Cooperative ITS for Safer Road Tunnels: Recommendations and Strategies
FINAL REPORT

AUTHORS: Azra Habibovic, Mahdere Amanuel, Lei Chen, Cristofer Englund
PROJECT: ITS Solutions for Safe Tunnels (initiated by Swedish Road Administration and co-financed by Trans-European Transport Network (TEN-T))
DATE: 2014-11-17

The sole responsibility of this publication lies with the author. The European Union is not responsible for any use that may be made of the information contained therein.
Abstract

The Stockholm Bypass tunnel will be one of the longest in the world. In this type of tunnel, traffic safety is a highly prioritized subject. In addition to the technology used for these purposes today (e.g., variable road signs, video cameras), new Cooperative Intelligent Transportation Systems (C-ITS) have shown potential of improving safety by allowing communication between vehicles and the tunnel infrastructure and enhance communication with other road users as well as with the traffic management centers.

As an important step in this work, the Stockholm Bypass project has been granted co-funding for research from the European Union through the Trans-European Transport Network (TEN-T). The aim of this study is to explore the role of C-ITS for safety improvements in long road tunnels such as the Stockholm Bypass tunnel, and to identify viable strategies and concepts. The focus is on the application of C-ITS in the following use cases: a) emergency management, b) standstill vehicles, and c) dangerous goods.

Based on an extensive literature review and discussions with various stakeholders, including road users, authorities, service providers and vehicle manufacturers, the following is concluded:

- It is important to start evaluating C-ITS in their operational environment on a national level (e.g., in the Lundby tunnel). However, in the long term a EU-wide solution will be necessary. To avoid fragmentation, a generic and holistic approach is needed.
- A C-ITS solution for tunnels must provide a clear commercial advantage or some other type of return, especially for vehicle manufacturers, and/or be required by authorities. Future studies should explore how voluntary data sharing can be facilitated and incorporated into such solutions.
- Accurate, reliable and personalized information is becoming more and more desirable. This includes multi-lingual, conclusive and useful information for each user.
- Positioning technologies that provide highly accurate position information are central enablers to contextualize C-ITS services in tunnels. The lack of GPS-signals is a major issue, however, positioning by means of wireless and future cellular networks is promising.
# Table of Contents

Abstract .......................................................................................................................... 2

Table of Contents ......................................................................................................... 3

List of Figures .................................................................................................................. 4

List of tables .................................................................................................................... 4

1 Introduction .................................................................................................................. 5
   1.1 Background ............................................................................................................. 5
   1.2 Aim ......................................................................................................................... 6
   1.3 Research questions .............................................................................................. 7
   1.4 Outline .................................................................................................................. 7

2 Method .......................................................................................................................... 7

3 Strategies and concepts .............................................................................................. 8
   3.1 Use case A: Emergency management ................................................................. 8
      3.1.1 Dynamic priority lane for buses ................................................................. 9
      3.1.2 Accident and evacuation support ............................................................. 12
      3.1.3 Support in normal traffic situations ......................................................... 14
      3.1.4 Up-to-date information about tunnels .................................................... 15
      3.1.5 Intelligent helmet ....................................................................................... 17
      3.1.6 Emergency evacuation support ............................................................. 18
      3.1.7 Assisted emergency evacuation ............................................................... 19
      3.1.8 Dynamic route planning and guidance ................................................. 19
   3.2 Use case B: Standstill vehicles ............................................................................ 21
      3.2.1 Access control to avoid standstill vehicles ........................................... 23
   3.3 Use case C: Dangerous goods .......................................................................... 24
      3.3.1 Dynamic priority lane for vehicles with dangerous goods ..................... 24
      3.3.2 Dynamic coordination of vehicles with dangerous goods .................... 25

4 The role of intelligent goods ..................................................................................... 26

5 The role of automated driving ................................................................................... 28

6 The role of communication technologies .................................................................. 29

7 The role of positioning technologies ..................................................................... 32
   7.1 Satellite based positioning ................................................................................. 32
   7.2 Radio signal based positioning .......................................................................... 32
   7.3 Future work ......................................................................................................... 34
      7.3.1 Cellular network based positioning methods ....................................... 34
      7.3.2 WiFi based positioning methods ............................................................ 35

8 Conclusions ............................................................................................................... 35
   8.1 Summary ............................................................................................................. 38

9 References ................................................................................................................. 39
List of Figures
Figure 1 Schematic view of the Stockholm Bypass tunnel..........................................................6
Figure 2 Schematic view of the interior in the Stockholm Bypass..............................................6
Figure 3 Illustration of the approach used to derive the concepts................................................8
Figure 5 Basic principle of a dynamic lane for buses [3].............................................................10
Figure 6 System components of the dynamic lane concept in Lisbon [3].................................11
Figure 7 Example of an intelligent helmet [6]...........................................................................17
Figure 8 Goods can be intelligent on several levels [21]..........................................................27
Figure 9 Platooning in the Grand Cooperative Driving Challenge (GCDC) [25].....................29

List of tables
Table 1 Examples of information to be provided to different road users in case of an accident.................................13
Table 2 Examples of information to be provided to road users in normal traffic situations.....15
Table 3 Examples of information about tunnels to be provided to different road users. 16
Table 4 Examples of information to be provided to different drivers for proper route selection.................................................................21
1 Introduction

1.1 Background
The study presented in this report is a part of the Trans European Transport (TEN-T) project (2011-SE-93119-S). Its goal is to study safety in the new road tunnel within Stockholm Bypass which is a new part of the European road E4 that will be located west of Stockholm (Sweden).

The tunnel (also referred to as Stockholm Bypass, see Figure 1) will consist of three lanes in each direction and there will be three exits and three entrances. There will be emergency exits (every 150 meters) and standard equipment such as road signs, emergency phones and fire-extinguisher, see Figure 2. With its length of 18 km, the Stockholm Bypass tunnel will be one of the longest in the world. The tunnel is expected to be ready for operation in 2025. It is estimated that the tunnel will be used by 140,000 vehicles per day by 2035.

Due to their characteristics, road tunnels are generally considered as complex traffic environments with high safety restrictions. Intelligent Transportation Systems (ITS) are today seen as a fundamental way to improve safety, and their role is expected to grow with the future technology developments [1]. ITS is the collective term for the application of various technologies in the context of traffic and transportation in order to make them more safe, reliable, efficient, and environmentally friendly. In 2004, the European Parliament adopted the EU directive (2004/54/EC) highlighting the minimum safety requirements for tunnels in the Trans-European Road Network. According to the European Tunnel Assessment Programme (EuroTAP) that conducts evaluation of tunnel safety with respect to the directive [2], ITS related safety countermeasures such as traffic surveillance and emergency management account for more than 50% of all points given for overall tunnel safety.

Currently, a range of solutions known as Cooperative Intelligent Transport Systems (C-ITS) that are based on various wireless communication technologies are under development. The development is forced both by the industry and by the society e.g., the European Commission. C-ITS have a great potential to improve traffic safety, increase traffic management efficiency and reduce the environmental impact of road transport by means of wireless communication between vehicles, infrastructure, and road users.
1.2 Aim

The overall aim of this study is to explore the role of C-ITS for safety improvements in long road tunnels such as the Stockholm Bypass tunnel. The study focuses on three use cases: emergency evacuation, standstill vehicles, and dangerous goods. The overall aim is divided into the following specific aims:

A. to develop concepts and strategies for design of C-ITS that together with standard equipment in the Stockholm Bypass will optimize the self-evacuation process.
B. to develop concepts and strategies for C-ITS that can be used to detect standstill vehicles and to make road users aware of these vehicles. This includes the development of strategies about how these vehicles can be handled (and information communicated) in different scenarios (e.g., in case of fire, incidents).
C. to develop concepts and strategies for C-ITS that can be used to identify that a vehicle is transporting dangerous goods and to make traffic management and other road users aware of these vehicles. This also includes the development of
strategies about how these vehicles can be handled (and information communicated) in different traffic scenarios (e.g., in the event of fire, during normal driving, in incidents).

1.3 Research questions
The research questions related to emergency evacuation (aim A) include:

- Which C-ITS is feasible for evacuation support in the Stockholm Bypass tunnel?
- Can C-ITS enable professional drivers to act as guides to other road users in case of an emergency? Do they need some complementary education/certification?
- How can C-ITS be used to support the road users that do not actively participate in the traffic (e.g., bus passengers) in case of an emergency?

The research questions related to standstill vehicles (aim B) include:

- Which information about standstill vehicles needs to be communicated to different stakeholders (e.g., traffic management, rescue teams, other road users)?
- How can C-ITS be used to detect standstill vehicles and communicate information about them to different stakeholders?
- Which requirements would this imply for different stakeholders?

The research questions related to dangerous goods (aim C) include:

- Which information about vehicles transporting dangerous goods needs to be communicated to different stakeholders (e.g., traffic management, rescue teams, other road users)?
- How can C-ITS be used to detect vehicles with dangerous goods and communicate information about them to different stakeholders?
- Which requirements would this imply for different stakeholders?

1.4 Outline
The rest of this report is organized as follows. Chapter 2 describes the method and the approach used to address the research questions. Chapter 3 presents different concepts and strategies that were identified in the study, followed by a description of the enablers for the C-ITS in road tunnels. The final chapter presents the conclusions.

2 Method
The concepts and strategies presented here are derived from the previous studies conducted within the project:

1. An in-depth literature review investigating current research and development in the area of ITS, with special focus on C-ITS for use in road tunnels. The review is exploring the three use cases and the results are available in three separate reports [3]–[5].
2. An analysis of different stakeholders’ support needs in relation to the three use cases. The needs are identified based on semi-structured workshops with:
The concepts and strategies are identified by answering the following questions: what is desirable, what is possible and what is viable (Figure 3).

![Figure 3 Illustration of the approach used to derive the concepts.](image)

### 3 Strategies and concepts

The following sections present a number of conceptual solutions that may be feasible to improve safety in the Stockholm Bypass tunnel. Also, recommendations/strategies on how to proceed with these concepts are given. The concepts are presented separately for each use case, however, it should be noted that some of them might also be relevant for other use cases.

#### 3.1 Use case A: Emergency management

Emergency management in road tunnels is an area where the use of ITS could bring great benefits [1]. By using ITS, new traffic management strategies for tunnels can be developed based on new sensor technologies, traffic control devices, and information providing methods. In 2004, the European Parliament adopted the EU directive (2004/54/EC) highlighting the minimum safety requirements for tunnels in the Trans-European Road Network. According to the European Tunnel Assessment Programme (EuroTAP) that conducts evaluation of tunnel safety with respect to the directive [2], ITS related functions such as traffic surveillance and emergency management account for more than 50% of all points.

Emergency management and decision making in emergency situations in road tunnels is in general challenging due to specific features of the tunnel environment. An important assumption for the evacuation in road tunnels is the internationally acknowledged self-
rescue or self-evacuation principle. According to this principle, it must be possible for road users to rescue themselves in dangerous situations. A fast and efficient response by the road users and relevant organizations in emergency situations is thus key for tunnel safety. For this, it is required that dangerous situations are detected in an early stage and that the information about them is quickly communicated to road users. It is also important to take into account that the information must be correct and provide all details needed to stimulate an appropriate evacuation behavior. In addition, it must be considered that different groups of road users may have different needs.

The discussions that were carried out within this project [6], show that vehicle drivers, passengers as well as other stakeholders need support in all phases of a dangerous situation, from information and warnings about dangers to support in decision-making and evacuation guidance (Figure 4). Most of all, they need solutions that will prevent dangerous situations from occurring. Also, solutions that provide feedback and confirmation are of great importance and would contribute to better trust and long-term learning.

The following sections describe C-ITS concepts that could address issues related to this use case.

3.1.1 Dynamic priority lane for buses

Motivation
The results from the workshops show that bus drivers and bus passengers are in general uncomfortable with traveling in long road tunnels. They highlighted that slow moving traffic, e.g., in case of traffic congestion, may cause panic and amplify the feeling of discomfort and insecurity. A countermeasure that ensures that a bus travel through a long tunnel takes as short time as possible and is unaffected by the other traffic would make both bus drivers and bus passengers feeling safer.

Basic principle
Dedicated bus lanes are a common measure to segregate buses from general traffic and to minimize bus delays. However, reserving one of the tunnel’s regular lanes for buses would create a bottleneck and generate excessive queues and delays for the rest of the

![Figure 4 Support and feedback is needed both in normal and safety-critical traffic situations.](image-url)
traffic. This since the other traffic cannot use one of the lanes, even when buses do not occupy the lane. Additionally, the implementation of an underutilized dedicated bus lane leaves less queue storage space for car traffic. This is likely to cause traffic queues to expand faster and longer. Further, the implementation of dedicated bus lanes may be infeasible or too expensive.

Dynamic priority lanes for buses are an alternative solution to reduce trip completion time for buses operating in long tunnels, without affecting the other traffic drastically. Such lanes become dedicated to buses only when at least one bus is present (Figure 5).

A dynamic lane consists basically of a lane that can change its status from regular lane (accessible for all vehicles) to a bus lane, for the time strictly necessary for a bus or set of buses to pass. The status of the dynamic lane is communicated to drivers using roadside message signs, information embedded in the roadway, and/or in-vehicle signage. The creation and removal of dedicated bus lanes is managed through a predefined coordination strategy that takes into account current traffic conditions and strategic information from e.g., traffic managers.

In the literature surveyed, there are two broad types of dynamic lanes for buses: Intermittent Bus Lanes (IBL) and Bus Lanes with Intermittent Priority (BLIP). Typically, in an IBL, the vehicles that are in the lane when it becomes dedicated for buses are allowed to continue travelling in the lane. In a BLIP, on the other hand, they have to change the lane. In [8] the IBL is described as follows:

*The concept of Intermittent Bus Lane (IBL) ... an innovative approach to achieve bus priority. The IBL consists of a lane in which the status of each section changes according to the presence or not of a bus ... when a bus is approaching such a section, the status of that lane is changed to BUS lane, and after the bus moves out of the section it becomes a normal lane again, open to general traffic. Therefore when bus services are not so frequent, general traffic will not suffer much, and bus priority can still be obtained.*

These principles are currently rather unexplored, especially when it comes to the application in real-world traffic. Consequently, there is no clear evidence which of them is more beneficial. Dynamic lanes in urban settings have been tested within a research project in Lisbon.
Furthermore, the system architecture varies depending on the type of the dynamic bus lane. For the BLIP system that was tested in Lisbon, four major system components can be distinguished: detection of vehicles, control of the lane, communication of the lane status, and wireless communication between these components (Figure 6). The system used inductive in-pavement sensors to determine the bus position and to measure the traffic flow in the lane of interest. The information captured by the sensors was then transmitted to the control unit determining which parts of the lane should be reserved for the buses. The lane status to the road users was communicated via variable message signs (VMS) and in-pavement lights. In addition, the system used static road signs to inform the road users that the lane may become dedicated for buses. It is unclear which type of communication technology was used.

A similar system outline was considered in other studies addressing dynamic bus lanes. However, some of them used GPS to determine the position of the buses. Also, depending on the system outline and control strategy, there may be a need for traffic coordination via a traffic control center. In addition, the information about lane status may be shown to the road users via in-vehicle interfaces.

![Figure 6 System components of the dynamic lane concept in Lisbon](image)

**Future work**

From a technology perspective, a dynamic bus lane may be feasible with the existing detection and communication technology. However, depending on the control strategy applied and the way of communicating information about the lane status to the drivers, the benefits of a dynamic lane may be affected by the technology penetration rate. For instance, if the lane status is conveyed by means of variable message signs positioned in the infrastructure, it may not be required that all vehicles are equipped with displays and wireless communication devices.

Future research should investigate which control strategies are appropriate for dynamic bus lanes in long road tunnels in general, and in Stockholm Bypass in particular. An important aspect to take into account is how these strategies would affect the rest of the traffic, and what are the implications for the technology used (i.e. what is required in terms of human-machine interface, communication devices, etc.). Also, it is important to explore the effect of these strategies for different traffic flow densities.
A first step could be to identify key stakeholders and to explore the idea in more detail with the goal to identify relevant system requirements and control strategies. In a next step, a realistic computer simulation could be carried out to estimate the potential advantages and disadvantages of the selected strategies in terms of e.g., traffic flow and traveling time. Depending on the results, the most appropriate solution(s) could be further explored in a driving simulator and/or in an existing road tunnel.

There is a pre-study project that is currently going on in Sweden with the aim to investigate applicability and constraints for dynamic bus lanes on roads in urban areas and entry links. The results from the project may be useful for the development of the concept suggested here. However, the project is not considering road tunnels in particular, and given that road tunnels are complex traffic environments from several aspects, one should be careful with generalizing the findings. The Swedish Road Administration is participating in the project, and having a similar initiative related to road tunnels would be complementary.

### 3.1.2 Accident and evacuation support

**Motivation**

Today, road users typically obtain information about accidents via radio and in some cases via variable road signs and navigation systems. However, this information is often not specific and detailed enough. A common issue is that the road users receive information too late, or that the information is not updated. Overall, they consider this information as insufficient and not personalized, and it is difficult to know if the information is relevant to them or not.

**Basic principle**

In case of an accident in a tunnel, or its vicinity, vehicle drivers as well as passengers are provided with brief information about the situation (i.e., what has happened and where), if the rescue team has arrived or if they are on the way, when the problem is expected to be solved, and how long it will take for them to pass the tunnel (see Table 1). They are also informed if some dangerous exhausts are present and if there are some vehicles with dangerous goods in their vicinity (before/after their own vehicle).

If the tunnel needs to be evacuated, vehicle drivers and passengers obtain clear information that they need to leave their vehicles and information about the direction in which they are expected to walk. Vehicle drivers, especially motorcyclists, are also informed if there are some alternative routes.

The accident and evacuation support is provided to vehicle drivers by means of in-vehicle displays, radio, and nomadic devices. However, such information should only be complementary to the information provided by roadside signs, markings and signals. Vehicle passengers obtain detailed information via smart-phones or similar devices. In addition, bus passengers obtain the most important information via in-vehicle displays.
and speakers. The information is multimodal and personalized (e.g., supports different languages).

This information is also important for the traffic management, rescue and police teams. In particular, the rescue and police teams obtain information on continuous basis via in-vehicle displays and nomadic devices.

**Table 1** Examples of information to be provided to different road users in case of an accident.

<table>
<thead>
<tr>
<th>Information</th>
<th>Truck drivers</th>
<th>Bus drivers</th>
<th>Taxi drivers</th>
<th>Passenger car drivers</th>
<th>MC drivers</th>
<th>Bus passengers</th>
<th>Car passengers</th>
</tr>
</thead>
<tbody>
<tr>
<td>The time when the problem is expected to be resolved</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>If there are some alternative routes</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>Step-by-step instructions explaining how to handle the situation</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>The need to leave the vehicle</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>The presence of vehicles with dangerous goods in the tunnel</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>The presence of goods that in combination could become ignitable, or create dangerous exhausts.</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>The time it would take to reach the destination by using alternative routes</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>Information explaining what has happened.</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>If the vehicle with dangerous goods is after or before own vehicle.</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>The time the rescue team is expected to arrive.</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

**Future work**

Collecting correct information about accidents is a prerequisite for this concept. Future work needs to identify how to obtain and integrate information from different sources, and extract useful information in real-time. Given the current development and use of smartphones and similar devices, it is likely that user generated information will play a key role. For this it is needed to identify incitements for voluntary data sharing (cf. Waze).
In addition, the future work should also develop detailed strategies on providing data to different users (e.g., which information to provide to whom and when it should be provided). It is also important to develop strategies for how this type of information can be integrated in the current traffic management and rescue strategies.

3.1.3 Support in normal traffic situations

Motivation
Information about traffic status is mainly received via radio, navigation systems, and (variable) traffic signs. Common issues are: a) road users receive information too late, b) information is not updated, c) information is not specific (not personalized), d) information is not detailed enough, and e) information is based on the past or current state, and not on how the state is expected to change within a relevant time period. Consequently, road users feel uncertain, anxious and do not know if the information applies to them or not.

A similar need is identified for the rescue and police teams as well as for the traffic management. Traffic management has access to a relatively high amount of traffic information. This information is mainly generated by traffic cameras and similar sensors positioned in the infrastructure. Also, a large portion of information comes from the road users who report problems via cell-phones. Consequently, important traffic information is sometimes delayed and/or not of sufficient quality for the use within traffic management. It is not guaranteed that traffic management obtains all necessary information. Having access to reliable real-time and predictive information would make it easier for them to plan resources and their actions (e.g., how to get to a place in case of an accident, when to open/close a lane for certain vehicles).

Basic principle
The information about the current and predicted traffic state is provided to the road users and other stakeholders, Table 2. The information is provided on a continuous basis, however road users can easily select which information they want to obtain. Another option would be to receive the most urgent information 3-4 exists before the tunnel and thereby allow the drivers to re-route if needed.

The most urgent information is displayed in the infrastructure. Other, more detailed and personalized/dedicated, information is received by means of smartphones or in-vehicle devices. The communication is bi-directional (i.e., users have opportunity to both obtain and share information).
Table 2 Examples of information to be provided to road users in normal traffic situations.

<table>
<thead>
<tr>
<th></th>
<th>Truck drivers</th>
<th>Bus drivers</th>
<th>Taxi drivers</th>
<th>Passenger car drivers</th>
<th>MC drivers</th>
<th>Bus passengers</th>
<th>Car passengers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Density</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temporary obstructions</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Time needed to pass the tunnel</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Reason for the slow moving traffic</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Road conditions</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>If the slow-moving traffic is caused by an accident that may result in a fire or some dangerous exhausts</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Changes that are expected within a relevant time period</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

**Future work**

The biggest challenge for this concept is collection of information. Road user generated data will be a crucial source, but the question is how to ensure that they are willing to share information. New cloud services need to be developed and integrated with the already existing data sources. Also, methods for extraction of relevant information are needed.

3.1.4 Up-to-date information about tunnels

**Motivation**

Today, vehicle drivers receive information about road tunnels via road signs and, in some cases, via in-vehicle systems for navigation. However, this information is often of limited detail and not updated.

Providing timely, up to date, and dedicated information about road tunnels to vehicle drivers would be beneficial in several different ways. Traffic safety would improve since drivers can plan their trip in a better way and make more timely decisions on lane changes or exit selections. Drivers would feel less anxious since they would know in advance “what is to come”. Information about tunnels is particularly important for truck and motorcycle drivers.
Basic principle
Table 3 shows examples of information that is provided to vehicle drivers including the main characteristics of the tunnel that they are approaching such as length, height, and number of lanes. Vehicle drivers can select which information they want to obtain. The information is provided prior to the tunnel in order to give opportunity for proper decision-making (e.g., choose another route).

Table 3 Examples of information about tunnels to be provided to different road users.

<table>
<thead>
<tr>
<th></th>
<th>Truck drivers</th>
<th>Bus drivers</th>
<th>Taxi drivers</th>
<th>Passenger car drivers</th>
<th>MC drivers</th>
<th>Bus passengers</th>
<th>Car passengers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road elevation at the entrance/exit of the tunnel</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Length of the tunnel</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Height of the tunnel</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Number of lanes</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Number of the exits in the tunnel</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Number of the exits after the tunnel</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Distance to the entrance/exit of the tunnel</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Load restrictions</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Other restrictions</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>If there is any bus lane in the tunnel</td>
<td>-</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>If there is any dedicated lane for trucks in the tunnel</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>If there are any restrictions regarding presence of vehicles with dangerous goods in the tunnel</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Future work
The information that is required to fulfill this particular need is available at the Swedish Road Administration (SRA). However, SRA is a governmental agency and is because of the law about free competition on the market not allowed to provide applications based on such information. A way to address this issue is to make the information available for organizations that are willing to develop commercial applications.
3.1.5 Intelligent helmet

Motivation
Driving in road tunnels is one of the major issues for motorcycle drivers. However, receiving information via conventional displays and nomadic devices is not a feasible option for them.

Basic principle
A combination of auditory and visual information is provided to the motorcyclists by means of speakers and a head-up display in the helmet. The helmet receives the information directly via cellular networks and/or via Bluetooth connection to a smartphone that is in turn connected to cellular networks (4G/5G). The information is displayed in the helmet by means of augmented reality.

Examples of the information that are provided via the intelligent helmet to improve safety in road tunnels include:

- **Preventive:** Traffic flow, road conditions, information about tunnel (inclusive road elevation at the entrance and exit), if there are some obstacles in the road.
- **Emergency:** location of the problem, brief description of the problem exhaust levels, space that can be used to reach the closest exit from the tunnel.

This type of intelligent helmet is currently under development. Two companies, from the US [9] and Russia [10], have recently demonstrated prototypes that mainly support motorcycle drivers in the navigation task (see Figure 7). These prototypes have, to the best knowledge of authors, not yet been systematically evaluated with regard to safety.

![Figure 7 Example of an intelligent helmet](image)

Future work
A future study should evaluate intelligent helmets with regard to safety and user acceptability. In addition to navigational information, it should be explored how to use such helmets for communication of safety-critical information. To start with, the evaluations could be carried out in a simulator. It is, however, important to test these helmets under realistic conditions to identify issues that could be encountered in
dynamic environments (e.g., will a dirty visor in combination with projected information be obstructive).

3.1.6 Emergency evacuation support

Motivation
Typically, road users are informed about the need to evacuate via speakers in tunnels and radio. The auditory information is often difficult to understand, and does not target people with impairment of hearing. In addition, such information does not allow for directed and a more structured evacuation. Another issue yet is that rescue teams have access to limited information about presence of road users with special needs (e.g., children, elderly).

Basic principle
The system is a virtual coacher for drivers and passengers. In case of evacuation need, it sends urgent message to the user and instructions on what the user is expected to do (e.g. leave the vehicle within 2 minutes and walk towards emergency exit nr x). A brief motivation for the evacuation is given as well as information about the presence of rescue teams. The instructions are obtained incrementally and designed in a way that it gives confirmation and feedback to the users.

The instructions are multimodal and are obtained via in-vehicle displays and speakers and via nomadic devices. Also, the most important information is given via road signs and markings.

The road users have the opportunity to manually enter information that they find important for the given situation, or to ask questions. Such information could be, for example, “I have disability and need help”.

Rescue teams and police receive real-time information about road users needs and the progress of the evacuation, both via in-vehicle displays and nomadic devices. The information is mostly visual and easy to capture.

Future work
Similarly to other concepts suggested here, collecting relevant and accurate information is the most challenging part. This concept could particularly benefit from information about road users and their individual needs. Such information may be obtained directly from users, but also by means of vehicle-based sensors (e.g., provide information about the number of people in the vehicle and presence of children). Future research should investigate how to obtain this type of information, and how to warrant information security. Future research should also explore various multimodal interfaces addressing their usability, acceptability and safety benefit. Some of these studies can be carried out in simulators. However, it is important to evaluate them in their operational environment.
3.1.7 Assisted emergency evacuation

Motivation
Reducing evacuation time is crucial in all emergencies, especially in road tunnels. It is also crucial that evacuation is carried out in a smooth way and that road users obtain the help that they need. Accidents in tunnels can cause traffic cognitions in their vicinity, delaying the arrival of the rescue teams. Also, depending on the number of people in the tunnel and the size of the area that needs to be evacuated, it may be difficult for the rescue team to assist all road users in the evacuation.

Basic principle
The idea is to allow professional drivers to support other road users and rescue teams in evacuation of road tunnels. The professional drivers obtain instructions via in-vehicle or nomadic devices on what is expected from them in the given situation (e.g., use the vehicle to block the traffic, direct other road users on choosing the most appropriate emergency exit). At the same time, the other road users are informed that they will get assistance from the professional drivers until the rescue team arrives (or along with the rescue team). The drivers receive confirmation from the traffic management that the actions they have taken are correct, which is important for creating more knowledge and confidence in similar situations. The instructions are in fact recommendations (i.e. not mandatory) and they leave room for own decisions.

Future work
The discussions with different drivers indicate that truck, bus and taxi drivers may be the most appropriate for assisted evacuation. A future study needs to investigate under which conditions they are ready to accept such a task and if some special incitements are needed. Emergency management is already a part of the truck and bus driver education. However, having opportunity to practice guidance and assistance under realistic conditions would be useful. Future studies need to explore in more detail how such training may be designed, who is going to pay for that and the time that these drivers spend guiding others. It is also needed to find out what type of instructions and recommendations that the drivers need to be provided with, and how to make them visible to other road users (e.g., special vests). An additional topic that requires attention is how to ensure that the other road users accept and trust in this type of assistance.

3.1.8 Dynamic route planning and guidance

Motivation
Currently, truck drivers and haulage contractors are to a high extent planning routes for transportation of goods manually. In order to determine which road is appropriate for transportation of a certain goods, they have to check a hard-copy map containing information about road restrictions, or to check road databases provided by e.g., Transportstyrelsen, SRA or Geodataportalen. However, it is somewhat difficult to find relevant information in these databases, and hard-copy maps are often not up to date.
Another issue is that neither maps nor databases are updated in real-time and do not include information about temporary restrictions caused by, for instance, accidents and obstacles on the road. Consequently, truck drivers may need to re-plan their trips along the way resulting in delays for customers, longer working hours for drivers, and extra costs for haulers. Also, as a consequence of insufficient route planning, truck drivers sometimes end-up in prohibited areas or roads, which may affect the overall traffic safety and endanger people living in that area.

In some cases, traffic management centers provide suggestions on alternative routes via local radio or via variable road signs. However, these suggestions come often too late and are not based on drivers’ individual needs and preferences, i.e., suggestions are not based on ones destination, type of vehicle, and type of goods.

Similar issues are identified for other types of drivers. In particular, bus drivers must be very careful when selecting an alternative route since a large deviation from the original plan could cause big delays. The workshop discussions show also that passengers in buses and taxis are often poorly informed about reasons for re-routing, which creates curiosity and in some cases anxiety.

By obtaining user-friendlier and more accurate support for route planning, the haulers and truck drivers could become more efficient. Basically, they would be able to get the most sufficient route based on the type of goods before the trip starts and, if needed, they could trust they will be re-routed a new most optimal road. Also, providing this type of support is expected to lead to improved traffic safety as the current traffic regulations and restrictions would be respected to a higher extent. In addition, sufficient route planning is expected to result in reduced emissions.

**Basic principle**

Dynamic route planning provides support to vehicle drivers, especially professional ones, in planning and re-planning of their routes. Accepting a suggested route is not mandatory, however, if further advancement on the original route could be safety-critical (e.g., due to the type of goods being transported), drivers are “forced” to re-route. If possible, re-routing takes place before reaching a tunnel, since changing the plan in a tunnel may be stressful. Both drivers and passengers obtain information about the reason for re-routing. In addition, drivers obtain an approximation of how much time they would save by choosing the alternate route as well as information about the traffic flow on the alternate route. Truck, bus, and MC drivers need also a brief description of the major characteristics of the route including special restrictions, presence of tunnels, and bridges.
Table 4 Examples of information to be provided to different drivers for proper route selection.

<table>
<thead>
<tr>
<th></th>
<th>Truck drivers</th>
<th>Bus drivers</th>
<th>Taxi drivers</th>
<th>Passenger car drivers</th>
<th>MC drivers</th>
<th>Bus passengers</th>
<th>Car passengers</th>
<th>Hauler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route suggestion based on the individual preferences and the type of goods</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Route suggestion based on the type of goods</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>Time it takes to reach the destination</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Traffic flow on the suggested route</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>Restrictions (permanent/temporary)</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>Information about the latest update</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Most optimal time to start the trip</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>Places and time slots for breaks</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>Reason for re-routing</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

**Future work**

For a reliable route planning, it is necessary to have access to accurate and real-time information about roads and traffic (e.g., traffic flow, permanent and temporary restrictions) as well as information about drivers’ destination(s), expected arrival time, type of goods, and their personal preferences (e.g., breaks). Information about roads and permanent restrictions for (dangerous) goods is to a high extent available in the databases at the Swedish Road Administration and the Swedish Transport Agency. However, these organizations should ensure that the information is updated frequently, preferably in real-time, taking into account the current traffic status including accidents and similar obstructions as well as the traffic flow and density.

**3.2 Use case B: Standstill vehicles**

Currently implemented traffic management approaches for road tunnels are primarily making use of infrastructure-based measures. Vision-based systems are typical examples of sensors that are used to provide traffic management centers with information about standstill vehicles in tunnels. In some cases, image processing software is used for automatic detection of such vehicles (e.g., [11], [12], [13]). Other examples include infrared beacons [14], various types of inductive loops positioned under the road surface [15], radars [16], or a combination of two or more of these technologies [17], [18]. Detection of standstill vehicles is also possible by means of
vehicle-based sensors, e.g., vehicles equipped with forward collision warnings and emergency-braking systems can detect and help drivers avoiding collisions with standstill vehicles. However, each of these approaches has its own limitations ranging from coverage problems to cost, penetration level, and impact by environmental conditions and occlusions. The literature reviewed, on the other hand, reveals that detection of standstill vehicles in road tunnels by means of C-ITS is a promising (complementary) solution that can eliminate several of these shortcomings.

In order to avoid accidents with standstill vehicles, it is important that drivers approaching such vehicles obtain timely information about them. This information is also crucial for traffic management, rescue teams and police; having information about standstill vehicles they can apply appropriate strategies for handling the situation. In addition, haulers would also gain from knowing if their vehicles have encountered any issues (e.g., they could inform their customers about delays).

The ETSI Basic Set of Application (BSA) distinguishes between two types of applications related to standstill vehicles: Stationary Vehicle – accident and Stationary Vehicle – problem [19]. Following the ETSI, the non-profit organization Car2Car Communication Consortium has listed a function called Stationary Vehicle Warning, V2X Rescue Signal [20] as one of the functions that vehicle manufactures will provide in the soon future. The Swedish research project ETTE has, for example, recently demonstrated such a function based on GPS positioning and V2V communication between a truck and a passenger car [21][22]. Given that GPS signals are not possible to obtain in long tunnels, this function may not be available in such environments.

Development of automated driving opens new opportunities for reducing consequences of standstill vehicles caused by drivers' health issues. Honda has recently demonstrated a C-ITS function that a driver can activate in case of inability to continue driving. When activated, the function allows the vehicle in front to take over steering control. That is, the vehicle in front becomes the lead vehicle in a platoon. The applicability of such a function for road tunnels should be investigated in more detail.

It is evident that accurate positioning and reliable communication is very beneficial for the quality of functions related to standstill vehicles. Looking at roads with more than one lane (in Stockholm Bypass there will be three lanes in each tube), an accurate distinction between lanes is necessary to distinct between dangerous and not dangerous situations.

Given these limitations, due to positioning issues in tunnels, the focus should be on preventing vehicles from becoming standstill in tunnels.
3.2.1 Access control to avoid standstill vehicles

Motivation
The workshop discussions with the truck drivers indicate that they are in general anxious about driving in long road tunnels. One of the aspects that they have highlighted is the risk of becoming standstill in such a tunnel due to vehicle malfunctions. The traffic management, police and rescue team have, on the other hand, expressed a need of having access to information about vehicles travelling in tunnels, especially when it comes to vehicles transporting dangerous goods. A solution that ensures that vehicles entering a tunnel meet minimum requirements for accessing the tunnel would improve safety for drivers and other road users using the tunnel, both from a proactive and reactive perspective. In addition, other types of vehicles could be controlled in the same way, or at least the traffic management could receive information for improved emergency preparedness and better statistical numbers for improved planning of short and long-term strategies.

Basic principle
Vehicles are allowed entrances based on their individual properties such as static vehicle information (e.g., physical dimensions) and dynamic vehicle information (e.g., malfunction codes). It is also important that the access control is based on static and dynamic information about goods being transported (e.g., type and amount of goods). The main process for obtaining a vehicle’s individual access rights is to compare the vehicle properties with an access policy defining the controlled areas and its access requirements. Basically, if there is a risk that the vehicle may have issues while travelling in the tunnel, the vehicle should be denied access to the tunnel. In that case, the vehicle should be re-routed to the most suitable road. It is important that the driver receives information and explanation for the re-routing in advance. The access policy is preferably specified by local, regional, and national authorities in accordance with their traffic management strategy.

The access to the tunnel can be controlled in several different ways. In [23], three different control strategies were identified:

- **Centralized access control.** The comparison is done at a central entity, which means that the vehicle properties must be sent from the vehicles, and the access rights are sent the other way.
- **Partial distributed access control.** The comparison is done at roadside, possibly a roadside unit (RSU) governing the control. This means a local interaction between the vehicles OBU and the RSU.
- **Fully distributed access control.** Vehicles receive information from other vehicles and the infrastructure, but information processing is done by a unit in the vehicles. This means that the access policy must be distributed to each vehicle that computes its own access rights.
Each of these strategies has their own advantages and disadvantages. In SMARTFREIGHT, for example, a partly distributed strategy was applied since the tunnel access was dependent on dynamic information on existing vehicles inside the tunnel [23].

Australian government has already deployed the Intelligent Access Program (IAP) for access control of vehicles transporting dangerous goods [24]. It is a voluntary program based on a combination of satellite tracking (GNSS) and wireless communications technology. Australia aims at further development of the IAP where all heavy vehicles buy their slot in the traffic system. Currently, there are discussions about introduction of a similar IAP in Sweden.

**Future work**
A more detailed investigation of information needed to avoid standstill vehicles is required as well as how to obtain such information. Australian IAP is an off-the shelf system that can be fitted into all types of vehicles. It is also important to develop a viable strategy for access control and handling of vehicles in case of denied access, and to investigate user acceptance of such strategies.

### 3.3 Use case C: Dangerous goods

What distinguishes road tunnels from many other traffic environments is the lower communication coverage and stricter safety regulations. Tunnels are closed sections with few entrances/ exits and an accident in such an environment could be highly disastrous. Hence, it is important to explore how tunnels can be controlled and monitored, among others by means of C-ITS that limit and manage the amount of dangerous goods in the tunnels and monitoring that improve the awareness on the vehicles present.

#### 3.3.1 Dynamic priority lane for vehicles with dangerous goods

**Motivation**
The workshop discussions show that vehicles transporting dangerous goods are considered as one of the major issues and threats in road tunnels, both by their own drivers and by other road users. Other stakeholders such as police, emergency teams, and traffic management are also considering dangerous goods as one of the major safety issues. A way to improve the safety in long tunnels such as Stockholm Bypass may be to introduce a dynamic priority lane for vehicles with dangerous goods.

A dynamic priority lane would warrant an optimal throughput of dangerous goods in tunnels independently of the other vehicles, and the other vehicles would be able to use all lanes in the tunnel when there are no approaching vehicles with dangerous goods. Also, the number of interactions between vehicles transporting dangerous goods and the rest of the traffic would be reduced. This way, the existing infrastructure could
create same benefits as dedicated lanes with less negative effects for the rest of the traffic.

To the best knowledge of the authors, dynamic lanes for trucks (with dangerous goods) are in general an unexplored area and the effects of such lanes are still not quantified.

**Basic principle**
With the dynamic lane concept, a lane in a road tunnel would be dedicated for vehicles with dangerous goods only when they are present there. When such vehicles pass, the lane becomes a normal lane again. The goal is to improve throughput time for vehicles transporting dangerous goods in tunnels without increasing the throughput time for other vehicles. This to guarantee a safe and smooth traffic use of the tunnels as far as possible both in the normal traffic situations and in case of incidents. As described in the previous section, the use of dynamic lanes for buses in urban areas has been explored in some research projects.

**Future work**
A prerequisite for dynamic truck lanes is that the vehicles transporting dangerous goods are connected, i.e. able to exchange information with the infrastructure and/or other vehicles. It is also required that the status of the vehicles (i.e. with/without dangerous goods) is known. Delivery constraints need also to be known (e.g., when is the goods expected to be delivered).

The possibilities and application areas for dynamic lane management at entry links to and inside tunnels should guarantee a safe and smooth traffic use of the tunnels as far as possible both in the normal case and in case of incidents. To this aim the traffic is guided on to the counter flow lane, the so-called counter-flow operation and guided together with the traffic in the counter-flow tube lane in case of closures in the tunnel or total closure of a tunnel tube.

### 3.3.2 Dynamic coordination of vehicles with dangerous goods

**Motivation**
The workshop results show a need for avoiding that two vehicles carrying dangerous goods are in a long tunnel at the same time, or at least that they are in close proximity to each other. A dynamic coordination of such vehicles that ensures that they are at a safe distance from each other while traveling in a tunnel could therefore increase overall road safety, and make road users feeling safer when traveling in long tunnels. The challenge is to make coordination in a way that amplify the positive and minimize the possible negative effects.

**Basic principle**
The speeds of vehicles transporting dangerous goods are harmonized to ensure that they reach a tunnel with a minimum safety distance between each other. The safety
distance may be a static or a dynamic value that depends on parameters such as average vehicle speed, vehicle density, type of goods being transported etc. The speed harmonization could be achieved by giving instructions to the drivers, or by automatically decelerating or accelerating the vehicle.

Future work
In the SMARTFREIGHT project, an application that controls the access to a tunnel was demonstrated. In the application demonstrated, the vehicle has to wait in a holding area if the amount of dangerous goods that is already in the tunnel has reached the maximum limit. In order to avoid that some vehicles have to wait, a future project should investigate how to create a dynamic coordination of vehicles that would by harmonizing vehicle speed ensure that they do not reach the tunnel in an inappropriate moment.

Future work should investigate the applicability of dynamic coordination of vehicles transporting dangerous goods and effects it may bring in terms of traffic flow, safety and energy efficiency. For this, it is necessary to define an appropriate vehicle coordination strategy as well as how to actually control the vehicle’s speed (i.e. automatically or by giving instructions to the drivers). A first step in the future work could be to define several coordination strategies and to evaluate them in computer simulations. The overall goal of such a strategy is to warrant the minimum safety distance without creating significant delays for the vehicles transporting dangerous goods as well as other vehicles.

4 The role of intelligent goods
Today, trucks are required to carry orange stickers containing coded information on how dangerous their goods is and which categories of tunnels they may pass through. However, there is no automated and generally accepted strategy for monitoring compliance with such rules. Having correct information about goods in tunnels is also important from other aspects. The information can, for instance, be used by rescue teams to plan appropriate resources and strategies in case of an accident, or by traffic management to give priority to vehicles with certain goods.

In many tunnels, video cameras and corresponding software are deployed to detect the stickers. However, video cameras cannot decode these stickers when visibility is poor or they are covered with dirt. An additional issue is that stickers on truck transporting dangerous goods are incorrect, or completely missing. That is, even if video detection would work perfectly some dangerous goods would still remain unidentified.

To solve these and similar issues, approaches making goods intelligent and thereby detectable have emerged. Goods can be made intelligent on different levels, from individual item level to packages, pallets, containers, and vehicles [25], see Figure 8.
According to [26], intelligent goods should have the following properties:

- Carrying crucial information about itself, such as a unique identity, special characteristics (e.g. dangerous goods) and origin-destination data.
- Being able to store information on events that may have an impact on the goods itself (e.g. high temperatures), or information on major delays.
- Taking actions on events that have exceeded predefined limits, for example by sending an alarm in case the location of the goods is not in line with the planned route data.
- Enabling a more accessible and feasible track and trace of the goods for actors involved in the value chain.
- Providing information to the control systems managing the transport of the items, by giving priority to certain types of goods in vulnerable parts of the transport systems (e.g. road tunnels).

Today, detection of goods is mainly done by means of Proximity Contactless Smart Cards in accordance with ISO/IEC 43443. These are generally based on Radio frequency identification (RFID), but even other types of communication are possible in combination with GPS. The major issue is that these devices are currently used in a low scale, and that a great part of goods is not possible to detect/track.

A topic for future research should be to identify how to obtain a large-scale deployment and if some incitements would be useful. Another topic that requires attention is integration and sharing of data between different stakeholders, independently of the chosen detection and communication technology. Research conducted by Boeck and Wamba (2008) identified a set of dimensions that were found to be important antecedents that influence the result of information sharing through RFID in buyer-seller relationships: communication and information sharing, cooperation, trust, commitment, relationship value, power imbalance and interdependence, adaption, and conflicts. The importance of information ownership does not appear clearly from this list but should not be disregarded. When introducing management systems based on intelligent goods across partners, there are some vital questions to address: Who owns the data, where is the data stored, how will they be shared across partners, and is payment required to access different levels of detail in the data?
5 The role of automated driving

The automation of the driving task has started many years ago with the development of Advanced Driver Assistance Systems (ADAS). Several of them are commercially available today (e.g., adaptive cruise control (ACC), forward collision warning (FCW)). Typically, these systems are designed to support vehicle drivers in safety-critical situations by providing information and warnings to them, or by automating the longitudinal control of the vehicle (i.e., speed and distance). Recent evaluations of ADAS in real-world traffic show that these systems are beneficial as they have the potential to reduce the number of accidents as well as to improve energy and time efficiency [27].

Introducing even more automation in vehicles is envisioned to enlarge these benefits, both for the individual vehicles and for the transportation system as a whole, and thereby addressing several of the major societal challenges [28]. Consequently, several stakeholders are ready to take the step beyond automated longitudinal control to introduce some level of lateral control. While some of them aim to develop automated control under specific conditions, others are working towards completely self-driving vehicles. As a result of that, the driving task is becoming increasingly automated every day, and fully automated vehicles may become a reality, albeit the timing remains uncertain.

To obtain full benefits of automation, it is necessary that vehicles are connected and can cooperate with each other and the infrastructure as well as other road users (e.g., via nomadic devices carried by pedestrians). Swedish vehicle manufacturers, suppliers, and authorities consider automation and cooperation as a key for safe, energy and time efficient vehicles, as well as for the entire transport system. They are actively participating in projects within this area, both at national and international level.

An automated function that has recently obtained a large attention and is expected to be of great benefit, especially in terms of safety and energy efficiency, is ACC. More specifically, augmenting ACC with wireless communication, called Cooperative Adaptive Cruise Control (CACC) has the potential to increase throughput by enabling vehicles to travel in “platoons” (Figure 9). Drivers normally maintain sufficient separation from the preceding vehicle to allow them to come to a safe stop if the vehicle ahead suddenly decelerates. The CACC senses speed changes and react far more quickly than can a human driver. Consequently, platooning can decrease the distance and time interval between vehicles following one another in a lane. Platooning where only the lead vehicle is operated by a driver is explored in several research projects such as the Grand Cooperative Driving Challenge (GCDC) [29] and SARTRE [30] that demonstrated automated platoon driving on a highways involving both trucks and passenger vehicles, and truck platooning in Japan [31], the US [32], and Sweden [33].
Currently, the platooning has been tested only on highways. The question is if platooning should be allowed in road tunnels, and under which conditions (e.g., what type and how many vehicles should be allowed in a platoon). Given that tunnels are rather controlled environments in terms of light and weather conditions, it is likely that platooning may be feasible even with current sensor technologies. However, it is needed to investigate in more detail which platooning strategies are the most appropriate for road tunnels. This could be done partly by means of computer simulations and partly in driving simulators. Depending on the results, evaluations in an existing road tunnel (e.g., Lundby tunnel) could be carried out. This would put Sweden in the forefront in this area and it could set the stage in development of regulations related to this topic.

Similar questions can be raised for other automated functions that are being developed such as traffic jam assistance and automated lane changing.

6 The role of communication technologies

Communication technology is an area that is in a continuous development and several stakeholders are trying to set the stage. Which type of communication will be used in future vehicles and transportation system is to a high extent affected by developments and trends in other fields such as telecommunication and information technology.

Cellular communication is widely used today in Sweden and there are indications that it will continue to expand. Recent developments in the forth generation cellular network (4G), such as long-term evolution (LTE) and LTE-Advanced, enable larger amounts of data to be transmitted as well as higher transmission rates. Consequently, many vehicle manufacturers and providers of aftermarket devices for in-vehicle use have adopted this technology and implemented it in their products. Furthermore, it is expected that the number of 4G/LTE-connected vehicles will grow rapidly in the near future. For instance, IHS Automotive forecasts that the number of LTE-connected vehicles worldwide will
grow from 1.2 million in 2015 to 16 million in 2017. Based on this and similar forecasts as well as discussions with experts in the field, a reasonable assumption is that a great majority of vehicles traveling on our roads will be connected with this technology by 2025 (the time point when the Stockholm Bypass tunnel is expected to be ready for public use), and cellular communications could potentially be a viable option for coverage. However, certain issues with cellular communications must be addressed.

First of all, it may be too optimistic to expect that the deployment rate will reach 100 percent and the penetration rate needs to be considered during the planning stage. The data rate for 4G/LTE decreases significantly when the user is moving, and this may need more base stations to be deployed within the tunnel. Another issue is that capacity of a system based on this technology may decrease in an area with many users. Furthermore, the cost and security issues need to be addressed. Though telecommunications industry is now working intensively on upgrading the current technology, the applicability for safety critical systems is not yet sure. For those above reasons, we conclude that cellular communications will provide excellent services for infotainment applications, but may not be a feasible for safety critical situations.

In addition to the development of cellular networks, dedicated short-range communication (DSRC) is becoming norm. In February 2014, the United States Department of Transportation (DOT) announced that all new light vehicles will need to be equipped with cooperative units, i.e. vehicle-to-vehicle and vehicle-to-infrastructure communication (V2X) based on 802.11p standard. Shortly thereafter, the European organizations ETSI and CEN finalized the definition of a basic set of communication standards for cooperative vehicles. The decision on heavy goods vehicles from US DOT will come later in 2014 or early 2015. For now, the standard focuses on advanced driver assistance through messages including cooperative awareness messages (CAM) and decentralized environmental notification messages (DENM) that are exchange among vehicles through wireless communications. A basic set of applications (BSA) has been defined and published. Applications included within BSA are considered to be Day-1 applications and are expected to be implemented from 2015. BSA include applications on road safety, traffic efficiency as well as location based services. The principle is to extend the drivers’ vision and provide better perception and early stage warnings in case of dangerous situations. ETSI and CEN are working on the second release that will provide enhanced vehicle communications, such as two-way communications, enhanced communication architecture and protocol, as well as enhanced set of applications that address more safe critical situations.

European vehicle manufacturers have through the Car2Car Communication Consortium committed to begin introducing DSRC systems in 2015 and it is likely that initial introductions would be on high-end vehicles and/or newly re-designed vehicle models. The so-called Amsterdam Group (consisting of European cities, infrastructure providers, organizations representing road users, vehicle manufacturers) has developed a
roadmap for the introduction of Cooperative ITS with focus on V2I, which builds on a larger pilot along a test route Rotterdam-Frankfurt-Vienna.

Activities on the infrastructure side in Europe are promising for a deployment corresponding to OEM introductions, but this is not a certainty. Advances in ITS have typically been fragmented and slow due to the EU Member States being sovereign nations. EasyWay, a major ITS deployment initiative sponsored by the European Commission, which supplements deployment funding at the national level, has published a Cooperative-ITS Roadmap aiming at 2017 deployment of V2X. In addition, the Amsterdam Group aims at 2015 deployment. Given these concerns, European Commission officials at the 2012 ITS World Congress noted they are discussing various instruments that could apply to deployment, such as incentives to road operators or cities.

Wi-Fi technology supports wireless connectivity and generally has higher data rates. The main drawback of Wi-Fi is its design for stationary terminals. Though Wi-Fi offers higher data rates than other options, it does not work nearly as well with moving terminals. In addition, any vehicle that enters the Wi-Fi hotspot must give its MAC (media access control) address and obtain the MAC address of all other vehicles in the hotspot before it can start communications. Though it uses the same basic radio system as DSRC, DSRC eliminates the need for users to gather MAC addresses before communication and thus communication establishment is much faster. In general, this means that Wi-Fi cannot support data exchanges with vehicles moving at road speeds. The costs and security risks associated with cellular also apply to Wi-Fi.

The future research and development needs to ensure

- Seamless handover between different communication protocols. This is not specific for road tunnels but should be tested in such an environment to eliminate potential issues.
- Congestion insensitivity. Complete congestion mitigation and scalability research to identify bandwidth congestion conditions that could impair performance of applications, and develop appropriate mitigation approaches. Not specific for road tunnels but the Stockholm Bypass tunnel could be used as a use case.
- DSRC in a tunnel environment. Besides the above general topics, DSRC based V2X communications have been mostly tested in open fields. In case of tunnel, radio signal will be either absorbed by the tunnel (depending on the tunnel material) or reflect back by the wall. This environment is also different from indoor environment where building structures is much more complicated. Studying on the V2X performance under the tunnel environment forms an important research topic that has seldom been addressed.
7 The role of positioning technologies

Broadly speaking, positioning methods include mainly satellite based and wireless radio signal based. Each of them, including their advantages and disadvantages, are briefly described in the following sections.

7.1 Satellite based positioning

Surface and outdoor positioning mostly are satellite based and rely on signals from satellites. Examples include Global Positioning System (GPS) from US, GLONASS from Russia, BeiDou from China and Galileo from EU. With proper support from ground stations such as EU EGNOS, satellite based positioning system can provide very accurate locations, however, they all require visibility to satellite signals.

In the case of Stockholm Bypass tunnel, satellite signal will mostly be very limited because of the tunnel length. Vehicles may keep tracking themselves for a certain time through inertial navigation system after they enter the tunnel, however, this will not last. For short duration GPS outages lasting a few seconds, devices can make use of inertial navigation units to predict the location of the vehicle. These units contain a number of accelerometers, gyros, and angular rate sensors that can be combined with mathematical models of vehicle dynamics to take the vehicle’s position at loss of GPS and estimate the position further for a few seconds. Because of noise and error build-up in the sensors, the accuracy of the estimated position degrades the longer the estimation runs. Currently there are no long-term solutions for extended-duration GPS outages.

7.2 Radio signal based positioning

Radio signal based positioning are based on radio signals from the deployed infrastructures, e.g. WiFi hotspots, cellular network base stations, etc. [34][35]. Radio signal based positioning is especially useful when there is no satellite signal such as indoor environments, underground, tunnels. Radio signal based positioning methods will be the most appropriate positioning methods. Potential radio signal based positioning methods are listed below, with general comments on their advantages and drawbacks.

Cellular network based positioning (e.g., GSM, UMTS, LTE, 5G) relies on existing cellular network infrastructures. The methods require that vehicles are able to receive cellular network signals, e.g. have a SIM card onboard. Depending on the positioning algorithm, different accuracies can be achieved.

A simple proximity sensing such as cell-id based methods detects positions based on the location of the base station and is able to achieve a hundred-meter accuracy. More advanced methods, such as triangulation and trilateration of the received signals, fingerprinting based on the received signal strength, or hybrid methods can achieve a better accuracy below one hundred meters. Those statistics are based on the current public cellular networks with no optimization for the positioning purposes and can be improved with future cellular networks.
Positioning accuracy based on cellular networks depends on the density of cellular towers. In dense scenarios such as urban cities, the positioning accuracy can be improved significantly, especially with the help of digital maps. Future cellular networks, such as in 5G, small cells may be deployed with a high density within the tunnel for providing a required level of coverage and capacity. In such cases, cellular network based positioning methods may provide very accurate results as to the level of meters or even better.

Besides cellular network, wireless local network also provides different methods for positioning without satellite signals. Typical methods include WiFi/WLAN, Bluetooth, Ultra Wide Band (UWB). The positioning methods based on wireless local networks are very similar to that of the cellular networks such as proximity positioning, signal triangulation or trilateration, fingerprinting, etc. Since cells in wireless local network may cover very small areas, high accuracy localization can be achieved.

WiFi is one of the commonly used indoor positioning methods that provide accuracy of up to certain meters. It deploys WiFi hotspots for the purpose of positioning and WiFi signal are used for devices to locate themselves. Due to the penetration of WiFi devices, a large number of commercial products are available based on WiFi positioning. Besides, hybrid methods combining cellular signals and WiFi signals may provide even better location results. Considering that WiFi may have very high penetration in future and vehicles may also have WiFi on-board, e.g. 802.11p based dedicated short-range communication, WiFi may provide a cost effective method for tunnel positioning. Besides, it also provides the services such as data communications.

Bluetooth is a short-range communication and can provide very accurate positioning. In the High Accuracy Indoor Positioning (HAIP) developed by NOKIA, up to 0.5m accuracy can be achieved. If combined with 3D maps, up to 10cm accuracy can be achieved. The deployment cost of such a system may be high as it needs a large number of Bluetooth transmitters and vehicles must have receivers for the purpose of positioning.

An emerging technology is visible light communication (VLC), [36]. Besides providing a new way for wireless communications, VLC also provide an alternative method for localization. VLC based positioning methods deploy LEDs for the purpose of both illumination and communication. Illumination and communication are then used for localization. VLC based positioning system is integrated with the lighting system, which requires no extra infrastructures. For localization, light sensors are needed and may also be integrated with the vehicles’ lighting system. VLC based positioning has been shown to achieve accuracy below one meter. Considering the high density of lights within the tunnel, high accuracy of positioning may be achieved. This method will mostly depend on the development of VLC industry. If VLC communication penetration is not high enough, deployment cost of such a system may be high.
Another similar positioning method is based on Ultra Wideband (UWB). The system needs to deploy UWB locators and tags. Representative systems such as Ubisense can achieve positioning accuracy up to 15 cm. However, dedicated devices are needed for UWB positioning and the deployment cost may be very high.

Other short-range communication-based localization methods include RFID, ZigBee that can provide one-meter level accuracy. However, they all need dedicated devices both in the infrastructure and the vehicle sides.

### 7.3 Future work

Based on the major non-GPS based positioning methods discussed above, we identify potential methods for accurate positioning within the Stockholm Bypass tunnel and propose future works for proof of concept. It is noticed that combing of different positioning methods, e.g., hybrid positioning, may also be considered for improving the accuracy, however the system complexity (and cost) must be considered.

#### 7.3.1 Cellular network based positioning methods

We propose this method based on the context of the intensive research of next generation cellular networks, e.g., 5G networks. As already discussed, cellular network has been widely used currently for positioning purposes. However, it is usually considered as a back-off method when GPS signals are lost and the accuracy is quite limited. Since LTE, 3GPP has been considering positioning as part of the standardization. This is partially driven by the demand of location based services market, and also from the government for emergency services. However, to provide continuously accurate positioning services such as in Stockholm Bypass tunnel, current system needs improvement and future networks such as 5G networks needs to be considered.

One advantage to consider the cellular network comes from the evolution of 5G networks, which aims to connect all things into the Internet all the time. The requirements of coverage and data services is driven by the data service, which means that the Stockholm Bypass tunnel is expected to deploy telecommunication infrastructures for data services. Base on the same infrastructure, and assume future vehicles are Internet-connected, positioning can be integrated into the telecommunication services. However, the accuracy of the positioning with LTE network and the coming 5G networks needs to be evaluated with field trials. To do this, we propose the following potential projects:

- **Field trial with telecom operators (Tre, Telia, etc).** Telecom operators will need to provide data services within the tunnel for a satisfied level of data throughput, which means they will need to deploy enough numbers of small cells within the tunnel. Besides providing data services, those small cells may provide very accurate positioning methods since their coverage area is much smaller and the density is quite high. The field trials will need to find out potential modifications on the infrastructure side for positioning purposes. In addition, research questions such as the density of the small cells, positioning algorithms at the
vehicles side are also open. Business models need to be considered as telecom operators need incentives for investigating and deploying such a system.

- **Field trial with Ericsson’s small cell solution.** Ericsson plays a key role in the future 5G networks. Field trials can be independently done with Ericsson or jointly with telecom operators. One method is to consider Ericsson’s indoor solutions, e.g. Radio dot. Radio dot is a small cell solution which aims to provide good data services for the indoor environment where the signals are usually bad. The small cell solution may suit very well for Stockholm Bypass tunnel. The solution provides good data services and with potential enhancements, positioning may be integrated. Similar research questions such as above mentioned require more research and field trials. It is worth mentioning that Ericsson’s Zero sight [37] solution which joints efforts with Philips may be considered for infrastructure planning. In zero sight, small cells are integrated with Philips’s lighting system. Basically, each of the light poles may also contain a small cell for the purpose of communications services. In such a case, positioning can be planned together with both the telecom services and the lighting system.

### 7.3.2 WiFi based positioning methods

WiFi has been widely used for indoor positioning purposes. Example services include Aeromcout, Ekahau, Cisco, Motorola, Google, Apple, Wifislam, Meridian, Wayfarer, Wifront, etc. Unlike the cellular-based positioning, WiFi positioning does not need infrastructures from telecom operators, and can be planned independently. However, since WiFi positioning is mostly used for indoor localization with low mobility, the performance needs re-evaluation under high mobility such as the case of Stockholm Bypass tunnel. Research project can be established for exploring the applicability of WiFi positioning for Stockholm Bypass tunnel. Similar research questions such as those of the cellular network-based positioning need to be addressed. Typical research questions include 1) the performance evaluation of WiFi positioning under high mobility, 2) the number and density of WiFi hotspots for achieving a certain level of accuracy, 3) the cost benefits evaluation to deploy such as system, e.g. only for positioning or both for positioning and data connection, 4) extra infrastructure and vehicle side requirements based on the positioning algorithms, etc. Research and field trials of WiFi positioning can be done independently or together with industries by deploying the system within an existing tunnel.

### 8 Conclusions

Based on an extensive literature review and discussions with various stakeholders, including road users, authorities, service providers and vehicle manufacturers, this study recognizes that C-ITS is a well addressed topic and that several concepts targeting safety have been suggested in research projects. To support development and deployment of C-ITS, leading European vehicle manufacturers are working together in the Car2Car Communication Consortium. At the end of 2012 they have signed a Memorandum of Understanding (MoU) on a common strategy for the development and
deployment of C-ITS. The MoU lists a number of day-one services that should be deployed from 2015. Although some of these services are relevant for road tunnels, the focus is mainly on the other traffic environments.

In addition, very few of the concepts suggested in the research projects and by the Car2Car Communication Consortium, have been evaluated in large scale. This requires viable business strategies and standards, which in turn requires tight collaboration between various stakeholders, both at a national and European level. However, before initiating such discussions on a European level, national feasibility evaluation in an operational setting (e.g., Lundby tunnel, Norra länken) is recommended. This would enable Sweden to “set the stage” and affect future standards at the same time as it would support competence development in the country and strengthen its international research competitiveness.

New communication technologies between vehicles and between vehicles and infrastructure and road users provide new opportunities for traffic management, rescue and police teams as well as authorities. Integrating such information in their strategies would offer great advantages for a safe, comfortable and efficient transport of the future. An in-depth analysis of how this integration should be achieved in practice and creation of a roadmap on this topic is recommended.

For the use case targeting standstill vehicles, the study suggests access control based on vehicle, driver, goods state to avoid unnecessary stops in the tunnel, and a system that informs drivers about the presence/position of a standstill vehicle.

For the use case b), the impotence of the following concepts is emphasized: dynamic coordination of vehicles transporting dangerous goods to warrant a minimum safety distance between these vehicles in the tunnel and dynamic priority lanes for vehicles transporting dangerous goods to optimize throughput of these vehicles in the tunnel.

In the context of use case c), the study identifies that C-ITS services focusing on driver and passenger coaching in both normal and safety critical situations are the most promising. This includes dynamic routing, and real-time, relevant, and predictive traffic information. In case of evacuation need, C-ITS should provide clear and concise instructions on what the road users are expected to do. More detailed instructions could be given to professional drivers (truck/bus/taxi) who, in turn, would guide other road users. The instructions should not be mandatory to follow. Professional drivers may need education and most importantly, it must be clear for the other road users that the professional drivers are authorized to guide them.

For all these solutions, it is important that the users receive feedback and confirmation. Also, the following technological enablers and challenges are identified for all use cases:
• Positioning technologies that provide highly accurate position information are central enablers to contextualize services and collected data and will be key for advanced tracking of vehicles, goods, and passengers.
• Positioning in long road tunnels is difficult due to lack of GPS-signals. Methods based on wireless and cellular networks are recommended for the Stockholm Bypass tunnel. The extensive development of the 5th generation of cellular networks (5G) is promising with regard to positioning capabilities. Positioning solutions need to be planned already in the beginning of the tunnel development.
• Dedicated short-range communication (DSRC) between vehicles will most likely be introduced in the coming years for the functions listed by the Car2Car Communication Consortium. Infrastructure managers can install specific Road Side Units (RSU) to enable communication between vehicles and road infrastructure. This concept is now being developed in a direction in which the cellular networks are also used to access some services.
• Cellular networks and mobile communications will be in a central role in the service provision to mobile devices and to support V2X communication.
• Cellular networks (4G/5G) and dedicated short-range communication (based on the 802.11p standard) are complementary rather than substitutes to each other. If the DSRC and cellular communications were properly combined, many new services would be enabled.
• Technologies enabling identification of goods and their properties are key for several C-ITS applications, especially for those related to dangerous goods. Although smart tags based on RFID have been in use for a while, this is an area that is still in its infancy and new solutions are expected to emerge.
• Future C-ITS must be interoperable, i.e., ensure seamless and secure exchange of data and access to data for all involved actors.
• C-ITS for road tunnels need to co-exist with other ITS-solutions and with vehicles without any particular ITS solutions.
• It is not viable to assume that all vehicles on our roads will have a connectivity solution in 2025. To obtain a high penetration level, future C-ITS should not only be possible to fit into new vehicles, but also vehicles that are already on the market.
• User-generated content will play a more and more important role in providing dynamic information. This will require new underlying business models and identification of incitements for (voluntary) data sharing.
• Massive data management, data fusion and data mining will be in the heart of many C-ITS applications. Development of such methods needs to be accelerated, with high emphasis on real-time requirements, extraction of relevant and dedicated information, and computing power. Cloud computing in its various forms provides solutions for the computing and data intensive tasks.
• Adoption of EU-wide regulations for management of data exchange and storage is a prerequisite for large-scale introduction of C-ITS.
• Development of methods for benefit estimation of C-ITS services before implementing them in a tunnel requires more attention in future research.
• Predictive modeling will play an important role both in normal and safety-critical traffic situations. Road users as well as traffic management, rescue and police teams would benefit from predictive information.
• Innovative, contextual and safe user interaction is one of the most important features of services in traffic context and new solutions utilizing, e.g., multimodal and ergonomic user interfaces are needed. In particular, augmented reality technology that enables information overlaying will play an important role.
• Nomadic devices (smartphones, tablets, etc.) provide a convenient way to interact with many of C-ITS services.
• Nomadic devices and in-vehicle displays should be seen as complementary to roadside information. The first two can be used to provide detailed and individual information, however, the most important/urgent information should also be displayed in the infrastructure. This is especially valid for safety-critical situations. In other words, roadside information will remain to be important, but the reliability of such information must be significantly improved.

8.1 Summary
Cooperative Intelligent Transportations Systems (C-ITS) have a great potential to improve traffic safety in general, and in long road tunnels in particular. Road tunnels are complex traffic environments where even small incidents can have large consequences. It is of utmost importance to prevent incidents from occurring, and the focus of future research should primarily be on utilizing C-ITS for that purpose.

• It is important to start exploring C-ITS on a national level (e.g. Sweden could become a test-bed for such functions). However, in the long term a EU-wide solution will be necessary. To avoid fragmentation, a generic and holistic approach is needed.
• A C-ITS solution for tunnels must provide a clear commercial advantage or some other type of return, especially for vehicle manufacturers, and/or be required by authorities. Future studies should explore how voluntary data sharing (cf. Waze) can be facilitated and incorporated into such solutions.
• Accurate, reliable and personalized information is becoming more and more desirable, and a future C-ITS should provide such information. This includes multi-lingual solutions that provide conclusive and useful information for each user.

On a final note, C-ITS discussed in this study should be seen as a complementary way of improving safety in road tunnels rather than a stand-alone solution. C-ITS for road tunnels cannot be considered as isolated solutions; they have to co-exits with the rest of the traffic and transportation system.
9 References


