

Fontaine, M.D., Edara, P.K. (2007) Assessing the benefits of smart work zone systems. Paper presented at the TRB 2007 Annual Meeting. Washington DC, USA.

Fitzsimmons, E., Oneyear, N., Hallmark, S., Hawkins, N., Maze, T. (2009) Synthesis of Traffic Calming Techniques in Work Zones. Research report. Center for Transportation Research and Education, Iowa State University, USA.

Fudala, N.J., Fontaine, M.D. (2010) Interaction Between System Design and Operations of Variable Speed Limit Systems in Work Zones. Transportation Research Record: Journal of the Transportation Research Board, V 2169, pp 1-10. DOI: 10.3141/2169-01

Highways England (2016) The Delivery Hub health, safety and environment. Raising the bar 27. Managing temporary traffic management incursions. https://www.gov.uk/government/publications/health-and-safety-for-major-road-schemes-managing-temporary-traffic-management-incursions Downloaded 11/11/2017

Highway Resource Solutions (2018) http://highwayresource.co.uk/ Downloaded 15/01/2018.

Highway Safety Hub (2018) Roadworks vehicle incursions campaign January 2018. http://www.highwayssafetyhub.com/roadworks-vehicle-incursions-2018.html Downloaded 15/01/2018.

Höhne and Overberg (2018) Oral information by Mr. Höhne and Mr. Overberg from Straßen Nordrhein-Westfalen, Germany.

Joerger, M. (2010) Photo Radar Speed Enforcement in a State Highway Work Zone: Yeon Avenue Demonstration Project. Report No. OR-RD-10-17. Oregon Department of Transportation, USA.

Idewu, W.I.A., Wolshon, B. (2010) Joint Merge and Its Impact on Merging Speeds in Lane Reduction Areas of Construction Zone. Transportation Research Record: Journal of the Transportation Research Board, V 2169, pp. 31-39 DOI: 10.3141/2169-04

Ihs, A., Sörensen, K., Augdal, A., Tiensuu, A. (2009) Road works during night. Recommendations for the visual environment. SINTEF Rapport A10221, 77 p. SINTEF report, Norway. https://brage.bibsys.no/xmlui/handle/11250/2380657

Kamyab, A., Maze, T.H. (2018) Iowa's Evaluation of the Wizard CB Alert System. https://ops.fhwa.dot.gov/wz/workshops/accessible/Maze.htm Downloaded 02/02/2018.

Lidström, P., Odermatt, N. (2010) Förändrad metod för etablering/avetablering: slutrapport. (Changed method of establishment / de-establishment: final report, in Swedish), Svevia, Borlänge, Sweden.

Luttrell, T., Robinson, M., Rephlo, J., Haas, R., Srour, J., Benekohal, R., Oh, J.S., Scriba, T. (2008) Comparative Analysis Report: The Benefits of Using Intelligent Transportation Systems in Work Zones. Report Number FHWA-HOP-09-002. Federal Highway Administration, USA.

Medina, J.C., Benekohal, R.F., Hajbabaie, A., Wang, M.H., Chitturi, M.V. (2009) Downstream Effects of Speed Photo-Radar Enforcement and Other Speed Reduction Treatments on

Work Zones. Transportation Research Record. V2017. Pp 24-33. https://doi.org/10.3141/2107-03

Meyer, E. (2000) Evaluation of Orange Removable Rumble Strips for Highway Work Zones. Transportation Research Record 1715: 36–42.

Persson, M. (2011) Slutrapport Säkrare vägarbetsplatser - Resultat från genomförda försök för att dämpa hastigheten förbi vägarbetsplatser. (Final report: Safer road workplaces - Results from completed trials to slow down the speed past road workplaces. In Swedish) Publikationsnummer: 2011:131, Trafikverket – Swedish Transport Administration.

PIARC (2012) Improvements in Safe Working on Roads. 2012R29EN. World Road Association (PIARC) http://www.piarc.org.

Schrock, S.D., Heaslip, K.P., Wang, M.Heng., Jasrotia, R., Rescot, R. (2010) Closed-Course Test and Analysis of Vibration and Sound Generated by Temporary Rumble Strips for Short-Term Work Zones. Transportation Research Record: Journal of the Transportation Research Board, V 2169, pp 21-30. DOI: 10.3141/2169-03

SEKO (2012) Konsten att bringa ner hastigheten förbi vägarbetsplatser. (The art of bringing down speed at road works. In Swedish). SEKO - Service and communication trade union report. Sweden.

Sesny, R., Lentz, L., Rensel, E. (2007) Act 229 Evaluation Report. Gannett Fleming Inc. Report No. FHWA- PA-2006-038-E00228-Wo7. USA.

Sörensen, G., Wiklund, M. (2010) Åtgärder för att minska hastighet förbi vägarbetsplatser. Utvärdering baserad på tre fältförsök. (Measures to reduce speed past road work zones. An investigation based on three field tests. In Swedish). VTI rapport 698, Swedish National Road and Transport Research Institute, Linköping, Sweden.

Stefan, C. (2006) Section Control – Automatic Speed Enforcement in the Kaisermühlen tunnel (Vienna A22 Motorway). Austria: Austrian Road Safety Board (KFV).

SVEVIA (2014) Automatiserad utsättning och upptagning av sidomarkeringsskärmar – förstudie. (Automated release and pick-up of side markers - pre-study. In Swedish). Working report of Svevia AB, Sweden. vpp.sbuf.se/Public/Documents/ProjectDocuments/7319795d-b27c-43cd-9b5e-9cb88e8523a1/FinalReport/SBUF%2012758%20Slutrapport%20Automatisering%20av%20uts%C3%A4ttning%20och%20upptagning%20av%20sidomarkeringssk%C3%A4rmar.pdf

Trafikverket (2012a) Utvärdering av VMS på TMA: test på väg 40 vid Grandalsmotet. (Evaluation of VMS on TMA: test on the road 40 at Grandalsmotet. In Swedish). Working report of Trafikverket, Sweden.

Trafikverket (2012) TRVÖK Apv, Trafikverkets övergripande krav för arbete på väg. (The Swedish Transport Administration's overall requirements for work on the road, in Swedish). TDOK 2012:87. Swedish Transport Administration.

Trafikverket (2013) TRVR Apv, Trafikverkets tekniska råd för Arbete på väg. (The Swedish Transport Administration's Technical Advice for Work on Road, in Swedish). TDOK 2012:88. Swedish Transport Administration.

Trafikverket (2014) TRVK Apv, Trafikverkets tekniska krav för Arbete på väg. (The Swedish Transport Administration's Technical Requirements for Work on Road, in Swedish). TDOK 2012:86. Swedish Transport Administration.

Trafikverket (2016) Trafikolyckor vid vägarbeten 2003-2015. (Traffic accidents at road works, in Swedish). Publication: 2016:122. Swedish Transport Administration.

TRB (2009) Improving the Safety of Mobile Lane Closures. Research Results Digest 339. National Cooperative Highway Research Program, National Academy of Sciences, Transportation Research Board, USA.ISBN 978-0-309-43572-7 | DOI 10.17226/23011. http://www.trb.org/Publications/Blurbs/162285.aspx Downloaded 21/11/2017

Trout, N.D., Finley, M.D., Ullman, G.L. (2010) Motorist Understanding of Alternative Displays for Speed Limits in Work Zones. Transportation Research Record: Journal of the Transportation Research Board, V2169, pp 81-87.

Ukkusuri, S.V., Gkritza, K., Qian, X., Sadri, A.M. (2016) Best Practices for Maximizing Driver Attention to Work Zone Warning Signs. Report number: FHWA/IN/JTRP-2016/15, Purdue University, USA. DOI: 10.5703/ 1288284316338.

Ullman, G.L., Finley, M.D., Pike, A.M., Knapp, K.K., Songchitruksa, P., Williams, A.A. (2008) Studies to improve temporary traffic control at urban freeway interchanges and pavement marking material selections in work zones. Technical report FHWA/TX-08/0-5238-2. Texas Transportation Institute, USA.

VDOT (2018) WORK ZONE SAFETY CHECKLIST. The Virginia Department of Transportation. USA. http://www.virginiadot.org/business/resources/te-97001.pdf

Vithen, C., Sillesen, U. (2009) New VMS to Improve Safety and Efficiency at Minor Road Works. Paper presented at the 16th world congress and exhibition on intelligent transport systems and services, Stockholm 21-25 September 2009.

Wang, M.H., Schrock, S.D., Bai, Y., Rescot, R.A. (2013) Evaluation of Innovative Traffic Safety Devices at Short-Term Work Zones. Report No. K-TRAN: KU-09-5R. The University of Kansas, USA.

Zwahlen, H.T. (2001) Evaluation of a Real-Time Travel Time Prediction System in a Freeway Construction Work Zone. Final report. Office of Traffic Engineering, Ohio Department of Transportation, Columbus, Ohio, USA

Annex 1 - Internet sites with Work Zone Safety Information

The Highway Safety Hub:
http://www.highwayssafetyhub.com/roadworks-vehicle-incursions-2018.html

Highways England's 'Raising the bar' initiative to identify best practice, raise standards and improve supply chain engagement within major projects.

https://www.gov.uk/government/collections/health-and-safety-for-major-road-schemes-raising-the-bar-initiative

Highway Resource Solutions:
http://highwayresource.co.uk/

Traffic Signs Manual, Chapter 8 - Traffic Safety Measures and Signs for Road Works and Temporary Situations, Part 1: Design

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/203669/traffic-signs-manual-chapter-08-part-01.pdf

Traffic Signs Manual, Chapter 8 - Traffic Safety Measures and Signs for Road Works and Temporary Situations, Part 2: Operations

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/203670/traffic-signs-manual-chapter-08-part-02.pdf

Traffic Signs Manual, Chapter 8 - Traffic Safety Measures and Signs for Road Works and Temporary Situations, Part 3: Update

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/594446/traffic-signs-manual-chapter-08-part-03.pdf

An ongoing German project aims at developing a driverless TMA vehicles that will be able to follow the work vehicles automatically during short term road works along the road.

http://www.bast.de/DE/Publikationen/BASt-aktuell/Downloads/BASt-aktuell-2017-01.pdf?__blob=publicationFile&v=2

https://www.afas-online.de/

The internet site "The National Work Zone Safety Information Clearinghouse" is operated by the American Road & Transportation Builders Association (ARTBA) in cooperation with the U.S. Federal Highway Administration and Texas A&M. The site "Guidelines for Work Zone Intrusion Countermeasures" lists measures, such as Rumble strips, Channelizing device spacing reduction, Flagger station enhanced setups, Work zone speed limit reductions, Police enforcement, Variable message signs, Drone radar.

https://www.workzonesafety.org/data-resources/other-resources/guidelines_wz_intrusion_countermeasures_police_enforcement/

Several best practices associated with work zone management strategies can be found on the FHWA Work Zone web site at:

http://www.fhwa.dot.gov/workzones