Traffic & Transport
Automotive Campus 30
5708 JZ Helmond
P.O. Box 756
5700 AT Helmond
The Netherlands

www.tno.nl

T +31 88 866 57 29
F +31 88 866 88 62

TNO report

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Feasibility study AEB system smart marker

Date	15 February 2022
Author(s)	Jeroen Uittenbogaard, Esra van Dam, Sjef van Montfort
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1 Introduction

Advanced Emergency Braking (AEB) systems are obligatory on new heavy duty vehicles which drive on European roads [1]. AEB systems currently on the market seem to not always react to all objects on the road, such as barriers or roadworks objects [2][3][4][5]. Rijkswaterstaat (RWS) and Dienst Wegverkeer (RDW) aim to improve road safety. They expect this can be accomplished by introducing a standardised marker that is to be applied on or near roadworks objects. This marker should make sure that this class of objects (roadworks objects) can be uniquely detected and classified by the truck's sensor system. To further address this topic RWS and RDW requested TNO to investigate the feasibility of the development and usage of such a standardised marker.

In this project the potential effect of an additional marker on roadworks to decrease the number of trucks crashing into them, compared to other solution directions, is analysed. Furthermore this project discusses the feasibility of the different solutions, including a standardised marker that has been identified by RWS, RDW and TNO.

The project carried out by TNO for this purpose consists of 5 work packages (WPs) as shown in Figure 1. In the first work package (WP1) the background of the problem for RWS is described in more detail. This is done based on examples and previous work provided by RWS and information found in literature. The results of this work package are described in Chapter 2. Chapter 3 elaborates on the mechanisms of AEB systems which are relevant in the discussion on the (technical) feasibility of an AEB marker. Several aspects of feasibility are investigated in WP2 and 3 (Chapter 4). WP4 considers a brief study on possible negative effects and safety benefits of the introduction of a standardised marker (Chapter 5). To conclude, results are summarized and discussed in Chapter 6.
As part of this project, TNO organised together with RWS and RDW an expert workshop with experts from the industry, governments and research institutes to get their feedback on feasibility aspects of a standardised marker. This workshop took place on August 31st 2021.
Based on feedback from a large part of the participants in the workshop, it was decided to perform the feasibility study and effect analysis not only for a standardised AEB marker, but also consider other solution directions to improve performance of AEB systems at road work objects.

Figure 1 Work package structure of the AEB systems marker project

2 Problem description and solution directions

The purpose of this chapter is to provide the background on which the feasibility study is build. In section 2.1 a short introduction is provided on the safety issue for the Dutch road authorities, Rijkswaterstaat (RWS). Section 2.2 summarizes several experiments previously performed by RWS. Section 2.3 describes the relevant regulations for AEB systems on trucks. Related safety issues which might benefit from a standardised AEB marker are listed in section 2.4. Next, section 2.5 summarizes the result of the expert workshop organised in this study and lastly section 2.6 presents the selection of solution directions evaluated in this feasibility study.

2.1 Safety issue for RWS

Accidents on highways due to trucks driving into roadworks occur on an (almost) weekly basis in the Netherlands [6]. Trucks sold nowadays are obliged to be equipped with an AEB system (UN/ECE R131 [9]). The number of accidents however did not traceably reduce [6]. A possible explanation, further explored in this report, is that the AEB system is not able to detect the roadworks and is therefore not activated.
Looking into accidents with trucks and roadworks objects, shows a large variety of scenarios. This variety makes it difficult to pin-point a (single) cause for the AEB system not being activated. Although for some of these accidents it is known that the truck was equipped with an AEB system, it is not always known whether it was active [2]. The AEB system can be switched off by the user, which is sometimes done [7][8]. Furthermore, the way AEB is implemented in a truck differs between brands, truck types, and year of construction. Current AEB systems are using various sensors (radar, camera, lidar, or a combination of multiple sensor types) and use different ways of processing and responding to this sensor data. Furthermore, AEB is still under development and hence constantly improving. As an example, in the new regulations for AEB systems on passenger cars, UN/ECE R152, not only AEB towards passenger vehicles, but also crossing pedestrians are considered [9]. Hence, even when assuming AEB was present, active and did not activate, it is almost impossible to derive from accident data *why* the AEB system was not activated.

2.2 Previous tests by RWS

To get a better understanding of the response of current AEB systems (on trucks) toward various objects, RWS performed several tests with trucks and passenger cars equipped with an AEB system [3][4][5][10][11][12]. In [10] it is concluded that the tested vehicles (both trucks and passenger cars) generally respond well to the European Vehicle Target (EVT), the Jetta soft target and the SFD target. The trucks tested in [3] responded well to a truck-trailer. A less consistent AEB response was found for the other test objects, among which road inspector vehicles (so called WIS cars) and motorcycles, collision absorbers and mobile road signs. Tests performed in [3] and [5] also showed inconsistent AEB responses towards actual passenger cars. The tests performed by RWS did not provide conclusions on where the inconsistent performance originates from. It should be noted that most of these experiments, for safety reasons, were performed such that mainly the Forward

Collision Warning (FCW) could be activated, and not yet an AEB activation. The experiments described in [10] *did* involve tests up to impact.

2.3 Approval regulations

It should be noted that the current regulations for type approval requirements for AEB systems (UN/ECE R131 [9]) aim at preventing rear-end in lane collisions or reducing their severity (-10 / -20 km/h) where the target vehicle is specified as category M (motor vehicles for the carriage of passengers with at least 4 wheels), N (motor vehicles for the carriage of goods with at least 4 wheels) and O ((semi)trailers). Approval is verified against a test with a standard (sedan) passenger car (or representative soft target):

> *"6.3.1. The target used for the tests shall be a regular high volume series production passenger car of category M1 AA saloon, or alternatively a 'soft target' representative of such a vehicle in terms of its identification characteristics applicable to the sensor system of the AEBS under test".*

Verification against other objects is not imposed. Furthermore, only a single test condition is used: flat, dry concrete surface, no wind liable to affect the results, target offset from centreline less than 0.5m, and velocity of vehicle under test of 80 km/h. A false positive test is included in the approval requirement.

Note that the UN/ECE R131 is about to be updated in line with the UN/ECE R152 (AEBS for a.o. passenger vehicles [14]) and will include pedestrian and bicycle targets for the AEB system.

2.4 Other safety issues

During the meetings on AEB systems for trucks of the UNECE (GRVA AEBS-HDV), several additional safety issues from across Europe have been raised. UK reported a safety issue concerning trucks running into emergency vehicles [13]. Trucks/busses running into barriers at railroad crossings or entrances of bridges and tunnels is a concern in France [15]. Accident analysis in Germany showed a high percentage of accidents involving trucks driving into the back of stationary vehicles (e.g. traffic jams) [16].

These safety issues are not actively considered in the current research, which focusses on trucks running into roadworks on highways, however it is good to keep (applicability to) these other safety issues in mind when feasibility of various solution directions is discussed.

2.5 Summary expert workshop

As part of the feasibility study of TNO, an expert workshop was organized on the topic of a standardised marker for AEB activation on August 31st, 2021. A group of 29 experts from industry, governments and research institutes participated in this virtual workshop [17]:

- During the introduction of the problem in this workshop, the experts pointed out they were trying to identify what the extent of this problem is. Although challenging, is there a way to quantify the issue better and make it more specific than we do now? Perhaps a more in-depth accidentology study can be performed or a deeper dive into the test results can help answer this question.

- The majority of the experts thought that a standardised marker is a possible solution worth to investigate (on a general level, not just from a technical perspective).
- There was no consensus if it will become a temporary solution only or will have added value in the future as well.
- Furthermore there was no common ground on how such a marker should present itself: as a unique identifier or by mimicking existing properties.
- There was also a clear division on the applicability of the marker for current or only new systems.

It should be noted that participants indicated several of these questions were difficult to answer since little detail is known about such a standardised marker.

During the technical feasibility brainstorm mainly the general advantages and disadvantages of each sensor were discussed. It became clear that creating a standardised marker is a complex challenge and each implementation needs to identify and prevent possible unwanted side effects. E.g. using a corner/cone radar reflector might work for early generation AEB systems, however may not be recognized by the newer (smarter) systems. On top of that such reflectors can have destructive interferences, make it difficult to estimate dimensions, possibly make smaller objects close by undetectable and can be vulnerable for misuse.
Summarizing, the workshop showed that there is no consensus yet on the best way forward in reducing accidents between trucks and road work objects on highways.

Other solution directions next to the standardised marker were mentioned, such as including (standardised) road work objects in AEB system approval, or introducing wireless infrastructure to vehicle (I2V) communication. Based on the feedback during this workshop it is decided to continue the project not only looking into the feasibility of a standardised marker, with a focus on its technical feasibility, but to look into other solution directions as well with an equal focus on all feasibility aspects. The solution directions investigated in this project are mentioned in the next section.

2.6 Solution directions

Based on the findings during the literature research (section 2.1 to 2.4) and the feedback from the expert workshop (section 2.5) it was decided in this project to continue the investigation for multiple solution directions with the aim to reduce accidents between AEB equipped trucks and roadworks objects. Focus will be on technical solutions with the aim to support AEB systems (on trucks) at roadworks areas (in highway scenarios). The solution directions in this study will focus on the braking function of the AEB system and not the warning function. Solutions directions with the purpose to alert / influence / nudge the (truck) driver are also directions which could be investigated, however these are not considered in the current study.
The following 4 solution directions are investigated in this study:

1. Place a standardised marker on roadworks objects;
2. Place a standardised marker at a certain distance before the roadworks objects (in lane);
3. Include road work object detection in truck AEB development;
4. Introduce communication between truck and roadworks objects.

The following sections provide a short description of each of the solution directions.

2.6.1 *AEB marker on roadworks objects*

For this solution direction it is assumed that a standardised AEB marker can be placed on the roadworks objects. It should be able to trigger the truck's AEB system if the roadworks objects with a marker attached is in the same lane as the truck. The marker should be detectable by the AEB sensor systems currently on the market, or that are expected in the near future, i.e. radar, camera, lidar and fused sensor systems.

Preferably the AEB marker is mountable on various kinds of roadworks objects, such as collision absorbers, traffic arrow trailers or WIS vehicles (see Figure 2).

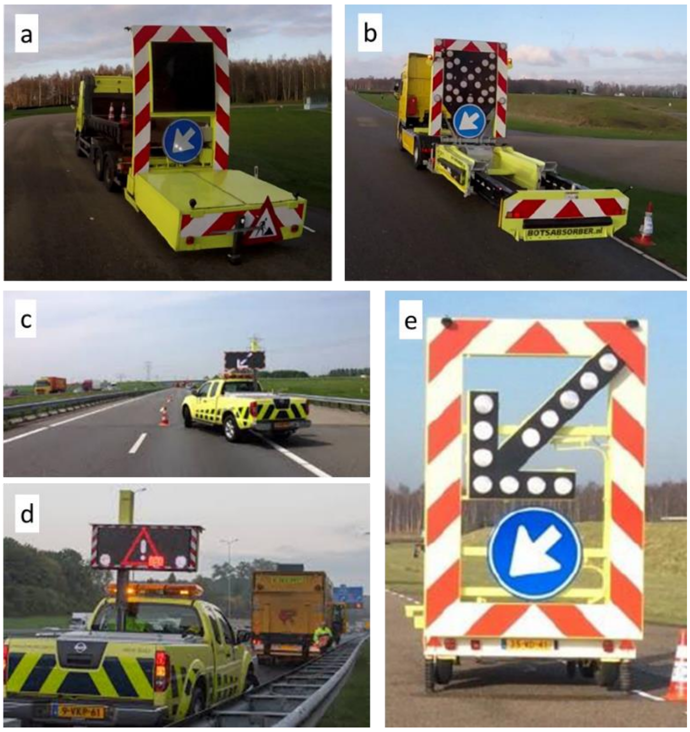

Figure 2 Examples of Dutch roadworks objects: collision absorber (a, b), WIS vehicle (c, d, with c in 'fend off' position) and a traffic arrow trailer (e)

2.6.2 *Stand-alone AEB marker*

The stand-alone standardised AEB marker is positioned at a certain, to be determined, distance from the roadworks object itself, in the lane where the road work object is positioned. As for the marker described in the previous section, the stand-alone marker should be detectable by radar, camera, lidar and fused sensor systems. The stand-alone marker should be positioned firmly in place, such that it does not move out of its lane.

2.6.3 *Include objects*

The third solution direction investigated in this project, is the explicit inclusion of roadworks objects into the AEB development and testing, assuring that these type of objects are correctly detected and classified by the AEBS.

Standardizing roadworks objects, e.g. over Europe, will be beneficial (or might even be needed) for this solution direction.

2.6.4 *Communication*

Another solution direction mentioned several times during the expert workshop is communication. Communication between road work objects and trucks allows to accurately inform approaching trucks on what they can expect ahead, either within their own lane or in other lanes. This solution direction assumes communication equipment is present at the roadworks area as well as in the truck. Furthermore it is required to establish communication protocols and standardized message sets to exchange information between both parties.

3 AEB systems

3.1 General AEB system

Advanced emergency braking systems (AEBS) in trucks should trigger a warning and initiate a brake action according to UNECE regulations [9]. Depending on the type and mass of the truck, the system should provide a warning 1.4s to 0s before the brake action and reduce speed with at least 10 - 20 km/h for a stationary M1 type vehicle. and complete avoidance for a moving M1 type vehicle (passenger car) at 80 km/h. An example of a target to be used in these tests is the European Vehicle Target (EVT) as shown in Figure 3 [18]. In this study the main focus will be on the braking function of the AEB system and not the warning function.

Figure 3 European Vehicle Target (EVT) which can be used in the approval process of AEB in trucks.

The complete action of an AEBS consists of the following 3 parts: it needs to detect objects in its surroundings (sense), decide on an appropriate action (think) and finally perform an appropriate action (act). In each of these different parts, different aspects are relevant for a good performance.

A general approach of an AEB system can be found in Figure 4. The AEBS is equipped with one or multiple sensors to detect, classify and trace objects in the direct environment. Based on the information collected by the sensors, a confidence level is estimated for each detected object. If the confidence is high enough, the object is included in the decision making process of the AEBS. When multiple sensors are present, a fusion algorithm will be used to combine the information of the different sensor into a single image of the environment with the positively identified objects. With this information the AEB system will, in the thinking phase, compute the collision risk by using internal models of the identified object(s). In the decision module it will make the decision to trigger an appropriate action. During the act phase it will typically warn the driver first and trigger the emergency brake second.

In order to come to a complete stop and avoid a collision with the object, the performance of the entire chain needs to be characterized which is done in section 3.2. Section 3.3 will elaborate on the sensor systems commonly used in current AEB systems.

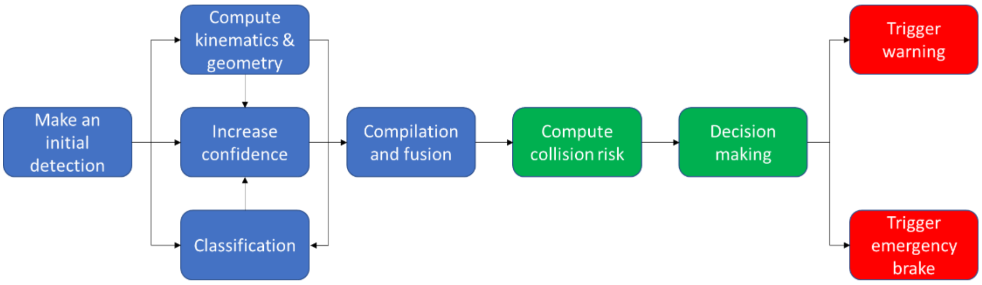

Figure 4 General approach of an AEB system, with the sensing (blue), thinking (green) and acting (red) phases.

3.2 AEB kinematics

In order to discuss the technical feasibility of an avoidance of roadworks objects, it is worth to get an indication of the complete kinematics during an AEB action. As an example, we take a truck that is driving on a highway at constant speed towards a roads works object that is blocking its lane. This exercise will provide an insight in the distances, velocities, accelerations and timings to be encountered by the complete system.

Figure 5 shows a generalised deceleration pulse which can be expected during an AEB action. It starts at time t=0s when the truck is driving with a constant speed V_0 km/h and at which the sensor systems makes an initial detection. In the time following this moment, the AEB system needs to go through the aforementioned sense, think and act phases before the truck actually starts decelerating. This will cause a time delay in the braking response of the AEBS which is characterized by the total delay t_d (s).

From that moment the deceleration increases linearly over time until the maximum deceleration is reached. This part is characterized by the ramp steepness (or jerk) J_r (m/s^3). The jerk is mostly dependent on how fast the brake system can build up the brake pressure and the mass of the truck. After that the truck keeps decelerating at its maximum deceleration until the truck comes to a stand-still. The time this phase will take is again dependent on the maturity of the brake system, mass of the truck, but also on the friction between the tyres and the road, where on a dry road this value will be substantially higher than on a wet or icy road.

From literature [19][20][21][22][23][24][25][26] and experience build up in customer projects from TNO (test)experts/engineers the range of all 3 variables for a truck AEB pulse (maximum deceleration, total delay and the ramp steepness), the actual implementation of this deceleration pulse can be quantified:

• Maximum deceleration (d_{max})	6 – 9 m/s^2
• Total delay (t_d)	0.2 – 0.6 s
• Ramp steepness (J_r)	10 – 50 m/s^3

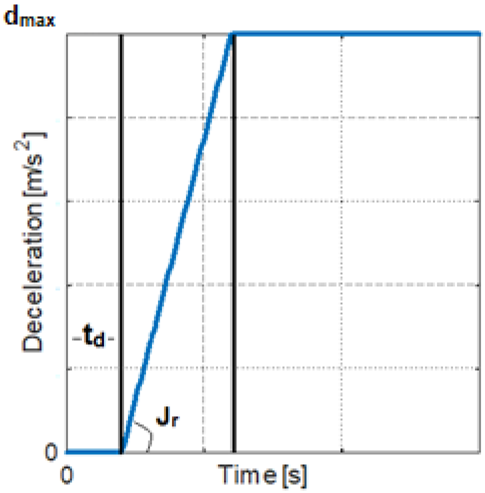

Figure 5 Generalised deceleration pulse which can be expected during an AEB action.

Figure 6 shows the distance needed to come to a complete stop using the average values listed above (hence d_{max} of 7.5 m/s^2, t_d = 0.4 s, J_r = 30 m/s^3) over a speed range around the maximum allowed speed of a truck in the Netherlands (80 +- 10 km/h). In the results each phase in the deceleration pulse is distinguished. The total distance needed from the moment of first detection to a complete stop ranges from 36m at 70 km/h to 55m at 90 km/h. Table 1 summarizes these distances for the characteristic speeds of 70, 80 and 90 km/h for the most optimal, average and worst combination of values listed above.

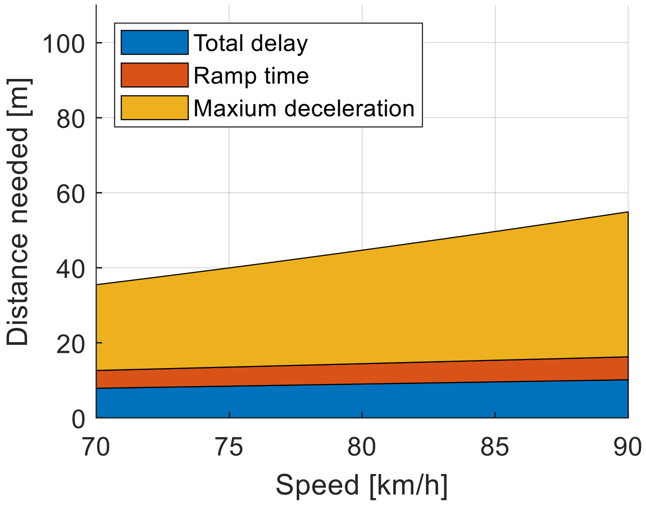

Figure 6 Distance covered in the separate phases of the AEB pulse until a complete stop for the average values from their respective ranges of the variables d_{max}, t_d and J_r as a function of the initial speed.

Table 1 Distance needed to come to a complete stop for characteristic speeds and optimal, average and worst values

Speed [km/h]	Distance needed to complete stop [m]		
	Optimal values	Average values	Worst values
70	27	36	49
80	34	45	61
90	42	55	75

In a similar way, the time to come to a complete stop can be computed. This is separated between the time from the initial detection and the time of actual deceleration to stand-still. Figure 7 shows both these time values using the average values of the variables d_{max}, t_d and J_r from their respective ranges as a function of the initial speed. At 70 km/h these values are 1.8s and 1.4s, while at 90 km/h they are 2.2s and 1.8s. Table 2 and Table 3 summarize these time values for the characteristic speeds of 70, 80 and 90 km/h for the optimal, average and worst combination of values listed above.

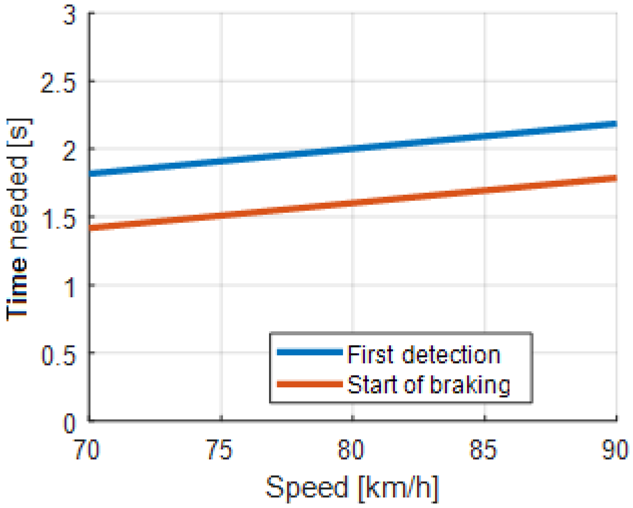

Figure 7 Time needed to come to a full stop from the first detection (blue) and from the start of deceleration (red) for the average values as a function of the initial speed.

Table 2 First detection needed to come to a complete stop for characteristic speeds and optimal, average and worst values

Speed [km/h]	First detection needed to complete stop [s]		
	Optimal values	Average values	Worst values
70	1.4	1.8	2.5
80	1.5	2.0	2.7
90	1.7	2.2	3.0

Table 3 Start deceleration needed to come to a complete stop for characteristic speeds and optimal, average and worst values

Speed [km/h]	Start deceleration needed to complete stop [s]		
	Optimal values	Average values	Worst values
70	1.2	1.4	1.9
80	1.3	1.6	2.1
90	1.5	1.8	2.4

3.3 Sensor systems

In the following section the most common sensor systems (camera, radar and lidar) are discussed. It should be noted that a large variety of sensor systems exists. For instance, there are systems that completely rely on a single sensor while others use a fusion of multiple sensors. Also for sensor systems that use fusion, a plethora of different approaches exists, where one system for example uses mainly a camera

system for close by objects and a radar system for further away objects and another uses both systems for all ranges focusing on the strengths of each system.
However, this variety does not exist only in terms of the hardware components and variations, but mostly in the detection part from the gathered data. A lot of different detection algorithms exist to extract objects from the captured data. Since all of the main sensors provide a snapshot/image of the world, a similar approach is usually followed where the actual algorithms can differ.
A traditional approach usually has 3 stages: region selection, feature extraction and classification. In the first stage, a coarse selection is made for possible location of an object within the data in order to prevent analysing the entire data set to save computational power and therefore time. A fast scanning algorithm can for example already classify the parts of the data that represent the sky, no objects can be expected there and can thus be skipped. This will be an improvement compared to an algorithm that uses a sliding window to search for objects, in which the entire image is scanned every time. In the second step features are extracted from the data to identify possible objects. An example of such typical algorithms in automotive are histograms of oriented gradients (HOG) and principle component analysis (PCA). The last step compares these extracted objects with the internal database to classify these objects with a certain confidence level. A typical algorithm for this task is support vector machines (SVM). However the Bayes decision rule and K Nearest Neighbour (KNN) are also used regularly. If the algorithm is confident enough about a positive comparison, a new object has been identified and classified. This object can then be tracked in time, throughout the following data samples making the computation of kinematics, such as velocity and time-to-collision, possible. A rule of thumb; the higher the framerate and confidence in the detection, the higher the accuracy of the computation of these kinematics. Modern approaches combine multiple steps of the traditional approach, mostly with a method called deep learning. In this method, neural networks are trained to find, feature and classify objects. It was practically implemented with convolutional neural networks (CNNs) in 2012, improved to region based CNNs (R-CNNs) around 2014 and branched outward creating a plethora of algorithms like SPP-net, FRCN, YOLO, etc. These approaches still require a lot of computational resources and still have limits with respect to detection confidence in relation to the framerate. All in all, a lot of different approaches are possible. The actual methods used by the suppliers of these sensors systems is classified, which means that it is not clear how exactly these sensor systems operate. That is why it is always important to involve industry when implementing one of the mentioned solution directions.

In the following sections, the 3 main sensor systems are elaborated upon in terms of their capabilities. Note that they are discussed separately and that the use of multiple (different or identical) sensor systems can overcome the mentioned limitations.

3.3.1 Camera sensor system

The camera is the most intuitive sensor for detecting objects in the vehicle environment, since it works similar to the human eye. A camera sensor system works by capturing images in a regular interval. These images are built-up of a certain number of pixels, where each pixel has 3 values for the RGB colour representation (in colour based cameras, only a single value in monochrome cameras). These images are scanned by the previously mentioned algorithms to find objects of interest.

The main advantage of cameras is that they can classify objects very well. Furthermore a major advantage of camera systems is that they can detect lane markers well, meaning that they can compute if objects ahead are in its own lane or not. The computation of the kinematics can be considered as sufficient, however not as accurate as for the radar and lidar systems which can measure these directly. The main disadvantage is that they will produce poor results in bad weather and low lighting conditions, since they need e.g. sufficient contrast with background to distinguish objects. Cameras also suffer from bright lighting sources (e.g. glare from the sun) and are “slow” to adjust to rapidly changing lighting conditions (e.g. entering and exiting a tunnel).

The size, in terms of pixels, of the object within the captured image is dependent on the field of view (FoV) of the camera, the total size of the captured image and the distance of the camera to the object. In order to detect an object, its size needs to be sufficient for a reliable detection. An actual minimal size is difficult to estimate due to the complex and diverse nature of all the different algorithms, however estimates of 16x16 to 64x64 pixels have been found for current systems depending on the quality (contrast, lighting, etc), the type of target to be classified and the precision and sensitivity required [33][34][35][36][37][38][39][40]. For this study a minimum size of 32x32 is assumed in order to compute the actual size of the detected objects with sufficient reliability.

If the field of view of a camera is larger, the advantage is that more objects could potentially be detected, however this will decrease the size of the objects within the captured image. Smaller FoV cameras on the other hand are able to detect fewer objects towards their sides, but will increase the size of the objects within the captured image. The FoV of current and near future automotive forward facing mono cameras typically range between 40 and 100 degrees depending on the versatility demand of the systems [25][26][27][28][29][30][31][32].
The larger the total size of the captured image, the larger the size of the object within the captured image will be. However larger sizes require more computational efforts and sufficient lighting for far away objects can become an issue. Current and near future automotive forward facing mono camera range from 0.3 to 4 million pixels. [28][29][30][31][32].
Figure 8 shows how many pixels represent a meter within a captured image as a function of the distance for cameras with a field of view from 40 to 100 degrees and 4 different image sizes (640x360 [VGA 0.3Mpx], 1280x720 [HdReady 1Mpx], 1920*1080 [FullHd 2Mpx] and 3840*2160 [4K 4Mpx]).

Figure 9 shows, based on the minimum 32 pixel size assumption, what the minimum actual size an object needs to be in order to be detected as a function of the distance for the field of views and resolutions of the cameras from Figure 8. A traffic arrow trailer with a width of 2.335m and the EVT target with a width of 1.712m are also shown in the same figure.
Table 1 shows that at 80km/h with average values a distance of about 45m is needed from the first detection. It can be seen that the EVT target should just be able to be detected with a 1MPx camera with a field of view of 70 degrees. When upgrading the camera to 2Mpx the object still needs to be at least 1m in size. At 90km/h in the worst deceleration conditions the distance needed increases to 75m, in which the object needs to have a minimum size of 1.8m for this 2Mpx and 70 degree camera. In the most optimistic scenario, near future 4K camera with a small 40 degree opening angle

can decrease the needed object size to about 0.5m (for positive camera detection only).

Figure 10 shows as an indication how a traffic arrow trailer with a width of 2.335m and the EVT target with a width of 1.712m is captured by a camera sensor at different pixels/meter at perfect lighting and focusing conditions. It can be seen that at 10 pixels/m both objects will have a small size (23 and 17 pixels) and will probably not be identified as an object. At 20 pixels/m the sizes have doubled and will increase just above the assumed minimum size of 32 pixels for object detection.

Higher framerates usually lead to better detections and higher accuracy of the computation of the object kinematics and a lower total delay. However increasing the framerate will lead, just as increasing the image size, to a higher computational effort. In current camera systems frame rates of 30 frames per second cameras are found up to 2Mpx (without downscaling) and can increase to 60 frames per second in the 0.3 – 1Mpx range [28][29][31][32].

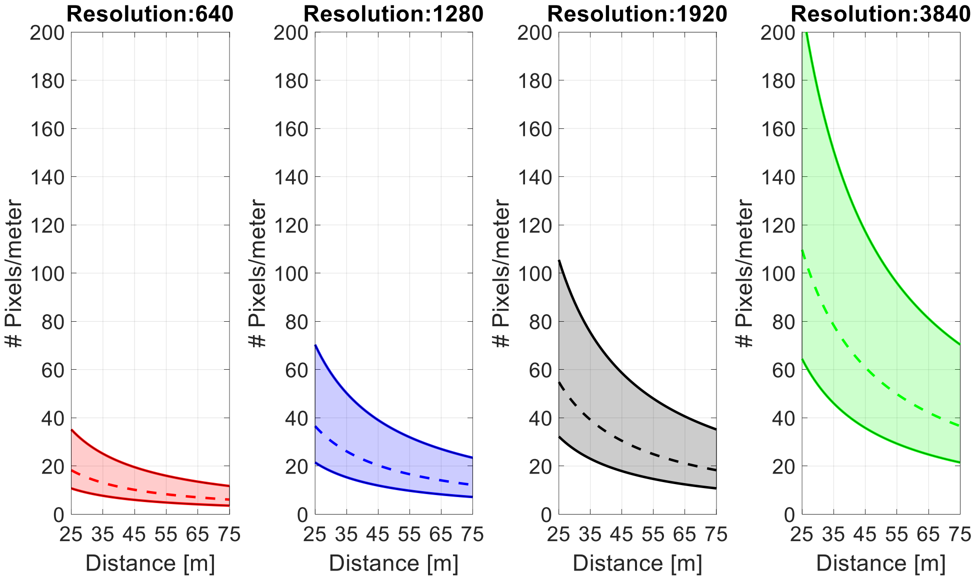

Figure 8 Pixels per meter of objects in the captured image as a function of distance for 4 different resolution cameras. Each plot shows a range of the field of view from 40 (top) to 100 degrees (bottom). The dashed line represents the average field of view of 70 degrees.

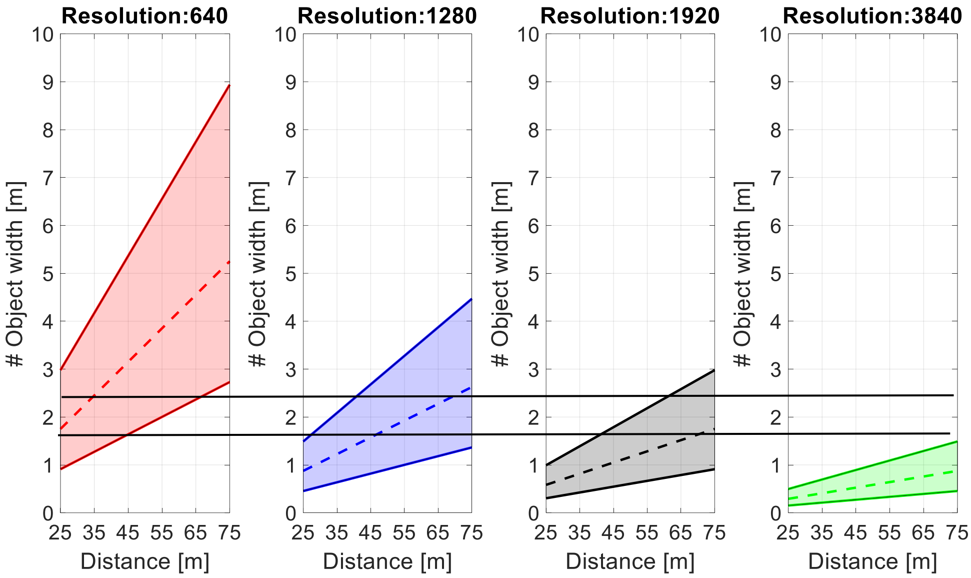

Figure 9 Potential minimum object size with the assumptions that a camera systems needs a minimum of 32 pixels in width to detect and classify an object as a function of distance for 4 different resolution cameras. Each plot shows a range of the field of view from 40 (bottom) to 100 degrees (top). The dashed line represents the average field of view of 70 degrees. The black lines represent a traffic arrow trailer (top) and EVT target (bottom) width.

Figure 10 Image of a traffic arrow trailer (width 2.335m) and the EVT target (width 1.712m) at different pixels per meter (10, 20, 30 and 60 from left to right). The traffic arrow trailer corresponds to 23, 46, 70 and 140 and the EVT target corresponds to 17, 35, 51 and 103 pixels in width respectively

3.3.2 *Radar sensor system*

Radar stands for **Ra**dio **D**etection **A**nd **R**anging. It has been used since 1999 in vehicles to support drivers with their driving tasks. In radar technology, a transmitter and a receiver side are distinguished. The transmitter transmits radio waves in targeted directions. These radio waves then get reflected when they reach objects.

This reflection is mostly dependent on the incident angle, shape, size and material of the object. The reflectiveness of objects is often expressed in the so-called Radar Cross Section (RCS). The higher the RCS, the more visible an object is for a radar sensor system.
The receiver picks up the waves that are reflected in the direction of the receiver. For automotive radars, the transmitter and receiver are combined in one single device. Using an accurate clock to determine the reflection time, a radar computes the range of the object and by measuring the Doppler-shift it can accurately compute the object's velocity. Together with the horizontal (azimuth) and vertical (elevation) angle a 3D 'image' of the reflection is created as a function of time. This can then be used for object detection.

Radar sensor system currently available consist mostly of multiple channels for short range (SRR), mid-range (MRR) and long range (LRR) detections, where the field of view is large for the SRR and drops for the LRR. Typical values can be found in Table 4 [45][46].

Table 4 Typical Ranges and field of views for different type of radar channels

	SRR	MRR	LRR
Field of view [°]	120 - 150	80 - 90	14 - 18
Range [m]	0 - 20	70 - 100	210 - 250

The main advantage of radar sensor systems is that they are less affected by weather conditions (only in extreme weather conditions), the transmission of radio waves is not affected by visibility and lighting. Therefore, radar performance is consistent across all environmental conditions. Furthermore, it can measure radial velocity directly, making this measurement very accurate. Main disadvantage of radar sensor systems is that they are relatively weak at measuring a precise and consistent shape of the a typical object. As a result, the system will have more difficulties to classify the object even though it will have no difficulties detecting that something is there. For example, the radar system will have difficulties distinguishing bicycles from motorcycles, even though it has no problem determining their velocities and location (range and angle). This classification is important to identify that something real is present, since radar sensor systems can be affected by ghost detections which may occur due to multiple reflections [41].
Also object separation is more challenging for radar sensor systems, which ranges from 1-3 degrees in current long range systems depending on RCS of the to be separated objects [43][44][45][46]. Figure 12 shows how far objects need to be apart as a function of distance.
Furthermore, a radar has more difficulties detecting stationary objects, since they will blend in more in the background, essentially losing the velocity component in the radar image which might cause the object to be filtered out by the radars internal processing. Also objects with a low RCS can be difficult to detect since they will not reflect enough radio waves.
Low RCS can be improved by adding a retro reflector, like a corner reflector (Figure 11), onto relevant objects. These reflectors, by using three 90 degree separated planes, will send the transmitted waves back to the sensor system. This will work quite consistently up until an angle of about 40 degrees [42][43]. Such retro reflector will make the desired object much more visible for the radar sensor system. It does however not help a lot for classification since it has a simple reflection. Note that this addition of reflectors needs to be learned/programmed by the algorithms in the radar

sensor systems and that adding such reflectors will alter the current reflection on the object and thus the classifier with the risk of not being able to be classified anymore. Furthermore, adding highly reflective corner reflectors to objects can have the effect that nearby lower reflective objects cannot be separated anymore.

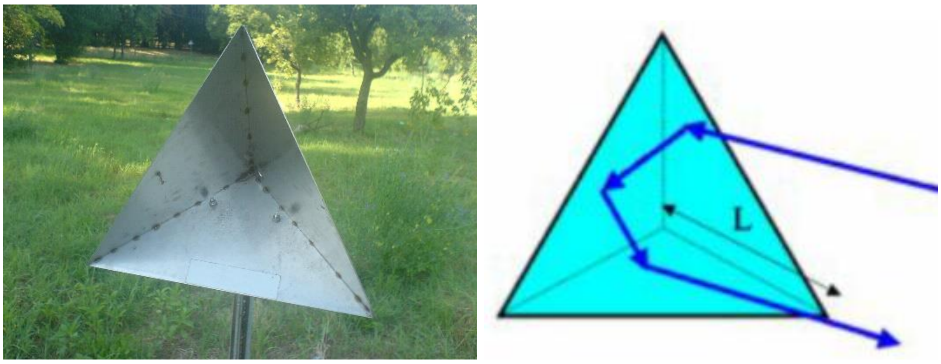

Figure 11 radar corner reflector and basic working principle.

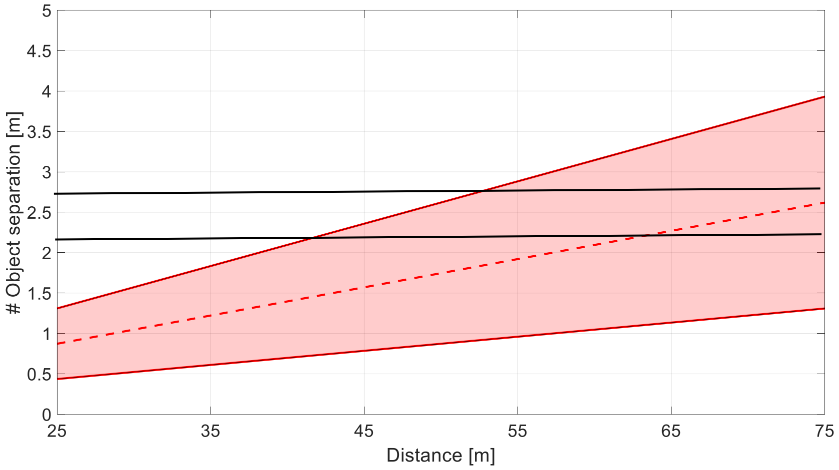

Figure 12 Minimum object separation as a function of distance. The plot shows a range of the separation from 1 (bottom) to 3 degrees (top). The dashed line represents the average separation of 2 degrees. The black lines represent a traffic arrow trailer (top) and EVT target (bottom) width.

3.3.3 *Lidar sensor system*

LiDAR stands for **li**ght **d**etection **a**nd **r**anging, adopting its name in the same way as radar. Despite its underlying mechanism being similar to radar, lidar sensor systems utilize laser lights instead of radio waves. Invisible laser lights are transmitted, reflected by objects and received at the sensor system again. Using an accurate clock, the computer calculates the distance. Lidar sensor systems are only quite recently present in the automotive domain and are not yet applied commercially on trucks, and therefore, lidar may not be applicable for this project. However due to their increasing popularity, they are worth to mention here shortly.

There are generally two types of lidar sensor systems: mechanical and solid state. The mechanical version is usually be found on the roof of vehicles scanning the environment in 360 degrees and are mostly used for research and innovation in the

domain of autonomous driving. The solid state version is placed on the front of the vehicle in a similar fashion as a radar sensor system.
Thanks to the small wave lengths of the laser light, lidar systems can achieve high resolutions at larger ranges with a high accuracy. Hence it is capable of measuring thousands of points at any moment in time, allowing it to model up a very precise 3D depiction of the surrounding environment. Here the ‘images’ are based on horizontal (azimuth), vertical (elevation) and range (hence 3D). This precise 3D representation makes it also possible to clearly detect dimensions of the object and its classification. Direct velocity measuring is also possible, however not as good as with a radar sensor system, due to the high frequencies which make doppler shifts more difficult to measure accurately. Note that camera sensor systems have a higher resolution, but do not directly get the range (and velocity) information. The aforementioned algorithms are again used to identify and classify objects. Lidar sensor systems are mostly unaffected by weather conditions and can be used in low (night) and high (glare) lighting conditions, just like radar systems. Also lidar sensor systems are able to distinguish some colour information and can also be trained to detect and classify lane information. Currently the main disadvantage of lidar sensor systems are the high costs. per unit and the high demands regarding computational power. Furthermore, the sensor is also the most affected by outside disturbances like temperature and interference with other systems.

3.3.4 Fusion

As mentioned before, all three sensor systems have their own weaknesses and strengths (summarized in Table 5 (based on literature and TNO expertise) and will achieve the best results when they are combined. This does increase the computational effort and will lead to longer delays. Early fusion systems merely checked if the object was detected by all sensor systems present before activating the AEB. Nowadays the fusion algorithm functions more in a way of world modelling: i.e. using all the relevant information from all sensor systems to recreate the environment around them as accurately as possible. Different kind of sensor systems are used each with their respective advantages. All the data of all sensors is ‘fused’ into a new dataset, which is the input for the decision and control algorithm of the AEBS.

Table 5 Qualities of the different sensor systems scored from 1 (worst) to 5 (best).

	Camera	Radar	Lidar
Object classification	5	2	3
Distance measurement	3	5	5
Velocity measurement	2	5	4
Low lighting conditions	1	5	5
Bad weather conditions	1	5	4
Range	2	5	4
Resolution	5	1	3
Costs	5	5	1

4 Feasibility aspects

This chapter discusses various feasibility aspects of the four proposed solution directions discussed in section 2.6: AEB marker on roadworks objects (1), stand-alone marker (2), include roadworks objects in development and testing (3) and using communication technology (4). Each section of this chapter focusses on one of five feasibility aspects:

- technical feasibility (section 4.1), e.g. technical possibilities / limitations of the solution directions
- operational feasibility (section 4.2), considering aspects on feasibility of implementation in operations, usage, maintenance, etc.
- legal feasibility (section 4.3), concerning legal aspects, legislation, standards, etc.
- economic feasibility (section 4.4), mainly involving costs of development, implementation, operation, etc.
- scheduling feasibility (section 4.5), e.g. timing of development and implementation of the solution direction

It should be noted that these feasibility aspects are connected to each other (choices to enhance one feasibility aspect might influence another feasibility aspect as well). Hence, where applicable, references to other feasibility aspect will be made in the following sections. All topics discussed in the sections on the feasibility aspects are summarized in Table 7 in Appendix A.

A summarized result with respect to these feasibility aspects, together with the results of the risk and benefit analysis (chapter 5), is presented in chapter 6.

4.1 Technical feasibility

This section discusses the technical feasibility of the four proposed solution directions introduced in section 2.6.

The first two solution directions both require an AEB marker (either on the roadworks objects or stand-alone). The most relevant requirement is that the AEB marker should be able to be detected at relevant distances by the most common sensor systems used currently and in the near future, i.e., camera, radar and lidar systems.

AEB marker placed on the roadworks object

For the solution direction where the marker will be placed on the roadworks object the marker can either be used to support the detection of the object by making it more visible for the different sensor systems or that it will be detected on its own. For the stand-alone marker solution direction only the latter option is possible.

Placing a marker on the roadworks objects to make it more easily detected has several aspects to be considered. The marker should be relatively small in terms of the output generated in order to not hide the key features for detection of the roadworks object itself. For camera systems this could be a high contrast marker (like a QR code) to be placed on the roadworks object. Estimating the size of this marker is difficult, since it will be a feature for the entire detection. The best estimate is that it should be a similar size as other key features camera systems use to detect objects, which include number plates, lighting units and wheels.

For radar systems a corner reflector could be used as explained in section 3.3.2. This reflector will send the transmitted radio waves by the radar directly back to the receiver, where it will be picked up as a point like image. This will greatly increase the roadworks object's radar reflectivity and therefore its potential visibility.

A similar reflector, based on light instead of radio waves, can be used for lidar systems. It should be noted that current and future AEB systems should be programmed in such a way that the increased potential visibility will lead to a detection. Older systems are known to react more when an objects radar reflectivity increases, however newer systems have the tendency to be more confident if the reflected radar profile represents an actual object, as it has learned to prevent false positives. Therefore these systems might be able to detect the roadworks object with the AEB marker more easily, however they need to know that roadworks objects will 'look' different with this marker attached. Otherwise the system may discard the detection since it will not be sure that it is an actual object.

Stand-alone AEB marker

The technical requirements become different when the AEB marker needs to be able to be detected on its own. In the solution direction where the marker is placed on the roadworks objects, the roadworks object's own features for detecting are thus not needed anymore. The roadworks object could even have a negative influence on the detectability of the marker if it can still be detected by the vehicle sensor systems. Section 3.3.1 details what a camera sensor system needs in terms of dimension for an object to be detected and correctly identified/classified. It shows that in order to come to a complete stop before the object the AEB system needs an initial detection between 35 and 55 meters with average estimated AEB characteristic values (Table 1). It was estimated that camera only current high end systems (FullHd - 2Mpx cameras) need the marker to be between 0.7 and 1.9m wide at a 45m longitudinal distance depending on the field of view of the camera. Future systems with more resolution (4K – 4Mpx) can decrease this size to 0.5 – 1.1m. It should be noted that this is under perfect conditions (lighting, contrast and focus being the main conditions). Furthermore, there are AEB systems currently on the road which have lower resolutions where the marker size should be even larger. Summarized it can be said that for a camera sensor system, to enable a truck to come to a full stop before it, a stand-alone AEB marker should have a similar size as a passenger vehicle for current systems and perhaps half that size for future systems. When the marker is allowed to be impacted (possible in the stand-alone solution direction), the detection distance (and therefore possibly the marker size (Figure 9)) decreases. This makes this solution direction technically more feasible.

For radar systems the visibility of an AEB marker should not be an issue by adding corner reflectors, however detection and classification is not trivial. Actual objects on the road have a typical characteristic signature for a radar system from all the parts that reflect the radio waves in their own way. Something similar can be done with the AEB marker, using the corner reflectors and perhaps other distinctive parts. It is difficult to estimate what this should look like exactly, however, it is not expected to be a show stopper and should result in a reasonably sized AEB maker. Note that radar systems themselves are not the best systems to classify (static) objects and are usually helped by camera systems for this in the fusion algorithm. A point of attention is that the AEB marker should not be too reflective for radar systems where close by other objects are not distinctive anymore.

Lidar systems have a larger angular resolution than radar systems and have an extra dimension compared to camera systems (range). Therefore the technical feasibility is not limited by this sensor system compared to the other two sensor systems as long as the AEB marker is made of light reflective material.

The aforementioned observations for the AEB marker are based on a passive solution. Active solutions are also possible, however require additional processing by the AEB system, which is not available in the current fleet. Furthermore, these technologies will require more investigation before a reliable and stable implementation is possible. Therefore passive markers are considered more technically feasible, however some active implementations are worth mentioning. For camera and, to a lesser degree, lidar systems, one can imagine sending light signals to transfer information about the object. For radar systems an active radar transmitter can be implemented, spoofing an (already known) object for the sensor system.

Include roadworks objects in AEBS development and testing
The solution direction to include roadworks objects into the AEB development should be technically feasible, since no new technology is needed. It does require additional training and/or programming of the algorithms in order to detect and classify such objects. The roadworks objects are not substantially different than other objects which should already be present in the training data of current systems and are therefore not expected to pose any substantial additional challenges. It should be noted that the ability to include these new objects in the AEB system could be very different between the suppliers of such sensor systems.

Use communication technology
The final solution direction is communication, in this case communication from the roadworks objects to the AEB system in the truck. This technology can send information that is accurate with a low chance of misinterpretation. It does mean that additional hardware needs to be integrated into the truck with AEB system in order to receive this information. Furthermore it can only send information about itself, which means that additional accurate sensors need to be available in the AEB system in the truck e.g. accurate GPS sensors to compute the relative distance. From a technological approach this solution is feasible, since the technology is available. Automotive communication standards are already developed or are in a mature state to be used in implementations like Green Light Optimised Speed Advisory (GLOSA, [48]) or Intelligent Speed Adaptation (ISA) [49]. For actual use on the road, this technology needs to undergo another maturity step which includes failure analysis, reliability, cybersecurity (to prevent misuse / hacking, also see section 4.3) and message content.

4.2 Operational feasibility

Operation feasibility considers aspects from the implementation of the solution direction, as well as the usage and maintenance of the solution direction. From an operational perspective, there are several aspects which should be considered when evaluating the feasibility of any of the solution directions.
For the first two solution directions (standardised AEB marker on the object, or as a stand-alone marker) the size and weight of the marker will have an effect on various operational aspects.

AEB marker placed on the roadworks object
First, in case the AEB marker should be placed on roadworks objects, the size and weight will determine on which objects it can be placed. Large markers are mainly suited to be positioned on larger objects, such as collision absorbers or traffic arrow trailers. To be mountable on a WIS vehicle (pick-up truck as shown in Figure 2) the

markers size should probably be somewhat smaller, whereas to be mountable on even smaller objects, like roadworks personnel or equipment, its size should be smaller still. In case a standardised marker is to be used at barriers near railroad crossings or entrances to bridges or tunnels (section 2.4), an even smaller and lighter marker is required, to maintain proper functionality of the barrier system.

If a certain size is required because of detectability, an alternative solution could be to design it in such a way that it can be folded / minimized in size such that it can be safely transported. This will result in a more complex design and hence will affect the costs of a marker (also see Economic feasibility, section 6.1.5) and more prone to improper installation or be forgotten to be installed at roadworks. In all cases it is important that the marker should not negatively influence the visibility of the object it is attached to and the recognizability of the situation for human drivers.

Stand-alone AEB marker

For a stand-alone AEB marker, the size and weight will have an effect on the placement of the marker at roadworks. A heavy, large size marker will take more effort, time, personnel and/or equipment to position it in front of roadworks. A protocol is likely required on how to safely place such a stand-alone marker in safe manner. Furthermore, in case of a stand-alone marker, it should be investigated how to best deal with moving roadworks and moving the marker along.

Though smaller sizes and light weight are beneficial for transportability and ease of handling, it does make the stand-alone marker more vulnerable to displacement, e.g. because of wind, harsh weather conditions, or traffic passing by, and consequently misplacement / misalignment of the marker. Especially when the detectability of the marker is dependent on accurate positioning and orientation this aspect becomes more relevant.

With respect to a stand-alone marker a choice should be made between whether the marker should be an object where any vehicle (without AEB) will (safely) crash into (in case it is missed by the driver), whether it would be something where any vehicle is able to drive over (like rumple strips), or anything in between. This choice will affect design choices for the stand-alone marker with respect to size, materials used and costs, as well as the positioning of such marker (is it intended to stop any vehicle or serve as an additional warning to the driver).

To gain the most effect on safety from a standardised AEB marker (either on roadworks objects or stand-alone) the marker should be made available at all roadworks areas. This will require effort in introducing such marker to roadworks authorities and personnel (training, instructions on use / placement) as well as effort and budget for maintenance. The more complex the marker, the more effort and budget is likely required for these introduction and maintenance tasks. Especially when active markers are considered, introduction and maintenance can become more elaborate (e.g. installing and checking of power supply / batteries).

In case a marker can be designed such that it can be easily mounted on various objects (see discussion above with respect to size and weight) its use might be extended towards other / new situation in which AEB systems encounter difficulties with detecting the relevant object.

Include roadworks objects in AEBS development and testing

The solution direction to include roadworks objects into the AEB development does not impact the current roadworks fleet, hence additional effort for introduction and maintenance as mentioned above are not applicable. Additional instruction on how to position a roadworks object for best recognizability might be desired for this

solution direction. It should be noted that including these roadworks object in the new AEB systems will not affect the current systems.
The larger the variety of objects that should be included, the more effort it will take to develop the AEB for it. To decrease this development time, it might be beneficial to standardise (parts of) the roadworks objects, or assure that it has standardised features (e.g. standardised rear lights). This latter option (introducing standardised features) is neighbouring the option as described in section 4.1 where a marker is placed on the roadworks object to make it more easily detected. If standardisation is chosen in this solution direction, these standardised roadworks objects or standardised features should be implemented in operations. Additional effort might be required in training of personnel (e.g. instructions of use, correct placement, etc.). It is expected this effort will be higher for higher levels of standardisation.

Use communication technology
Introducing communication between roadworks objects and trucks requires adding communication devices to both the roadworks objects and trucks. Like with the AEB marker (on roadworks object or stand-alone) such device will require operation and maintenance. Compared to the AEB marker the effort required for introduction of such systems (training / instructions on use) is expected to be less, since, once communication technology, protocols and messages sets are established, the amount of work to use or set-up the communication by roadworks personnel is limited.
To obtain a safety benefit via this solution direction, communication should be possible for a large portion of the trucks on the road. It is not likely communication will be developed solely for this purpose (avoiding roadworks objects), however this solution direction becomes more feasible once communication with road side equipment is being implemented for other features (such as GLOSA and ISA)_and becomes more common.

4.3 Legal feasibility

This section discusses legal feasibility aspects of the four solution directions introduced in section 2.6.

For all solution directions the effect on safety will be larger for higher penetration rates of the application. Also for all solution directions (more or less) effort is required from the industry to develop the AEB system. Hence, any solution direction would benefit from creating incentives for the industry to develop their systems towards such a direction. This can be done either by enforcing certain AEB functionality by law or legislation, or encourage these developments by rewarding improved AEB functionalities (e.g. through consumer safety ratings, such as Euro NCAP, or reduced insurance fees).

AEB marker placed on the roadworks object or stand-alone AEB marker
With respect to the standardised AEB marker (on roadworks objects or stand-alone), its design, properties relevant for the sensor systems (e.g. size, shape, colour, radar reflection, lidar reflection), as well as the desired response of the AEB system when detecting this marker should be specified in legislation.
For the marker mounted on roadworks objects, additionally it should be specified where and in what orientation the marker should be positioned. Similarly, for the stand-alone marker, the position within the lane and its orientation should be

specified. Aforementioned specifications should be agreed upon among different stakeholders (e.g. industry, governments, also see process in section 4.5).
To have the most impact on safety, it should also be formalized in legislations that the markers are actually implemented on the roadworks objects or at roadworks areas (for the stand-alone marker). When either one of these solution directions is chosen, it can be expected that the sensor systems will become dependent on the presence of these markers for accurate detection / classification of roadworks in general. Absence of the marker at roadworks might induce the AEB to ignore the objects.
The level of consensus among different stakeholders will have a substantial effect on the legal feasibility. In case consensus is present with respect to the problem and the solution direction to follow, coming to an agreement on legislation can be a smooth process too. However, in case no consensus is present (yet) on the problem to solve or the approach to best solve this problem, coming to an agreement on what is included in legislation or non-mandatory regulations like consumer safety ratings is a (far) more time consuming process, if feasible at all.

Include roadworks objects in AEBS development and testing
For the third solution direction, including roadworks objects into the AEB system, having the AEB system respond to these objects should be a requirement in legislation, or other regulations like consumer safety ratings, to create incentive at industry. In case standardisation of (features of) roadworks objects is required this should be included in legislation as well. Since, compared to the first two solution directions, no artificial objects are to be developed in this solution direction, it is expected that legal feasibility can be higher for this solution direction compared to legal feasibility of solution direction 1 and 2.

Use communication technology
For the fourth solution direction, communication, communication protocols and performance requirements should be established and implemented in legislation. Cybersecurity is a very relevant topic for this solution direction, e.g. securing communication to avoid misuse of the system, avoid leaking or theft of personal / vehicle data, etc. (see for example UN regulation No.155 [47]). Another aspect that should be considered when using communication for AEB activation is the fact that two separate systems (with different “owners”) are responsible for the proper activation. The AEB system must be activated on information not collected by the system itself, but send by the communication device at the roadworks areas. The AEB system will have to trust on the information send by another party being correct. In case of a malfunction or accident finding which party (parties) is (are) to blame might prove difficult.
Although development with respect to communication in automotive solutions is ongoing, it is still a complex, elaborate problem for which many issues (cybersecurity, shared responsibility) have to be resolved. Hence, coming to a consensus required to establish legislation is expected to be complicated at this point in time.

4.4 Economic feasibility

This section focuses on the economic implications of the solution directions. The potential costs savings of the solution directions are not taken into account, because this depends mostly on the potential added AEB performance of the solution directions. This will lead to less collisions or reduced crash severity, which will thus lead to fewer loss of equipment and expenses due to injured drivers. Instead the focus will be on extra costs each solution direction will introduce, which here mainly refers to costs of implementation and maintenance.

In the first and second solution direction, an AEB marker, either on roadworks objects or stand-alone, should be developed. The economic feasibility of either solution direction will be highly dependent on the actual physical implementation of the AEB marker. Section 3.3 shows the complexity of all the different sensor systems and which qualities the marker should have, thus indicating that the introduction of an AEB marker will at least have a noticeable economic effect.

AEB marker placed on the roadworks object
For the AEB marker on roadworks objects, costs can increase rapidly since they need to be added to each object in the entire roadworks fleet. An expensive marker will easily multiply to large added costs.

Stand-alone AEB marker
The second solution direction, the stand-alone AEB marker does not need to be added to each roadworks object, however it does need to be part of all roadworks areas. This probably means that fewer AEB markers are needed, however they do require to be setup properly each time. This may increase operational costs, but this is not expected to be substantial. Furthermore, for this solution direction it can be chosen to place them further away from the roadworks objects and make them impactable. This will increase the detectability and technical feasibility (section 3.3), however will lead to increase costs since the AEB marker needs to be able to withstand impacts and will likely need to be repaired and/or replaced more often. Moreover, both markers should be standardised and produced by companies that are willing to comply and maybe even continuously improve the marker. Development costs by the OEMs and AEB system suppliers to be able to detect and react to the AEB markers should also be considered, however this additional cost is expected to be in the same order of magnitude for both solution directions. As mentioned in section 3.3, active markers could be a possibility from a technological view, however this will decrease the economic feasibility due to the large added costs of such a marker compared to a passive version, mostly due to development, costs per marker and keeping it operational.

Include roadworks objects in AEBS development and testing
The third solution direction, learning new objects, should in general not lead to substantial additional costs. It is expected to be similar for the AEB system manufactures to ‘learn’ the AEB marker or additional roadworks objects. Perhaps the variety of all the difference roadworks objects will increase the costs, however this is not expected to be substantially different than putting a AEB marker on all roadworks objects with the goal of increasing the probability of detection. If the roadworks objects need standardisation, costs are expected to increase substantially. Depending on the level of standardisation (whole object to certain features), this will require more effort to apply and will decrease its economic feasibility.

Use communication technology
In the fourth solution direction, communication equipment should be added to both all roadworks objects/areas as well as the AEB in trucks, which will increase costs substantially. It is not expected that this can be justified by solving the roadworks

accidents alone, but needs a larger incentive. When the use of communication will become a standard in different functions on board trucks in the future, this solution direction will become more economically feasible.

4.5 Scheduling feasibility

To realize any of the solution directions consecutive steps should be followed to decide on and implement the solution. Since scheduling might be difficult to quantify, the development of the cyclist-AEB test system within the CATS project [49] will be used as an illustrative example in this section.

The first step is to reach consensus by relevant stakeholders (e.g. industry and government) on the approach / solution direction to follow. These steps should be performed for all four solution directions discussed in this study. The more clear and acknowledged the problem to solve, the easier it will be to come to an approach which is supported by all parties. Information on the problem at hand will help defining an appropriate solution (e.g., is the object not detected, not recognized, detected too late, obscured by surrounding signals like bright lights or high radar reflections, or is the confidence of the detection not high enough to be classified as relevant object). For the CATS project, there was a clear incentive for industry to develop cyclist-AEB, since Euro NCAP was going to include cyclist-AEB in the safety assessment from 2018 (which in itself of course was based on a safety issue of accidents between vehicles and cyclists). Also, the approach was clear at the start of the project and supported by all industry partners: a cyclist-AEB dummy (representing a real cyclist) and test protocol (based on relevant car-cyclist accident scenarios) was to be developed.

The second step involves the design and development any kind of new object or adaptation to existing objects, depending on the solution direction which is followed. This step is relevant for all solution directions in this study, except from solution direction 3 in which no (feature) standardisation of roadworks objects is included. In the CATS project a representative cyclist dummy was developed (see Figure 13). The existing pedestrian dummy was used as a basis for the cyclist. Characteristics for relevant sensor systems were taken into account, like radar reflectivity, colour, shape/size and bicyclist posture, micro-doppler of rotating wheels, as well as practical aspects for testing like crashworthiness and stability.

Figure 13 4a Cyclist dummy developed within the CATS project as presented at the FISITA in 2016

As a third step, a test protocol should be developed to verify the implementation of the AEB. A test protocol should be able to verify that the developed feature (AEB in this case) is implemented as desired (i.e. the AEB response on the target meets a set of predefined requirements). The test protocol describes the test set-up, targets used and expected response of the AEB. Development of a test protocol usually is a balance between covering the majority of relevant scenarios versus having a test protocol which is practically feasible (time, costs, test setup possibilities). This step is relevant for all solution directions evaluated in this study. In the CATS project the test scenarios were based on accident analysis (EU), literature study and real life measurements. Relevant car-cyclist accident scenarios were investigated as well as scenario parameter variations such as vehicle and cyclist velocity, presence of view blocking obstructions and collision point on the vehicle. Verification workshops (prototype testing) were organized to verify the (feasibility of the) test protocol.

The fourth step is to establish the new object (if applicable) and test protocol into legislation (e.g. UN regulation, or national legislation), normative (e.g. ISO norm) or other forms of non-mandatory regulations like consumer safety ratings or reduced insurance fee.

The fifth and final step is the implementation of the application (solution direction), involving introduction of the new system (and (test) protocols), implementation of AEB improvements and training / instruction if needed. In this step, a possible update of current AEB systems (of vehicles already on the road) could be included.

The CATS project mainly covered step 2 and 3 in this process and it provided input to step 4. Consensus on the approach (step 1) was largely established before the project start. Main part of the CATS project was the design and development of the test target (step 2) and test protocol (step 3) for cyclist-AEB systems. To complete these steps, the CATS project covered a bit over two years. Subsequently Euro NCAP used these results for their safety rating test protocols and rating (step 4 and 5), which took approximately another two years.

AEB marker placed on the roadworks object or stand-alone AEB marker

The first two solution directions, AEB marker on roadworks objects or stand-alone, will have to proceed through all four steps mentioned above. As mentioned before, with a clearly defined problem it will be easier to get consensus on the best way forward from industry and government (step 1). For these two solution directions even more background on the problem might be requested by the industry, since something artificial will be added to the environment (based on feedback during the expert workshop, section 2.5). In the second step an AEB marker should be designed and developed. This includes detailed specification of the marker properties (shape, size, colour, reflective properties for radar and lidar, etc.) as well as specifications on how the marker should be mounted on the roadworks object, or positioned before the roadworks (protocol). In the third step a test protocol is developed to verify the performance of AEB system toward the AEB marker. In the fourth step, the marker design and test protocol are established in legislation (e.g. supplementary to UN/ECE R131 [9]). Step 5 is the dissemination of the standardised marker. This includes introduction of the marker to the roadworks fleet, as well as instruction/training of the roadworks personnel. A more complex marker will require somewhat more effort in this step, however this is not expected to influence scheduling feasibility significantly.

Include roadworks objects in AEBS development and testing

For the third solution direction where roadworks objects are added to the AEB systems, step 2 from the above process is not required (no new objects have to be designed). In case (features of) roadworks objects are standardised, step 2 *is* required to discuss the amount of standardisation and what this should look like.

A test protocol to verify the performance of AEB system towards these roadworks objects (step 3) *is* required. Step 4 mainly involves inclusion in legislation (comparable timing for this solution direction compared the first two (marker)). Dissemination (step 5) is limited (including new AEB version in trucks) since no new objects / equipment are introduced. This step will become more elaborate in case adaptations / replacement of roadworks objects is required in case of (feature) standardisation.

Use communication technology

The fourth solution direction, communication, will need to proceed through all four steps described above. Since it is not expected communication will be developed for this purpose only, scheduling of this solution direction will very much depend on other developments which use communication. Hence, the choice for this solution direction will likely only be made in combination with other developments (step 1).

Step 2 will in this case focus on development of a communication protocol (which message should be sent, what should they contain, via which protocol, at what timing, etc.). It should furthermore be discussed what should be the desired response of the AEB system.

Scheduling of step 3 (development of test protocol) is expected to be comparable to the other solution directions. Inclusion in legislation (step 4) is expected to be more elaborate in case of communication, because of the complexity of the legal aspects (cybersecurity, shared responsibility, see section 4.3). Step 5, implementation of the application, is expected to have comparable scheduling as the two marker solution directions.

5 Effect analysis

In this chapter the potential additional effects are discussed of the 4 solution directions introduced in section 2.6: AEB marker on roadworks objects (1), stand-alone AEB marker (2), include objects in AEB development and assessment (3) and making use of I2V communication (4). First additional potential risks are elaborated on, followed by the additional potential benefits. A summary of the effect analysis is added in Table 7 in Appendix A.

5.1 Potential additional risk

AEB marker placed on the roadworks object or stand-alone AEB marker
In the first and second solution direction, an AEB marker, either on roadworks objects or stand-alone, is introduced. Additional potential risks for both these solution direction are discussed together.
Firstly it should be noted that developing an AEB marker could lead to less incentive for car manufactures and their suppliers to include the actual objects in the development process. This could slow down progress towards the detection of the plethora of other relevant (new) objects. Another potential additional risk of introducing an AEB marker, is the increase of false positives. For example, trucks driving in other lanes could recognize and detect the AEB marker in such a way that they will falsely act on it. Another potential additional risk for both AEB marker solutions is that they could affect the recognizability of the situation for human drivers. Especially the features of the AEB markers needed for camera (-only) systems will change the appearance of the situation for human drivers. Furthermore, if AEB systems need to be able to detect an AEB marker on its own and come to a complete stop before it, it needs to be quite large as section 3.3 showed. In solution direction 1, the marker could be smaller if it is used as an additional feature to improve detection of the object by the sensor systems. Still the human recognizability of the roadworks object on which the marker is placed, should be part of the development process. In solution direction 2, the marker could be made impactable and placed far before the roadworks area, meaning that the AEB system could brake later, thus detect the AEB marker later, thus allowing it to be smaller. However, since it is placed stand-alone on the road, the human drivers should definitely be able to recognize it as well. In this case the human behaviour towards the stand-alone AEB marker should be included in the development process, even more so than in solution direction 1, where the AEB marker is on the roadworks objects.
Misuse, e.g. using it by unauthorized people in undesired situations, is an additional potential risk for both AEB marker solution directions, however in a slightly different way. In solution direction 1, this is dependent on how easily the AEB marker could be detached from the object. This is obviously dependent on the actual implementation. If it will be part of the roadworks object permanently, this is not an issue, however if a marker will be used to be attached on any roadworks object, misuse is more probable. The additional potential risk of misuse is also dependent on the AEB marker strategy in solution direction 1. When the AEB marker is used as an added feature for detection, misuse will be less likely compared to the strategy where the AEB system needs to detect and act on the AEB marker alone. In solution direction 2, the probability of misuse is higher since it is a stand-alone AEB marker to which the AEB system needs to act to, depending on the actual implementation and protocols used during use

Currently available AEB systems could also present an additional potential risk for both AEB marker solution directions, since it is usually not possible to retrofit/update them with new software which includes the roadworks objects or AEB markers. By placing an AEB marker on the roadworks objects, AEB systems currently on the road may fail to detect the roadworks object whereas they would have without the AEB marker, increasing the number of collisions in the short term. The stand-alone marker will most likely not be detected by current systems, unless a clear requirement is set in the development phase to ensure current systems act on it.

Another identified potential additional risk for solution direction 2, is that it needs to be placed on and collected from the road. Even though the roadworks personnel already has to place cones or other equipment most of the time, this will slightly increase the risk of an accident involving people. A protocol for placement of the stand-alone AEB marker is highly advised.

Finally it should be noted that the absence of either of the AEB markers at roadworks objects/areas could induce the AEB system to ignore the objects when AEB markers become commonly used and included in AEB systems.

Include roadworks objects in AEBS development and testing

Since, nothing noteworthy will change in solution direction 3, where the roadworks objects are included as to be detected objects into the sensor systems, there does not seem to be any additional potential risks. However, from experience, some possible negatives effects could be mentioned, which will not be valid for all the sensor systems or AEB implementations available. This should be discussed with the suppliers of the these sensor systems. Firstly there is the additional risk that the AEB system will show a lower performance with the already included objects, since its database of objects to classify will increase substantially, especially when no standardisation of the roadworks objects is performed. Furthermore, the additional risk exists that more false positives of the AEB are triggered due to the amount of new objects. This could lead to drivers switching of the entire system. This effect is, again, very dependent on the sensor system and AEB implementation and its ability to learn these new objects.

Use communication technology

In solution direction 4, communication from the roadworks objects/areas, the main additional potential risk is misuse. Since these systems are connected to the rest of the world, the possibility of entering the communication system is ever present, with possible severe consequences. Cybersecurity is therefore extremely important to protect these systems. Since communication will most likely not be added for AEB applications only, this topic of cybersecurity will be valid for the entire communication system.

5.2 Potential added benefit

Potential added benefit is more complex to describe, since it is in this stage not possible to accurately estimate the number of accidents prevented, let alone the number of serious injuries and fatalities. Therefore a relative and qualitative argument will be given, meaning that the solution directions are compared among each other with arguments about different aspects without actually quantifying it. Furthermore, the mentioned feasibility issues and potential added risk are taken into consideration. In the following part the 4 different solution directions will be discussed together.

The solution direction with the highest added safety potential, is expected to be adding communication between roadworks objects and the truck. With this implementation, assuming it is implemented well, there should not be a need for an emergency braking action to avoid collision with the roadworks as the driver/truck is able to anticipate well ahead of time on the location of the roadworks. In the most basic implementation the driver will be alerted and if no action is taken the truck should come to a stop in a comfortable manner to avoid colliding into the roadworks objects/areas.

Solution direction 1 and 3 are considered equal in terms of added benefit. If both the AEB marker on the roadworks object or the addition on road work objects in the AEB development are on a current/ near future level, there should be little difference in performance. Standardisation of the road work objects is thought to have a positive effect on the added benefit, however this is not expected to be substantial. Perhaps classification could be performed faster and slightly better when the roadworks objects are standardised, however when all road work objects are taken into account in the development process, this advantage is not large. The performance increase with this solution direction and substantial added benefit can be expected, just not on a level as adding communication will be.

Solution direction 2, developing a stand-alone marker, is thought to have more added benefit compared to the 2 previous mentioned solution directions (1 and 3). The main difference is that it can be located away from the roadworks area itself and could be allowed to be impacted. Locating it away means that no influence of the roadworks object is present anymore, meaning that the stand-alone AEB marker could be optimally designed for detection and classification. Making it impactable, allows for later start of braking and later detection and classification when the truck is closer to the stand-alone AEB marker. This will increase performance substantially.

6 Discussion and conclusions

The purpose of this chapter is to summarize results, draw conclusions and discuss the approach and result of the feasibility study.
First, in section 6.1, a summary is provided on the feasibility and risk/benefit analysis for the four solution directions evaluated in this study. Next, discussion points on this feasibility study are elaborated on in section 6.2. Finally, section 6.3 summarizes the conclusions of this study.

6.1 Summary on feasibility and risk/benefit analysis

The sections in chapter 4 discuss various relevant feasibility aspects for the four solution directions. To support the possibility to draw an overall conclusion on the feasibility of the various solution directions, these aspects are summarized per solution direction even further into a feasibility rating matrix, see Table 6.
Rating in the table is done on a 5-step scale; from a low to a high rating. The feasibilities are shown using symbols (from ▼▼ to ▲▲) and the added benefit and additional risk using wording (from very low to very high).
Each row in the matrix represents one of the four solution directions evaluated in this study. As a reference solution direction, the option to “do nothing” is added. This solution direction means that no action is taken on the current situation with respect to improving AEB for roadworks. Since nothing changes the feasibilities cannot be rated (rated NA) and does not introduce any additional risks (rated **None**), however there is no added safety benefit at all (rated **None**).
The purple column contains the rating with respect to potential benefits of the solution directions (the more expected added safety benefit, the higher the rating). The orange column contains the rating with respect to additional risks introduced by the solution directions (the higher the rating, the less additional risks are introduced). It should be stressed that, to improve safety at roadworks areas, added benefit without inducing to much additional risk is an important factor to choose a certain solution direction (or at least the risk should be mitigated to an acceptable level). The blue columns contain the rating with respect to the various feasibility aspects (technical, operational, legal, economic and scheduling feasibility). The reasoning behind the rating in the matrix is discussed in the following sections.

6.1.1 Benefit

As discussed solution direction 4., adding communication, is expected to have the highest potential to add most safety benefits, rating a **Very high**. On the other hand, doing nothing (0.) will have no added benefit, rating a **None**. From the other 3 solution directions, developing a stand-alone AEB marker (2.) is thought to have the most added benefits, due to it being located away from the roadworks and possibility of being impactable. Adding an AEB marker on the road work objects (1.) or adding the roadworks objects into the AEB development (3.) are thought to have similar added benefits and somewhat lower than the stand-alone marker, however still substantial. Standardisation of the road work objects (3.) is not thought to have a large added benefit compared to when all road work objects are taken into account. Therefore solution direction 2. is awarded a **High** and solution direction 1. and 3. a **Moderate**.

Table 6 Rating with respect to feasibility, additional introduced risk and benefit:
Added benefit: Very high, High, Moderate, Low, Very low
Additional risk: Very low, Low, Moderate, High, Very high
Feasibilities: ▲▲, ▲, ▼▲, ▼, ▼▼

Feasibility aspects → Solution direction ↓	Added benefit	Technical feasibility	Operational feasibility	Legal feasibility	Economic feasibility	Scheduling feasibility	Additional risk
0. Do nothing	None	NA	NA	NA	NA	NA	None
1. AEB marker on vehicle	Moderate	▼	▲	▼▲	▲**	▼▲	Low
2. Stand-alone AEB marker	High	▼▲	▼▲	▼▲	▲**	▼▲	Moderate
3. Learn specific objects	Moderate	▲	▼▲ to ▲▲*	▼▲ to ▲*	▼▲ to ▲*	▼▲ to ▲*	Very low
4. Communication	Very high	▼	▼	▼	▼	▼▼	High

** depending on whether standardisation of roadworks vehicles (and equipment) is required;*
if yes → ▼▲, if no → ▲▲ / ▲ (and anything in between)
** costs of marker will be highly dependent on actual implementation and use

6.1.2 *Technical feasibility*

Technical development is also required for the two solution directions with the AEB marker (1. & 2.), where it is expected that it is technically more complicated to find a solution for a marker which is attached to the roadworks object (due to possible disturbance / masking of the markers signal by the object it is attached to). The stand-alone marker is therefore rated ▼▲, whereas the marker on the roadworks object is rated ▼.

Since the technique of learning new objects (for detection and classification) is already available and mature (and already used by the industry), the technical feasibility is high for the third solution directions (3.) Note: the fact that this solution direction is technically very feasible does not mean the effort required to implement it is limited. Technical feasibility for solution direction 3. is hence rated ▲.

The techniques for the fourth solution direction (4.), communication, are also already demonstrated, however not yet very mature, hence more technical development is required (rating ▼).

6.1.3 *Operational feasibility*

With respect to operational feasibility both standardised marker solution directions (1. & 2.) are rated average or above. For both solution directions the standardised marker should be introduced to (all) roadworks objects / areas, which will require some effort in implementation, use and maintenance. In case of a stand-alone marker (2.), operational use is expected to be a bit more complicated compared to the marker on a roadworks object (1.), since instructions / a protocol should be designed to safely position it (proper positioning might be relevant for adequate functioning of the marker, see section 4.2). For this reason the stand-alone marker (2.) is rated ▼▲, whereas the marker on the object (1.) is rated ▲.

The operational feasibility of the third solution direction (3.) will depend on the amount of standardisation required in roadworks objects. In case no standardisation is requested, operational feasibility is very high since basically nothing has to change in usage of the trucks equipped with AEB or the roadworks objects. Again, note that this does not mean no development is required in the AEB system, however, in an operational view no additional effort is required. Alternatively, to support detectability and classification of the roadworks objects for AEB, standardisation of roadworks objects does require additional operational effort, e.g. on replacements of objects and possibly additional training for the roadworks personnel. The amount of effort will depend on the amount of standardisation required (large design changes or only small adaptations). For this reason the operational feasibility of solution direction 3. is rated ▲▲ for operational feasibility in case no standardisation of roadworks objects is required, down to ▼▲ in case major adaptations are required for the roadworks fleet.

To introduce communication (4.) a significant amount of equipment (both in truck and at road side / roadworks), operational protocols and training is required, hence this solution direction is rated ▼ for operational feasibility.

6.1.4 Legal feasibility

For all solution directions (except from doing nothing) having the solution direction solidified in regulation or legislation is important to create incentive at the industry, either through (inter)national regulations or for example consumer tests. Solution direction 1. and 2. are both rated ▼▲ with respect to legal feasibility, since effort needs to be put in establishing regulations with respect to design of the marker, required response of the AEB system and approval or consumer tests. Solution direction 3. will require comparable effort in case standardisation of roadworks objects is required. In case no standardisation of roadworks objects is required the legal process is expected to become more easy, since no discussions on design have to be held (rated ▼▲ to ▲). Solution direction 4. is rated ▼ with respect to legal feasibility, since next to having communication protocols etc. into regulations, it also has to deal with a shared responsibility of the functioning of the system and cybersecurity in a complicated stakeholder field. It is expected that legal feasibility of this solution direction (4.) will increase once communication is further developed (and implemented) for other automotive applications.

6.1.5 Economic feasibility

From the 4 solution directions, adding communication (solution direction 4.) is expected to be the least economically feasible. This is mostly due to all the hardware and supporting infrastructure that has to be added to all AEB systems and roadworks objects. As discussed before, this will not be done for this use case only and perhaps this could be combined with other early communication use cases. For that reason solution direction 4. is rated with a ▼. The rating for the economic feasibility of solution direction 3. is dependent on if standardisation will be included in the process and to what extent. If standardisation of all roadworks objects is part of this process, this will make it economically less feasible compared to learning various roadworks objects separately. For that reason it is awarded with a rating ranging from ▼▲ to ▲. Introducing an AEB marker, either on the roadworks object (1.), or as a stand-alone version (2.) is thought to have a similar economically feasibility. On the one hand, for solution direction 1., the AEB marker has to be placed on all objects and added to the AEB development for all road work objects if increasing detection is the goal or once when it has to be detected on its own. The stand-alone AEB marker from solution direction 2., is only needed for each roadworks area instead of all road work objects, however needs some extra development for making it stand-alone and perhaps impactable (adding repair and replacements costs). Both solution direction are thought of being economically feasible and are both awarded a ▲. It should be noted that this rating for both AEB markers (1. & 2.) is highly dependent on the actual implementation and the development for the sensor suppliers and could have a reduced rating if a more complex implementation is actually introduced.

6.1.6 Scheduling feasibility

For scheduling feasibility, communication (solution direction 4.) is rated lowest (▼▼), since, as mentioned before, it is not expected this solution direction will be followed for this purpose only, and hence it will have to “wait” to join in with other developments that benefit from communication (e.g. truck platooning). Solution direction 1. and 2., as well as solution direction 3., in case standardisation of roadworks objects is required, will need to go through the process of reaching consensus on the approach and design of marker or standardised roadworks object, development of such marker or standardised roadworks object, development of test protocols, legislation and implementation (step 1 to 5 as explained in section 4.5). Since this is quite an elaborate process, scheduling feasibility is rating reasonable (▼▲). In case no standardisation is required for the roadworks objects (3.), the step to design these standards can be minimized (testing should still be included in standards), resulting in a faster process and hence higher feasibility rating of ▲.

6.1.7 Additional risk

The baseline option of doing nothing (0.) has obviously no additional risks and is therefore set on a rating of **None** (though it should be strongly noted it will also not improve anything). Although lower performance and false positives are mentioned as potential added risk for solution direction 3., this is not expected to be substantial (especially after standardisation), which will therefore also be set at **Very low**. For the AEB marker on the roadworks objects (1.) and as a stand-alone AEB marker (2.) several potential added risks are identified, i.e. increase of false positives, less incentive to further development, human recognizability, current AEB detectability, misuse and practical implementation. With an optimal development process of these markers, it is thought that the potential added risk will be limited, however not zero. Especially for the stand-alone marker the potential added risk seem to be a bit larger, mostly for misuse and practical implementation. Therefore solution direction 1., AEB marker on roadworks object, is awarded a **Low**, while solution direction 2., stand-alone AEB marker is awarded a **Moderate**. Adding communication (4.) has an additional risk of misuse since the systems are connected to the rest of the world. The potential impact of this misuse could be very high. Therefore this solution direction is rated **High**.

6.2 Discussion

The current feasibility study should be regarded as an initial feasibility study based on current expert knowledge within the project team of TNO, RWS and RDW and feedback from the expert workshop. The feasibility ratings in Table 6 are a subjective rating from the TNO experts within the project and should not be considered without the argumentation described in chapter 4, and sections 6.1.1 to 6.1.6. Since AEB is under constant development, scoring might also change over time. Since automotive systems and relevant legislation is under constant development which can be of influence on various aspects in this study (feasibility, risks, benefits), the rating supplied in this project is a reflection of the current situation, which might alter over time. Since AEB is under constant development, rating might also change over time.

6.3 Conclusions

This study is carried out by TNO on request of, and together with, RWS and RDW to investigate the feasibility of a standardised AEB marker. The purpose of such a marker would be to increase safety at roadworks by reducing the accidents of trucks crashing into roadworks. A summary of the available background information on this problem is provided and an expert workshop was organized with experts from industry, government and research institutes, to discuss (technical) implementation, usage, and design of a standardised AEB marker. Research performed so far by RWS indicated inconsistent responses of AEB system towards roadworks objects, but did not provide conclusions on where the inconsistent performance originated from. Questions and concerns raised during the expert workshop were not only related to technical feasibility, but were often regarding a higher level as to why a marker was required and whether or not such marker would be the right way forward. Therefore, it was decided in consultation with RWS and RDW to continue the feasibility study for a larger set of solution directions and from a broader feasibility perspective. Four solution directions are evaluated in this study: 1) a standardised marker to be mounted on roadworks objects, 2) a stand-alone standardised marker to be placed in front of a roadworks area, 3) include roadworks objects in the AEB system development and testing and 4) communication.

To enable discussion on ways to improve AEB response towards roadworks objects, an introduction on the operation and kinematics of AEB systems and its sensors has been provided.

For the aforementioned solution directions several feasibility aspects have been discussed, categorised in technical, operational, economic, legal, and scheduling feasibility. Furthermore a brief analysis has been performed on possible additional risks by these solution directions and their added benefit. Combining these results with respect to feasibility of the 4 solution directions, together with potential additional risks and added benefits, has resulted in a rating matrix.

- The rating matrix shows the stand-alone marker (solution direction 2.) provides a high safety potential, while showing a reasonable result with respect to feasibility. Solution direction 4., communication, has an even higher safety potential (highest among the evaluated solutions), however several feasibility aspects are low (especially scheduling feasibility) and it is not regarded as a feasible solution as long as communication is not yet (to be) implemented for other functionalities. Compared to the stand-alone marker (solution direction 2.) a more feasible solution might be solution direction 3., inclusion of roadworks in case no standardisation of these objects is requested, however safety benefits are expected to be lower for this solution.
- Another important conclusion from this study is that creating support within governmental bodies and industry for the issue at hand, as well as for the solution direction to follow, is very important in case any of the solution directions is to be successfully implemented. Having a solid basis will help to get consensus on the safety issue and the way forward. Furthermore, incentive should be created at industry to implement changes in AEB systems, by adding requirements which capture the relevant scenarios either in legislation, consumer tests safety ratings or other encouraging systems like reduced insurance fee or subsidies.

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8 Signature

Helmond, 15 February 2022

TNO

J Uittenbogaard

Bastiaan Krosse
Head of department

Jeroen Uittenbogaard
Author

Appendix A Feasibility matrix

Below table summarizes the various feasibility aspects for the four solution directions as discussed in chapter 4. The four rows contain the four solution directions, the 5 columns represent the 5 feasibility aspects. In case a specific aspect is applicable to multiple solution directions, its text is distributed over multiple rows.

Table 7 Summary of the feasibility aspects discussed in detail in chapter 4. Note: object = roadworks vehicle (and/or equipment), vehicle = truck

Feasibility aspects → **Solution direction ↓**	**Technical feasibility**		**Operational feasibility**		**Legal Feasibility**		**Economic Feasibility**	**Scheduling feasibility**	**Effect Analysis**	
1. AEBS marker on object	- Should work for various sensor types (radar, camera, fused, lidar). Dimensions (based on detectability at relevant distance), contrast (w.r.t vehicle or surrounding), radar reflectivity, lidar properties - Active systems like active radar, light signals, requires additional processing techniques - Obscuring of nearby objects (e.g. due to high radar reflectivity or bright lights) should be prevented)	- Marker to be detected on its own → Object behind marker can be of (negative) influence for detection, size should be relatively large to be detectable in time by camera system - Marker to support detection of object → small size compared to object (no obscuring)	- Might be used in new / other situations where AEB systems perceive difficulties (note: sufficient space available in case of standalone marker) - Active systems require more maintenance	- Marker size and weight will determine on which objects it can be used (alternative for large size: foldable / retractable during transport)	- Marker design, properties and desired response should be included in legislation for detection by AEBS - Level of consensus among relevant stakeholders will have a substantial effect on legal feasibility	- Application of marker on all relevant objects should be included in legislation	- Should be added to all road works vehicles → becomes increasingly more expensive for more expensive marker - Active systems are more expensive in purchase and maintenance compared to passive systems	- Steps in process: 1. consensus on approach by government(s) and industry 2. consensus on design and development of marker 3. development test protocol 4. legislation creation 5. implementation of application - Complexity of marker will influence mainly timing of step 1-3 and in lesser amount 4 and 5	- Marker should not affect recognizability of situation for human drivers - Artificial marker should not induce AEBS response in other lanes (additional false positives) - Less incentive for manufacturers to include the actual objects in performance of system (hampers development?) - Should not negatively affect current performance of AEBS (introduction false positives, confusion of systems, obtrusion/masking, failure to recognize) - Absence of AEB marker could lead to ignoring road works object (false negatives)	- Misuse mainly a risk in case marker is easily detached from object, light weight and small size
2. Standalone AEBS marker		- Size of stand-alone marker should be relatively large to be detectable in time by camera system (~size passenger car) - Size can be smaller if it is allowed to be impacted		- Marker size and weight will affect ease of positioning the marker - Safety of placing such marker at certain distance before road works should be considered - Stability of marker is important (for safety and detectability) - How to deal with moving road works?		- Application of marker at all road work areas should be included in legislation	- Marker required for all road works area’s - Impactable stand-alone marker may involve higher cost (replacement, repair) - Active systems are more expensive in purchase and maintenance compared to passive systems			- Risk during placement and collection - Inherently more vulnerable to misuse compared to marker on vehicle since it functions on its own (anywhere) - The easier the standalone marker is to move, the more vulnerable it becomes to theft (and misuse)
3. Include specific objects	- No new technology needed, but additional training / programming required - Unsure whether all complex situations / objects can be detected by future systems		- Additional instruction on how (not) to position a road works vehicle or object for best recognizability might be desired - In case (feature) standardisation is required, these should be implemented in operation (in general more standardisation → more effort)		- Since no artificial objects are to be developed, it is expected that legal feasibility can be higher for this solution direction compared to solution direction 1 and 2 - Having the AEBS respond to these objects should be a requirement in legislation to create incentive at industry		- Learning new object should not be expensive (might depend on amount of (feature) standardization of road works vehicles) - Standardization of (features of) road works involves costs	- In case road works are added to AEBS, step 2 is not required. Step 4 mainly involves inclusion in legislation - In case (features of) road works vehicles are standardized, step 2 *is* part of the process and step 5 is more elaborate	- Limited additional risks expected - Possibly more false positives due to amount of new objects - Possible lower performance of AEBS w.r.t. already included objects, since classification database will become larger	
4. Communication	- Accurate information, less chance of misinterpretation - Technology is available, but not mature enough (quality, failure, reliability and cybersecurity)		- Additional devices for communicating require (limited) additional training, maintenance		- Clear agreement on communication protocol - Trust in external information source. Who guarantees trustworthy signals? - AEB must be activated on information not collected by the system itself. Who is at fault during a failure? - Cybersecurity is a relevant topic to consider in development		- Needs a lot of equipment on both the object and the vehicles - Communication equipment possibly available in trucks in future for other applications	- Dependent on introduction other communication applications - Similar steps as above should be followed to establish communication protocol	- Misuse (Cybersecurity)	