COOPERATIVE ROAD TRAFFIC SIGNALLING – POTENTIAL COSTS, BENEFITS AND DATA EXCHANGE REQUIREMENTS

Version: Issue 2

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Executive summary

The cooperative road traffic signalling study is part of the DfT Horizons programme of research. DfT Horizons is an opportunity for innovative researchers to conduct ground-breaking work identifying and investigating areas where change in the external environment (e.g. technological advance, social trends, environmental or economic challenges) could affect the policies or operation of the Department. Projects in the Horizons programme look at ideas that could be applicable beyond the government’s 10-year plan.

The idea behind the cooperative road traffic signalling project is that vehicle control and management systems are becoming increasingly sophisticated with a wealth of information passing between components on in-vehicle data busses. Communications with moving vehicles are also developing so that in the future it will be possible to exchange data between the infrastructure and vehicles at very low cost. The project has examined the potential benefits of the use and exchange of information between intelligent vehicles and intelligent traffic signal control systems. In particular, the aim is to look ahead and provide the DfT with information on which to base its future policy for traffic signal control. Without that information it is possible that technological developments and the commercial interests of others, such as traffic signal systems and car manufacturers, would dictate the future direction of signal control. Furthermore design decisions about in-vehicle telematics devices would be made without any awareness or consideration of the needs for new control protocols that might be supported on the same application platform. In this way an opportunity to include new protocols at very low marginal cost would be lost.

The study has investigated a number of concepts that could form the parts of cooperative control systems. Benefits have been quantified as well as potential risks. Costs have also been assessed. However, the cost of implementing these new protocols will vary enormously according to whether or not they can be hosted on platforms that will be implemented primarily for other purposes. Investigation into other related development indicates that it is highly likely that cooperative traffic control could be implemented on the back of other developments, which makes the business case far more attractive.

In summary, we have concluded that many of the ideas for cooperative traffic signal control identified in this study would appear to offer real benefits in improved efficiency of junction signalling and green waves. There are concerns about drivers abusing some use-cases that we have considered, such as advance notification of impending signal change, unless a strict enforcement scheme is provided. Introduction of these controls would require governmental policy decisions.

One instance where large benefits would be obtained by preventing system abuse is in preventing red-running at traffic signals. The combination of cooperative traffic signal control and external vehicle control has been estimated to have the potential to reduce costs due to accidents by up to £125M per annum. Further benefits are predicted where different movements on an approach are signalled to start at different times, e.g. right-turning vehicles start before the straight-ahead movement. False starts would be reduced by providing customised information to drivers on which movements are about to start. Further benefits would be obtained by external control preventing vehicles starting to move that will not proceed in the permitted direction.

Use of probe vehicle data is also predicted to have the potential for large benefits. It would be used to tune the parameters in existing dynamic traffic control systems, but the largest benefit is predicted to come from using the data to identify exit blocking due to problems downstream from a junction. Some of the benefit would come from allowing the signal control systems to respond better to partial exit blocking, but a larger benefit is expected from the ability to identify and quantify problems to justify action to reduce the basic problem. For example, to target parking enforcement teams to locations where illegal parking is having a particularly serious effect on traffic movements.

Temporary traffic signals are often a cause of frustration to motorists when they can be clearly seen to be operating inefficiently. Probe vehicle data would allow signals to automatically adjust to the demands of the site where they are currently in use and control vehicles efficiently saving both delay and frustration.
It is recommended that the requirements for cooperative traffic signal control are embedded into related developments of in-vehicle telematic platforms, floating-car data gathering systems etc, rather than invest in a dedicated capability. In this way it should be possible to phase-in enhancements as the penetration of suitably equipped vehicles reaches levels at which correct operation of these advanced control systems is possible. It is also noted that some of the benefits from cooperative traffic control can only be achieved by a step change to vehicle operations where all vehicles are required to operate in a new way at intersections. It is important that in-vehicle telematics units that will be installed in the intervening period will be able to support the cooperative control applications should a decision be taken to deploy them at some future date. In principle it would be possible to update the applications running on all these in-vehicle systems to provide a new set of capabilities that could then all be turned on at the same time, to allow a step change to be implemented.

A number of targeted follow-on actions are recommended to ensure that current developments take account of the requirements of cooperative traffic control so that the benefits from those systems will be delivered in a cost effective and timely way.
1 Introduction

The cooperative road traffic signalling study is part of the DfT Horizons programme of research. DfT Horizons is an opportunity for innovative researchers to conduct ground-breaking work identifying and investigating areas where change in the external environment (e.g. technological advance, social trends, environmental or economic challenges) could affect the policies or operation of the Department. Projects in the Horizons programme look at ideas that could be applicable beyond the government’s 10-year plan. The idea behind the cooperative road traffic signalling project is that vehicle control and management systems are becoming increasingly sophisticated with a wealth of information passing between components on in-vehicle data busses. Communications with moving vehicles are also developing so that in the future it will be possible to exchange data between the infrastructure and vehicles. The project has examined the potential benefits of the use and exchange of information between intelligent vehicles and intelligent traffic signal control systems. In particular, the aim is to look ahead and provide the DfT with information on which to base its future policy for traffic signal control. Without that information it is possible that technological developments and the commercial interests of car manufacturers would dictate the future direction of signal control. Indeed, lack of convergent thinking may result in developments of vehicle and infrastructure “intelligence” moving forward in isolation with no coordination. In this way the opportunity to move to a common architecture that would support cooperative signal control would be lost.

This is the final report from the project. One of the requirements is to identify potential policy issues that might be of interest to DfT. Section 2 summarises the policy issues that have been identified throughout the different stages of the project and when considering the components of a cooperative traffic signalling system. The conceptual architecture is then described in section 3. The project has considered various components of a cooperative traffic signalling system. The interactions between components and development paths are summarised in section 4. Possibilities for using cooperative signals for demand management are considered in section 5, followed by the analysis of the potential individual operational modes in sections 6 to 17. Section 18 considers a futuristic concept of virtual traffic signals, which could be one way of avoiding fatalities at junctions, and indeed could be extended to protect vulnerable road users. The objective of this section is to consider compatibility with the other concepts rather than a detailed analysis. Section 19 considers the requirements for an in-vehicle system to support these operational modes. Section 20 reviews options for determining the vehicle location, and Section 21 explores communications options. The implementation costs are considered in Section 22, and the overall business case is considered in the Conclusions, Section 23. Section 24 presents recommendations for follow-on activity as a result of this project.
2 Policy issues

An important objective of the Horizons programme is to alert DfT to potential policy issues, both in terms of developments that may give rise to policy issues and to potentially desirable developments that may not happen unless there are enabling actions in the public sector. The various policy issues arising throughout the project have been brought together in this section. It is an important part of the Horizons programme that potentially worthwhile developments are not overlooked or prevented because of lack of action. The identification of enabling actions that are required to allow particular developments is, therefore, particularly important. In this study we have identified a number of policy issues that would need to be resolved if the cooperative traffic control is to be taken forward. Whilst this study helps to set the scene for policy issues in relation to cooperative traffic signals, it cannot consider the wider aspects that would have to be taken into consideration to understand these policy options fully nor can it make recommendations. Further working is suggested in the recommendations section.

One enabling action required from the public sector has been highlighted by the conceptual architecture through considering the element “Static Infrastructure Information.” That information will need to include details of traffic signal locations and operation for cooperative traffic signalling to be a viable proposition. As noted below, a good static infrastructure inventory may also be needed for other applications.

2.1 Static infrastructure inventory

To enable the cooperation of intelligent vehicles with an intelligent infrastructure there is a need for a database describing the infrastructure, effectively an electronic inventory of the road network with the location of junctions, method of control and location of stoplines. Private sector suppliers of map databases are providing increasing detail in their products as dictated by the needs of their clients. Typically for navigation systems the locations of junctions are required together with a description that can be used in the navigation instructions, e.g. “Turn right at traffic signals in 200m.” The details of the signal staging and positions of stoplines will not be required. It would appear likely that details of signal operation, such as the time of operation of peak only right-turn stages, would only be kept up to date if the highway authority takes responsibility for supplying the information.

It should be noted that the “highway authority” is not a single body for the whole country. In any one area the local authority, County Council, Unitary Authority, or London Borough will be responsible for traffic signals on local roads, but the Highways Agency and Transport for London are responsible for signals on the primary route network. Therefore, an arrangement is required not only for an individual Highway Authority to maintain an electronic inventory of its signals, but also to link those individual databases or to amalgamate them in some way.

The issue of speed limits is not so directly relevant to cooperative traffic signalling, but it is worth noting that a database of speed limits would also probably be best maintained by the highway authorities responsible for setting the limits. Speed limit data is of use to route guidance systems and essential for systems such as Intelligent Speed Adaptation, that help, or force, drivers to obey speed limits.

2.2 Implications from individual concepts

There are several ways in which information passed between vehicles and the infrastructure could be used within a traffic signal control system:

- Modify signal timings to cater for individual (probably bad) driving
- Take enforcement action on red running
- Take control of vehicles to prevent red running
- Modify signal timings in response to information from vehicles on their projected behaviour
• Modify signal timings in response to information from vehicles on adverse road conditions
• Modify signal timings for different types of vehicles
• Inform drivers and/or vehicles of coming signal changes
• Optimise signal timings for the proposed routes of vehicles

The policy implications of the various possibilities are explored in the following sections. One factor that is always of concern when information is exchanged is that privacy may be infringed. Most of the information that it is proposed to extract from individual vehicles will be anonymous, relating to the type or behaviour of the vehicle without identifying it. The exception is for enforcement action, when the vehicle and/or the driver will need to be identified, in the same way that the vehicle registration number is read from the images recorded by red light enforcement cameras.

2.2.1 Modify signal timings to cater for individual (probably bad) driving

Individual events can have safety implications. For instance, some drivers do not always stop at the beginning of red. Equipped vehicles could calculate that a safety related incident is imminent and communicate the information to the signal control system to take appropriate action. For the red-running example, the control system could delay the start of green on opposing phases. The policy question is:

• Is it acceptable to take action to attempt to reduce the safety implications of the actions of individual drivers where there is a danger that responding may make such behaviour more likely in the future? Enforcement of all such offences may be sufficient to keep such abuse to a very low level, so that it does not create a problem. (see below).

2.2.2 Take enforcement action on system information

The combination of infrastructure and in-vehicle information could provide evidence of bad driving. The most likely example for a traffic signal system is of drivers not stopping for a red signal or not stopping in response to an amber signal, when it would have been possible to stop without a significant risk of causing an accident. Similarly, advance notice of green, or just the perception that there is no other traffic using the junction may cause the driver to start on Red. The policy issues to be decided are:

• Is it acceptable to use system information for enforcement purposes? The normal privacy safeguards would have to be overridden when enforcement action was taken.
• Will there be any exemptions from automatic enforcement? Diplomats? Emergency vehicles, without blue lights activated? Emergency vehicles with blue lights activated, when the system could ignore the offence?
• If enforcement is acceptable, is it then acceptable to provide drivers with information that they might abuse? See, section 2.2.7 on providing advance information of losing right-of-way, for example.

2.2.3 Take external control of vehicles to enhance safety

In theory, with suitable equipment, traffic signals could be automatically obeyed by vehicles without intervention by drivers. There are, however, considerable liability and public acceptability issues. External vehicle control at traffic signals could be implemented in stages, for example:

• Prevent vehicles starting up from rest in such a way that they could not cross the stopline before the start of green.
Enforce a stop for a red signal when a stop can be achieved with a maximum braking level of $x$, where $x$ is believed to be acceptable to most drivers, and there are no closely following vehicles.

The policy issues to be decided are:

- Is it acceptable in any circumstances for an external system to take full control from the driver in such a way that the driver cannot override the external control?
- Is it acceptable in any circumstances for an external system to take partial, e.g. speed, but not steering control, from the driver in such a way that the driver cannot override the external control? In particular, is loss of partial control likely to be more confusing and potentially dangerous for the driver than loss of full control?
- If there are circumstances in which external vehicle control is acceptable, what are the limits, if any?
- If an incremental approach to external vehicle control is adopted, do the ultimate limits of that control have to be publicised at the start?

2.2.4 Modify signal timings in response to information from vehicles on their projected behaviour

It is possible that a vehicle could inform the control system that it is going to stop at red signals and that information could be used to reduce the stopping amber, where all vehicles that could be affected have confirmed that they will stop. The policy question is:

- Is it acceptable to shorten the safety related intergreen period in response to information from vehicles?

2.2.5 Modify signal timings in response to adverse road conditions

The project has investigated the technical issues of the reliability of being able to predict road surface conditions from in-vehicle information and the scope for accident reduction from modifying signal timings appropriately. The technical issues do not provide a strong case for action, but the policy issues should still be noted. They are:

- Is it acceptable to vary intergreen times in a way that means that drivers may not know what to expect? N.B. Speed assessment and discrimination systems currently extend the intergreen in some circumstances.
- Driver response – is it acceptable to operate signals in such a way that irresponsible drivers may take the message that they need not modify their driving in adverse conditions when approaching signals as the control system will look after them?

2.2.6 Modify signal timings for different types of vehicles

There are several potential ways that signals could be modified because of the presence of particular vehicles:

- Extend the green time to prevent stopping particular vehicles at the start of red, e.g. a slow vehicle because it would delay the discharge of vehicles at the start of the next green.
- Optimise the signal timings based on the mix of vehicle types and / or occupancies
- Provide universal priority to selected vehicles, e.g. emergency vehicles when their blue lights are switched on.

Some of the consequent policy questions listed below are not new and already need consideration:
• Are there any limits on what level of priority is acceptable for particular vehicles?
• What are suitable criteria for optimising signal timings – People? Total value of occupants’
time? Full economic costs, occupants plus vehicles? How to include non-equipped vehicles,
including cyclists, and pedestrians?
• How to decide who should be entitled to what level of priority? – N.B. there could be
analogies with the high publicity case about whether an ambulance driver was entitled to
break the speed limit when delivering a transplant organ rather than a whole person.
• Is it acceptable for individuals to purchase priority?

2.2.7 Inform drivers and/or vehicles of coming signal changes
There is evidence that some drivers respond in an inappropriate way to information on the future
actions of control systems. For instance, when information has been provided that an approach is
about to lose right-of-way, to allow drivers to slow down in comfort, some drivers accelerated to try
to beat the coming signal change, while providing information that green will start soon may lead to
some drivers starting to move too early. The policy issues relating to the ability to abuse information
are:
• Is it acceptable to provide information to drivers that could be abused?
• Is it acceptable to provide such information just to vehicles that are equipped to respond
appropriately and their drivers are, or are not, allowed to override the external vehicle
control?

Good traffic responsive signal control systems are more efficient at controlling traffic than are fixed-
time systems. However, they are limited by the information available to them; they cannot accurately
predict the effect of signal changes on vehicles that they do not have current information on. Current
information can only be available from a point in advance of the signals from which the arrival at the
signals can be reliably predicted. Current systems have detectors positioned as far in advance of the
signals as can be economically justified and from which the journey time can be predicted. For
instance, SCOOT detectors are normally placed just after a junction to predict arrivals at the next
junction.

A consequence of the limited time horizon of the demand data is that decisions should be made as late
as possible before a stage change may happen, in order to make most use of the available information.
Consequently it is not possible with current efficient control system to provide reliable advance
information on signal changes. The policy questions are:
• Is it acceptable to warn drivers that they will be losing right-of-way sometimes, but not at
others. Drivers would not be able to predict whether they should expect a warning or not?
• Is it acceptable to reduce the efficiency of the control system in order to be able to
consistently warn drivers of forthcoming stage changes?

2.2.8 Optimise signal timings for vehicle routes
Information on the proposed routes of vehicles is potentially available from vehicles equipped with
route guidance systems, when the driver has chosen to enter journey details into the guidance system.
It is not anticipated that full information will ever be available; even if all vehicles are equipped, some
drivers will not bother to enter journey details for short familiar trips.

The principal policy issue will be how to reconcile the desire of route guidance providers to use all
roads in the network and the objective of the network operator to encourage vehicles to use the most
“appropriate” roads, e.g. avoid residential roads where possible. There will need to be some
cooperation between the network operator and the route guidance providers.
The network can be used most efficiently if the traffic signal timings are optimised to match the traffic on the network and, theoretically at least, the optimisation will be improved by taking advance information from vehicles about their future routes through the network. Such advance information cannot be obtained from normal vehicle detectors. The degree to which the routes chosen by the in-vehicle guidance system accord with the policy makers preferred use of the network will depend on the level of cooperation between the route guidance providers and the network operator. There may be a need for the cooperative signalling system to adjust its response to route guidance information if the route guidance does not agree with the policy for use of the network. Specific questions are:

- How is the road network to be classified and what influence should the class of a road have on its use within a route guidance system?

- If there is not good cooperation with all the route guidance providers, how is the balance between using route information from vehicles to maximise the efficiency of the traffic control system and the use of the different classes of roads to be specified? E.g. make the value of one unit of delay depend on the road class.
3 Proposed conceptual architecture

The conceptual architecture developed in the project and proposed for cooperative traffic signalling is shown below in Figure 3-1. Analysis of the individual concepts is required to determine which calculations are undertaken in the infrastructure signal control algorithms and which in the vehicle component of intelligent signalling systems. The analysis will also determine the security and integrity required for communications of each item of information.

![Figure 3-1: Conceptual architecture](image)

**Glossary**

- **ABS**  Anti-lock Braking System
- **AGNSS** Augmented Global Navigations Satellite System
- **CALM** Emerging communications protocol
- **CAN** Car Area Network data transmission protocol
- **ECU** Engine Control Unit
- **ESP** Electronic Stabilisation Programme
- **HMI** Human Machine Interface
- **ITS** Intelligent Transport Systems
- **Temp.** External temperature sensor
- **Trans.** Transmission system (indicator of status, e.g. gear selected)
The architecture shows the systems within the infrastructure and within the vehicle. Cooperation is shown as being implemented via a combination of short-range and long-range telecommunications technology. In practice these would probably be connected via the emerging CALM protocol.

3.1 Comparison with draft ISO standard

Many of the functions of cooperative traffic signal systems are specialised uses of probe vehicle data. In addition, the proposed architecture includes the capability to transmit enforcement data. Because much of the use of the proposed architecture will be for probe vehicle information it is compatible with the ISO draft “Vehicle probe data for wide area communications” ISO/CD 22837 developed by ISO TC 204/ WG16 (ISO 2004). That standard emphasises the need for probe vehicle data to be anonymous and not contain information that could identify the vehicle. The proposed data exchange for cooperative traffic signalling as detailed in the following sections does not include vehicle identification for any data that is to be used for traffic signal control.

The use of data for automatic enforcement of red-running offences in section 11 does require explicit and auditable vehicle, or driver, identification information. However, enforcement information is not probe vehicle data. The proposed ISO standard does include provisions for non-probe information, such as data related to the need for the vehicle to be serviced, to identify the vehicle. The use of the cooperative traffic signal architecture for enforcement purposes is another use of the provision in the ISO standard for identifiable data to be transmitted for non-probe purposes.

The ISO draft allows for commands to be transmitted from the infrastructure to probe vehicles. Some of the proposals in this study, such as the estimation of saturation flow in section 13.2 and the detection of exit blocking in section 15.2, require more detailed commands than are given in the examples in the standard, but nothing in the standard excludes such commands.

The architecture shown in Figure 3-1 has two elements, “ITS Apps. Processor” and “HMI” that are not included in the draft ISO standard, as the scope of that standard is limited to collecting data from the infrastructure and not presenting the results back to drivers. In the standard, the “Probe message generation” module is responsible for interpreting commands for data from the infrastructure to the vehicle. The explicit provision of the, “Vehicle component of intelligent signalling system” module in the proposed architecture emphasises that the control of the vehicle can be affected by the new system, whereas a pure probe vehicle application will only take information from the vehicle and not affect its performance.

It was not proposed that this project would define the format of data packets to the same level of detail as the ISO draft. That draft may be consulted for information on the size of the data packets, including header information.

3.2 Information available

3.2.1 In the infrastructure:

- Static Infrastructure Information: road network, location of stop lines, conflict areas in junctions etc.
- Probe vehicle data
  - Processed data including trend information: time & day demand predictions based on historic data analysis; current climate; surface conditions; overall current demand
  - Raw data, short-term information from individual equipped vehicles
- Signal Control Algorithms output: Current and future signal status
- Existing data from conventional vehicle detectors
The Infrastructure shows the use of long-range communications to collect probe data, but this can also be collected over the short-range communications system. The short range communications is used primarily to collect time stamped data from individual vehicles. These data can be used to extract probe data but are primarily used to collect specific data for immediate use by the signal control system. The signal control algorithms also take account of static data on the intersection topology and configuration, and the overall demand and environmental conditions data collected from probe vehicles. Appropriate information about forthcoming signal changes, recommended speed for green waves etc will be passed to vehicles via a short-range communications system.

3.2.2 In an individual vehicle

- From the Augmented Global Navigation Satellite System (AGNSS) location system: vehicle position, velocity and possibly acceleration
- Current actuation of vehicle controls, indicators and ancillary equipment
- Processed information, e.g. road surface condition from a combination of sensors and systems ABS, ESP, wipers, temperature, possibly associated with road features (such as roundabouts) by using the GNSS input and map-matching

The vehicle architecture shows the provision of a dedicated Intelligent Transport Systems (ITS) bus. This provides connection between the AGNSS, the map-matching and route navigation, human-machine interfaces, and a link through to the CAN bus which gives access to standard-build systems such as: Antilock Braking System (ABS), Electronic Stabilisation Programme (ESP), Engine Control Unit (ECU), Transmission management, Turn Indicator, Wipers, Temperature, Headlights etc.

3.3 Accuracy of location information

Some of the concepts require highly accurate location information. The vehicle’s position must be reliably known to less than a metre. Developments of satellite navigation, such as the European AGNSS system EGNOS (European Geostationary Navigation Overlay Service) and a little further into the future the Galileo project will improve its accuracy. However, to provide reliable locations in all situations including urban canyons, satellite navigation will need to be supplemented. Map matching and inertial navigation in the vehicle is one possibility, as is taking location information from dedicated short range communications systems. It is assumed in this report that reliable and accurate location will be a standard fitment by the time that cooperative traffic signal systems can become operational. Location technology is further considered in section 20.

3.4 Longer term architecture migration

One aspect of the project has been to consider the control system requirements that might be required to accommodate the Swedish Vision Zero concept of avoiding all deaths from road traffic accidents. The objective of considering Vision Zero is to avoid recommending developments that could inhibit progress towards the goal of eliminating deaths on the road. The project has built on the Vision Zero idea, but has not used any of the architecture or designs from Sweden.

Vision Zero might require that all vehicles be fitted with cooperative safety systems that would be able to take control of the vehicle from the driver in order to prevent an accident. For the concept to be successful and acceptable, the automated systems (including status assessment, context analysis, communications, accident avoidance management and actuation) would have to achieve a better, more reliable performance than could be achieved by an experienced and competent driver.

The architecture might need to be enhanced to accommodate interaction with vulnerable users and non-equipped vehicles as shown in Figure 3-2. This requires the provision of an interactive pedestrian unit (that can also be used by cyclists, horse riders etc.) The longer term architecture increases the amount of control provided within the vehicles, using shared information, and cooperation algorithms.
The pedestrian unit would contain, as a minimum, an AGNSS module and map matching to enable the precise location of the pedestrians to be known, and risk to be assessed based on the context of their locations. The unit would enable pedestrians to indicate their wish to cross the road, and an indication to them of when it is safe to cross the road. The pedestrian unit would interact with the infrastructure in an urban environment, but would need to interact directly with vehicles in rural areas, and sometimes in urban areas.

Figure 3-2: Vision Zero conceptual architecture
4 Overview of individual cooperative signal concepts

The provision of a communications link between the status and command systems in individual vehicles and traffic management and control systems in the infrastructure would enable a diverse range of novel applications to be implemented. In general these applications will not be entirely independent, but will build one upon the other. The concepts are presented in the following sections, in an order which allow the incremental build to be understood.

Figure 4-1 introduces the different concepts, and highlights aspects of the information flow. The traffic signal control system is labelled as UTMC, however, the concepts are not limited to coordinated systems, isolated signal control systems and temporary traffic signals are considered alongside coordinated ones. Information flows include:

- Vehicle status and driver intention (control operation) information collected from the vehicle and information such as demand data, road conditions, downstream problems derived from the raw data (Colour-coded Light Green in Figure 4-1)
- Status and planned signal change information from the control system to individual vehicles. (Colour coded Dark Green)
- Command and Control messages from the traffic control system to individual vehicles (colour coded Red)
- Status and permission information transferred directly between vehicles (shown Dark Blue in Figure 4-2)

![Figure 4-1: Inter-relationship of cooperative signalling applications](image-url)
Probe Vehicle data can include:

- Origin & Destination
- Speed
- Link transit times
- External Temperature
- Precipitation
- Use of headlights
- Areas of slippery road surface

This can be processed in a statistical way to derive:

- Demand Statistics
- Areas where there are potential hazards (rain, ice, slippery conditions, poor visibility etc)
- Traffic flow blockages, which might present problems downstream of a junction, and need to be accounted for when optimising signalling.

This information can be used to manage the road network by setting warning signs, speed limits, sending out maintenance teams, and feeding into junction control systems.

Additionally, information from an individual vehicle may be used locally at the junction:

- Driver’s turn intentions
- Route-guidance systems recommended route
- Vehicle classification
- Any priority that has been allocated to the vehicle.
- Assessment of whether a vehicle will stop at the junction, or will attempt red-running.

The Traffic Control and Management system will be able to use this additional information to:

- Optimise the signal operation, using conventional traffic signals (traffic lights).
- Use the data gathered to control temporary signals efficiently, where no loop data is available.
- Exploit the additional ability to signal specific information to individual vehicles, eg to warn them of an impending loss of right of way, or to confirm that a green-wave is in operation, or to pre-warn of the timing of a change to green.
- Add a command and control capability to prevent red-running, and early starting, in order to prevent misuse of this information.
4.1 Virtual control systems

Ultimately cooperation between vehicles and the infrastructure could lead to a concept of virtual traffic signals. Figure 4-2 shows a vision for a de-centralised method of controlling traffic, whereby all road users negotiate with nearby road-users and grant each other permission to take priority at junctions, or crossings. This shows the inclusion of pedestrians with active interfaces to identify themselves to vehicles and the control system. Signals to operate such a system are shown dark blue. A connection to the infrastructure control system is shown for completeness, although it is arguable that, ultimately, there would be no central control system at all.

![Diagram of virtual traffic signals](image)

**Figure 4-2: Direct co-operation and negotiation between all road users**

4.2 Potential uses of cooperative traffic signalling systems

The individual concepts that could be included in a cooperative traffic signalling system are described in the following sections. The concepts and section numbers are:

5) Use for demand management – This section does not refer to a single concept, but looks at all the possible ways that cooperative signalling could be used as part of a demand management system.

6) Use of route information – Again, not strictly a single concept, but looking at the usefulness of route information for traffic control in normal and abnormal conditions.

7) Information to vehicles that they will lose right-of-way – Warnings to drivers and further in the future external vehicle control
8) Information to vehicles about start of green – Considerations as for loss of right-of-way

9) Green wave information to the vehicle – The advantages and disadvantages of aiming for smooth progressions on major routes

10) Use of vehicle stopping information – Is it possible to use information that individual vehicles will stop to improve efficiency

11) Response to red runners – Reducing the propensity to red run and the accident risk

12) Prevention of red running – External vehicle control

13) Probe vehicle information – Use of probe vehicle information to optimise signal control parameters

14) Response to information about slippery roads

15) Response to downstream problems – enhanced detection and response to exit blocking

16) Temporary signals – using probe vehicles to improve the control at temporary signals

17) Vehicle class information – using information about individual vehicles to determine the priority that they are given

18) Virtual traffic signals
5 Use for demand management

One aspect of managing traffic is to modify the demand for travel by particular modes, possibly just at particular times. In this section we consider the scope for using a cooperative signalling system for demand management. The control method available to a cooperative signalling system is that provided by traffic signals, supplemented by on-street Variable Message Signs (VMS) and in vehicle information displays. There would be potential for much more granular control of vehicle movements.

Classically, specific vehicle movements may be forbidden for specified times; the time during which a red aspect is shown to vehicles wishing to make the movements. Traffic signals are already used in some circumstances as limited restraint tools, for example by employing the SCOOT gating facility. The advantage of cooperative signalling systems is that the restraint could be targeted at specific vehicles.

There are, however, difficulties with targeting restraint measures.

- It is very difficult to delay an individual vehicle without also delaying all the following vehicles.
- If certain vehicles are to be forbidden from using a section of road, then there needs to be an escape route for drivers who ignore the warnings and find that they have reached a point that they are not authorised to pass. They need to be able to turn round without causing undue delay to other road users.
- The use of information from a vehicle to instigate a restraint measure to restrict the operation of that vehicle, or delay it on its proposed route is unlikely to be acceptable. Drivers will be reluctant to provide any information that can be used to their disbenefit. Obtaining the information for a service that benefits the driver, but also using it for restraint purposes will cause resentment.
- Alternatively the information from the vehicle could be used to allow it through access control restrictions. Such a white list, rather than a black list, procedure is likely to be more acceptable to the drivers of equipped vehicles, but could be politically difficult as it could be castigated as the rich, who can afford the equipment, buying privileges over other motorists.

There are several scenarios in which cooperative signalling could be used as a demand management tool as described in the following sub-sections.

5.1 Prevention of rat running

Highway authorities try to prevent rat running, drivers choosing to take inappropriate routes through sensitive areas, e.g. commuters avoiding queues on a main road by diverting through residential streets. Several control techniques could be implemented based on cooperative signalling:

- Extended red signals in the rat run direction could be used to increase the delay to rat runners at traffic signals, which would make the use of the rat run less attractive, motivating choice of another route. However, valid users of that route would also be delayed, unnecessarily.
- The navigation system in the vehicle could interact with the infrastructure to determine whether a particular route could be used, before presenting this route to the driver. However, existing navigation systems do not have this capability, and drivers would be unlikely to upgrade to a new system that did not offer them the optimum routes.
  - Each decision point, a point at which it is desired to classify vehicles as rat runners or approved, in the network would have to be specified and status updated during the day.
  - For each decision point a database of valid origins would be required to identify approved vehicles.
The database of decision points and valid origins would have to be maintained. A potentially onerous task with modifications to the network and new developments.

- A policy would be needed to classify unequipped vehicles as rat runners – unauthorised to use that route (this would motivate people to upgrade their systems)

When all the systems have been set up to reliably identify rat runners and approved vehicles there is still the problem of applying selective restraint. It is highly unlikely that it will be practical to separate vehicles into two streams, rat runners sent to queue and approved vehicles directed along an undelayed route. Drivers will not willingly obey such instructions and there is unlikely to be sufficient road space to allow such separation to work efficiently. Therefore, restraint is likely to have to be imposed on a mixed traffic stream containing both rat runners and approved vehicles. What action should be implemented?

- Restrict the green whenever rat runners are detected in the queue?
- Assess, over time, the proportion of rat runners by time of day and impose suitable timings for average conditions?
- Modify the level of restraint depending on the current proportion of rat runners in the queue?

Whichever method is adopted, non-rat runners will be penalised at some times. The more reactive method will selectively disadvantage equipped rat runners, not the best way to encourage take up and use of the equipment!

The problem of rat running of long haul traffic via residential areas is similar to the problem of restricting entry to sensitive areas.

Route information could be used to identify when an undesirable volume of traffic is approaching a sensitive area and the system could then impose restrictions. The idea is basically the same as SCOOT gating where conditions in the sensitive area are used to trigger the restraint. The advantage of using the cooperative signalling system is that earlier warning of the approach of an excessive volume of traffic could be available. There would be the same problems as with gating of finding somewhere to store the excess traffic and the possibility of also inconveniencing traffic not heading for the sensitive destination. It would be better than gating in that it could predict the overload, rather than have to respond to build up in the sensitive area by which time too much traffic could have passed the restraint points. However, there would be resistance if the action is seen as using information from vehicles to initiate action that will delay those vehicles. Careful design and selling of restraint systems can result in successful and acceptable schemes. The Bitterne Road scheme in Southampton is an example of using traffic restraint to redistribute delay and at the same time provide bus priority. SCOOT gating to prevent lock-up of the gyratory in Kingston-upon-Thames resulted in an overall reduction in delay despite imposing delay at entry points. Cooperative traffic signalling would allow some refinement of such schemes, but there have been few examples to date where engineers have been able to design readily acceptable traffic restraint.

5.2 Extended delay at traffic signals

Junctions would have to be provided with two queuing lanes: one for authorised vehicles and one for unauthorised, delayed vehicles. The lanes would need to be long enough to avoid the queue of delayed vehicles delaying authorised vehicles. External vehicle control would probably be needed to avoid drivers joining the wrong queue to reduce their delay. The impact of this approach has been discussed above.
5.3 Access control

Information from the vehicle that it is entitled to access could be used for direct operation of access control equipment. Systems to perform this function already exist, using various methods: vehicle transponders and special detector, automatic number plate reading equipment coupled with a white list of permitted vehicles etc. The advantage of operating through a cooperative traffic signalling system is that no new equipment would be needed on the vehicle and the communications and infrastructure would be part of the standard implementation. One way to operate would be to have a white list of permitted vehicles in the access control system and the vehicle would have virtual detector points built into it to call for access when approaching the control equipment. Such a system would be no worse to set up in the vehicle than existing bus priority systems that use AVL, but, equally an existing AVL system could perform the same function with an appropriate link to the access control system.

An interim stage might be to use automatically controlled rising bollards with:

- associated traffic signals at the gated entry point
- an effective escape route
- VMS information at the upstream junction to minimise the number of unauthorised vehicles approaching the access control

Signal control at the junction would need to take account of the changes in flow from the use of different access control policies at different times. Approaching valid users would be detected and the traffic signals would insert an appropriate stage when needed by an authorised vehicle.

Each driver who wanted to use the controlled route would need clear information on whether they were allowed to enter the access-controlled zone. Traffic signals in isolation would not be able to convey this information. Variable message signs could announce which classes of vehicle could use the route at that time, however, this would introduce the complication of the driver recognising whether his vehicle fell into one of the allowed categories, and distraction may become an issue.

5.3.1 Effects of fitment level

All vehicles wishing to benefit from access control would have to be fitted with the cooperative signalling equipment.

Treatment of rat runners and limiting traffic approaching sensitive destination are two examples of restraining particular vehicles because of their choice of route and time of travel. The reliability of identifying origins and destinations is considered in more detail in section 6.3. Good dynamic traffic restraint will require at least 50% of vehicle to be equipped.

5.3.2 Authorised vehicles

Residents or employers based in a protected area would be able to enter the detail for their vehicles and their guest and employees. These vehicles would remain valid for a period of up to a year, and would prompt the person who registered these, before they are taken off the system.

Block exemptions would be given to certain classes of vehicles such as: emergency services, utilities, public transport, taxis, delivery vehicles (up to a weight limit).
5.4 Vehicle tracking and enforcement

Physical access control should prove to be a temporary measure. In the long term (20 years +) virtually all vehicles would be fitted with a telematics platform that would enable the vehicle to be identified by the infrastructure and for permission to use a particular route to be displayed to each driver, according to that vehicle’s classification and authorisation.

At that point it would be possible to implement the access control policies that have been identified above by communicating the correct route for the driver to follow, and alerting the driver to any restrictions if he strays off the authorised route. Vehicles that use rat runs or other unauthorised routes will be detected and enforcement action can be taken.

This system would not require the installation of any access control hardware, but would require the development and maintenance of databases, and effective control strategies.

5.5 Road user charging

An alternative to firm access control systems would be to use a road pricing scheme that charged a significant premium for using the rat runs and sensitive zones. This would have a number of advantages:

- Specific vehicles could be authorised on specific routes at certain times
- Other vehicles would be discouraged from using unauthorised routes, but allowed to use these routes subject to payment of a premium. The premium could be varied to manage the number of drivers choosing to use the route.
- The collection of road user charges would be subject to commercial transaction rules, rather than requiring the gathering of evidential quality information to support the demand for payment of fines.
- The principle is very similar to the American HOT lanes, where High Occupancy Vehicles (HOV) are entitled to use higher speed lanes, along with other drivers who are prepared to pay a surcharge for using the lane.

5.6 Mandatory route planning

With highly granular dynamic road pricing it would be very difficult for the driver to make sensible decisions without becoming very distracted. One way round this is to mandate the use of a dynamic route guidance system which would ask the driver to enter their intended destination and required time of arrival. The system would advise the driver to start at a particular time and follow a cost effective route. Drivers might be able to request a choice of routes:

- Cheapest route
- Quickest route
- Cheapest time of day
- Optimum route (paying a premium to avoid major delays, but avoiding premium priced routes)

Without this tool, drivers would choose their own route, and only discover the cost of that route later. Mandating the use of dynamic route guidance would yield a significant number of advantages for network controllers. It would allow comprehensive analysis of Origin-Destination data, and would allow a central control system to take direct steps to spread the peak network load by offering specific discounts to drivers who accepted a different time of travel from the one initially requested.
5.7 Data needs

The data needs are very dependent upon the operational protocol that is to be used. The main requirements for the cases considered above are identified below:

5.7.1 Extended delay at traffic signals

Either short range or universal coverage communications technology could be used. Message transfer would be the same as for access control, because the entitlement of each vehicle claiming access right would need to be checked by a central controller.

5.7.2 Access control

Access control may use a short range communications with a roadside node, and on to a central control point, or may use 2G / 3G universal coverage. The vehicle identity and classification would be checked to make sure that it was properly authorised. In all cases there would need to be a control channel from the central control to the individual bollard.

5.7.3 Mandatory route planning

Drivers would normally pre-enter their route by a convenient method, e.g. from a fixed terminal via broadband, via a 2G or 3G cellphone, key in the data from the driver’s console in the vehicle etc. This process would use conventional communications. The system would presumably download waypoints. The vehicle would contact the central traffic control system at the way point to confirm the route choice to be followed. A few kilobytes of data would be exchanged in a non-time critical way. Way points would also be set to alert the infrastructure should a physical access control point be approached. If standard way points are defined for use along a particular route, then it would be possible to use short range communications to a communications node fixed at the way point. If it is necessary to be possible to fix way points anywhere, then it will be necessary to use universal coverage technology (such as 2G and 3G).

5.8 Conclusions

The potential for cooperative traffic signalling systems to be used for demand management in isolation is limited, not least because of the difficulty of selectively delaying a vehicle without also delaying following vehicles. However, the signalling may be part of a larger scheme, associated with variable message signs, and road user charging strategies, integrated into a dynamic route guidance system.

Access control could take advantage of cooperative signalling equipment and communications, but would only be feasible if all vehicles requiring access were equipped.

Restraint of traffic approaching sensitive areas could be made to act earlier than current systems, but only at high fitment levels and by using information from vehicles to restrain their progress.

Cooperative traffic signalling is unlikely to make it significantly easier to design politically acceptable traffic restraint schemes.

A number of approaches have been identified. A high penetration of equipped vehicles would be needed for implementation of a physical access control system to work. All vehicles would need to be equipped if virtual access control is to be implemented. A major problem is the acceptability of using information collected from a vehicle to impose restraint on its journey, or conversely to give advantages over other unequipped vehicles, which could be portrayed as buying privileges.

The most effective technique appears to be the introduction of a highly granular, dynamic urban road use charge supported by dynamic route guidance so that the driver can easily assimilate the route
options and understand the cost implications that would be used to motivate choice of the most appropriate route (in terms of its impact on society). This is a rich area for further research, and a further study is proposed in the recommendations section.
6 Use of route information

6.1 Concept
Intelligent vehicles will be able to provide information on their routing intentions in several ways:

- Full route information from in-vehicle route guidance equipment. Route guidance is not, however, expected to ever provide data for all vehicles. Even if all vehicles were equipped some drivers on short regular journeys would not bother to use the guidance for such a journey. Unless the use of centrally co-ordinated route-planning and dynamic route guidance is mandated as in the Demand Management use case above!

- Shortly before the junction from turn indicators (where used by the driver!)

- Vehicle location system, with or without a navigation system, could provide turn information after the manoeuvre has been performed. A full history of the route could be built up after the event.

The intelligent signal control system could use the information from route guidance systems as current information for its optimisation of timings. Turn indicators may be useable in the optimisation of turning movement stages. The data of what vehicles did could be used to build up O-D matrices for the junction to be used in the optimisation.

6.1.1 Unconventional junction control
Additional information could make it possible to operate a signalled junction in a more flexible manner than is possible with conventional vehicle detection. For instance, at a T junction with only room for one lane in each direction, a right-turn filter light could be used to allow a vehicle to turn right. The filter would only be used when a car is known to be waiting to turn right and is holding up traffic from behind. If the arrival of a vehicle that will turn is foreseen, then the sequence and timing may be optimised in ways that are not possible using conventional loop detectors.

6.2 Benefits and disbenefits

6.2.1 Congestion / delay
The aim of this concept is to improve traffic control by making use of more information than can be obtained from vehicle detectors alone. The Italian UTC system UTOPIA and the German MOTION system include routines to estimate Origin-Destination (O-D) information at junctions and then to use that information in the optimisation of the signal timings. The published assessments of the control systems do not attempt to isolate the benefit of the O-D estimation and provide no information on the benefit of using that information. It is hard to compare one UTC system with another unless they have been evaluated in the same network or both evaluated against a common base, usually up to date fixed-time plans calculated by TRANSYT. In addition, the objectives of one system may be somewhat different from another, with greater emphasis on priority for LRT for example. It is not, therefore, possible to definitely compare UTOPIA or MOTION against SCOOT, but there is no evidence from the existing evaluations that either reduces delay compared with SCOOT. The benefit, in terms of reduced delay under normal conditions, of using O-D information in signal optimisation, is not, therefore, considered to justify the cost of the development of a traffic control system to use that information.

O-D information does, however, have other benefits for traffic management. Good knowledge of O-D enables effective response to incidents. A working group considered the benefits of broadcasting traffic information in the late 1970s (TRRL 1979). Further work was done on the benefits of route guidance during traffic incidents at Southampton University (McDonald et. al. 1987). Up-rating the
benefits to current values of time (TAG, 2004) gives estimates of the potential UK wide reductions in delay from traffic incidents due to traffic broadcasting of £14M and from Dynamic Route Guidance (DRG) of £420M per year. The estimates for traffic broadcasting are of providing information to drivers about incidents and leaving them to respond as they see fit. The DRG estimates are considerably larger as they consider responding to more incidents, a threefold increase in the saving per incident from the positive guidance and an increase in the number and duration of incidents.

The use of O-D information in a UTMC supervisor, or similar system, linked to a cooperative traffic signalling system would allow the calculation of both appropriate diversion information and compatible signal timings. Motorway diversion strategies have been successfully used in the Kent corridor based on an on-line model (MOLA), but the motorway situation is simpler than the urban one, because of the fewer alternatives and no need to adjust traffic signal control.

There is no work that directly quantifies the value of a supervisor optimising both diversion routing and signal control. An incident will cause rapid, large changes in the traffic patterns. The normal responsiveness of dynamic control systems such as SCOOT may not respond rapidly enough, as they are designed to have a balance between stability and responsiveness that is suitable for normal conditions. Therefore, a supervisor will have advantages over existing systems of traffic control. In addition it will have better information than any individual DRG system on the condition in the network and could act as the source of rerouting recommendations for both equipped vehicles through their route guidance systems and via broadcasting and VMS to unequipped vehicles.

Based on the above arguments, it is considered that a cooperative traffic signalling and supervisor system could improve the management of incidents beyond the benefits from the best DRG systems. As an estimate of the potential benefits, it is predicted that cooperative signalling should produce additional delay savings in incident conditions of at least 1% of the estimated benefits of DRG for incidents and probably up to 10%. That is a benefit of between £4M and £40M per annum in the UK.

The O-D information will also be a valuable input into any strategic network control under non-incident conditions. There are various estimates used of the costs of congestion, but it is uncertain how accurate these are. It is also unclear how much congestion could be reduced by strategic management based on good O-D information. That information would provide scope for modelling to identify priority routes and roads for traffic management improvements, revised signal timings, targeted parking enforcement etc. The model would also provide opportunities to examine the benefits of active management to modify drivers’ routes and trip times. However, the actual benefits achieved would depend on the local network, traffic management expertise and available tools. Recurrent congestion causes considerably more delay than incidents. Therefore a similar benefit to that estimated for incident management, £4M to £40M should be a conservative estimate of the benefit.

The total benefit from both normal operation and response to incidents from using route information in cooperative signalling systems is estimated to be:

\[
\text{Benefit of reduced delay from using route information} = £8M \text{ to } £80M \text{ per annum}
\]

6.2.2 Environmental

Reducing delay will also reduce the emission of pollutants due to better vehicle operating conditions. The probable reduction in emissions can be calculated. The total of the value of time of the occupants and the operating cost for one hour of a typical vehicle is £14 at typical urban operating speeds (TAG 2004). Therefore, we can convert the value of the time saving into a number of vehicle-hours:

\[
£80M \text{ per annum} = 5.71M \text{ vehicle-hours per annum}
\]

Assuming that the reduction in delay arises from an increase in average speed from 10 mph to 15 mph

\[
5.71M \text{ vehicle-hours} = 171M \text{ vehicle-miles at } 15 \text{ mph rather than } 10 \text{ mph}
\]

Using emissions factors relevant to urban conditions the saving in emissions are shown in Table 6-1 for both the low estimate (£8M) and high estimate (£80M) of delay savings.
Table 6-1: Estimated emissions savings, tonnes per annum in UK

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>CO₂</th>
<th>HC</th>
<th>NOx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low estimate</td>
<td>41</td>
<td>1450</td>
<td>3.4</td>
<td>0.7</td>
</tr>
<tr>
<td>High estimate</td>
<td>410</td>
<td>14500</td>
<td>34</td>
<td>7</td>
</tr>
</tbody>
</table>

6.2.3 Safety

Relatively little change in accidents is anticipated, although the use of Automatic Incident Detection (AID) and display of warning information on motorway signs on the M1 resulted in an 18% reduction in accidents (Sommersgill et. al. 1998). The effect of the systems envisaged here would be much less than the benefits of AID on motorways as the effect would be to reduce queues from the incident by diverting traffic and modifying signal timings rather than alerting high-speed vehicles to unexpected queues ahead. Drivers expect queues on the approaches to traffic signals, although with incidents the queues can be in unexpected locations.

6.2.4 Social and accessibility

There will be community benefits to those affected by the reduced delay, but that benefit has already been included in the delay benefit by using the normal economic valuation of time savings. It should be remembered that although the benefit has been valued as a time saving, in principle, the reduction in delay could be used to improve conditions for a particular class of travellers, rather than to all vehicle occupants. For instance, pedestrian facilities, or bus priority may be enhanced without increasing delay to others. Without the improved efficiency of the control, such changes would result in increased delay to other vehicles.

6.3 Effects of fitment level

The fitment level to be considered is of vehicles fitted with both route guidance and a cooperative vehicle-signalling system. It should be noted that the market penetration may not be the same as the proportion of equipped vehicles on a particular link. If equipped vehicles are used more intensively than other vehicles then the proportion of equipped vehicles travelling on the network will be greater than the proportion of equipped vehicles in the national fleet. Other characteristics of how vehicles are used will also affect the proportion on any link. Van Aerde et. al. (1993) explored the possibilities. They also estimated the fitment level required to provide acceptable accuracy for estimating the current O-D flows in quarter-hour periods. Their conclusions was that for an estimate of the dynamic O-D flows where the RMS error of the estimate does not exceed 20% of the average observed O-D flow then a market penetration of 40% is required. This conclusion is specifically for a test simulation network at a reasonably busy time at the start of the morning peak. The test network included freeway and arterial links with typical North American flows.

For a supervisor system for non-incident conditions, a reasonably up to date O-D matrix is required. At the strategic level, the supervisor would be working to manage the network for average conditions. For incident response and management of day-to-day fluctuations in traffic levels current O-D demands would be required to provide full benefits. In all cases, precautions will need to be taken to avoid biased estimates due to equipped vehicles not being typical vehicles, for example they may be more expensive and starting points biased to more expensive neighbourhoods, or commuting journeys, which tend to start at different times from the average.

Using the figures from Van Aerde et. al. as a guide, we can estimate the penetration levels required for O-D estimation. For an O-D matrix for “typical” conditions, the data can be collected over several days and updated using smoothed average techniques. The standard error of the demand estimate for any O-D pair is inversely proportional to the number of observations. Therefore, collecting data over
a 10-day period (two working weeks) will reduce the standard error by a factor of $1/\sqrt{10}$, or about 1/3.

Such a reduction would give an RMS error of the O-D estimate that does not exceed 20% of the average demand from a fitment level of 10%.

Therefore, useful data for a non-incident supervisor will be available from fitment levels of about 10%, but for incident response systems, considerably higher fitment levels are required, 40% or above. There are two provisos that must be met:

- The origin and destination zones at the lower fitment levels will need to be defined to be major generators and receivers of traffic or the absolute numbers of equipped vehicles travelling between any pair, in a time period, may be zero or too small to be representative.
- Checks must be made to avoid bias due to different use characteristics of the equipped, probe, vehicles from those of the general vehicle fleet.

6.4 Data needs

For vehicles using route guidance information, route intentions would be transmitted. In principle, the whole route could be sent at the start of the journey, but the control algorithm will not be sufficiently accurate to predict the exact arrival time some miles ahead. Because of the unpredictability of detailed journey times it is not sensible to look further ahead than about 5 junctions. Therefore, the amount of data to be transmitted at any one time is unlikely to be large: turning movements at 5 junctions, with the locations of those junctions, vehicle’s current position and expected desire speeds. Route guidance systems estimate arrival times, it is possible that they already note typical speeds used by the driver on various classes of road to improve the accuracy of their predictions; it is certainly a possible way to increase the accuracy of the predictions from route guidance systems.

Transmission of information on the use of turn indicators would not require much data, but it would have a high timeliness requirement.

The route taken and turns made would not be onerous on the data transmission system, little data with a low timeliness requirement.

6.5 Conclusions

- Benefits are expected from improved possibilities for traffic management from estimates of O-D demand.
- A supervisor system would need to be built to use the information.
- Delay savings worth in the region of £4M to £40M are expected due to improved response to incidents. Similar savings are likely due to better routine management of the network.
- Emissions will be reduced due to the reduction in delay
- Benefits in non-incident conditions will be possible with fitment of coordinated signal systems and route guidance in 10% of the fleet.
- The benefits from unconventional junction control have not been estimated, but would give additional benefits.
7 Information to vehicles that they will lose right-of-way

7.1 Concept
Vehicles could be informed that the traffic signals will have changed against them before they arrive at the stopline, allowing a more gradual slowing to a stop than continuing at normal speed until the signals change. The information could be presented to the driver or implemented by the vehicle control system to enforce the stop.

7.1.1 Policy issues relevant to this concept
The policy issues relevant to this concept are included in section 2.2.7, Inform drivers and / or vehicles of coming signal changes

7.2 Benefits and disbenefits

7.2.1 Congestion / delay
There is likely to be little effect on the overall delay to vehicles from drivers’ reactions to the warning of an impending loss of right-of-way, but there will be winners and losers. Evidence from simulator experiments on flashing green lights to warn of an impending change and implementation of various types of advance warning systems show a greater degree of uncertainty associated with the decision of whether to stop (see for example Federal Highway Administration, 2003).

Where the system does not automatically manage the deceleration of the vehicle, the driver may respond to the new information in two ways:

- Those drivers who choose to stop, but would have continued if there had been no warning, will experience extra delay.
- Conversely drivers will experience less delay if they see the warning as a message to speed up so that they cross the junction where they would otherwise have had to stop.

A larger effect will come from the loss of efficiency in traffic signal control. UK control systems, SCOOT, MOVA and Vehicle Actuation using system D are designed to be efficient. They respond to traffic and immediately implement any decision to change stage. There is not a delay between the decision and implementation during which a warning of the change could be given. The effect of delaying implementing the decision will vary between control systems and, at least for SCOOT, with the length of the link. Some work has been done on the effect on SCOOT of data transmission delays forcing the system to make decisions early. The result of that work is that a few seconds of delay in implementing a decision (up to 4 seconds) would increase delay by around 1%. That does not sound much, but there are nearly 2000 signals on SCOOT in London alone. Assuming an average queue at traffic signals in the SCOOT controlled areas of London of 14 vehicles over a 10-hour period gives:

\[
1\% \text{ extra delay} = 0.01 \times 10 \times 14 \times 2000 = 2800 \text{ vehicle-hours per day}
\]

Taking 250 working days per year gives:

Cost of 1% extra delay during 10 hours on each of 250 days = £9.8M

Assuming typical delays at weekends of 60% of those during the working day and 20% average over the other 14 hours of each day gives:

Cost of 1% extra delay = £16M annually in the SCOOT controlled area of London

There will also be extra delay at signals controlled by MOVA and VA. The total number of signals in the UK and their method of control are not known exactly, but there are over 1000 signals in Greater Manchester and nearly 700 in the West Midlands under UTC control. As an indication of the likely
size of the extra delay at all signals in the UK, UTC and isolated, it would seem reasonable to multiply the estimate for the SCOOT signals in London by a factor of 4, giving:

Cost of extra delay due to less efficient control of traffic signals in UK > £60M per annum

These figures exclude the effects on pedestrian crossings, Puffins, Pelicans and Toucans where the situation is somewhat more complicated. To give drivers warning that they are about to lose right-of-way at a pedestrian crossing will mean that it will not be possible to give a quick response to a pedestrian pushing the button in some situation where that would currently happen. If there is an equipped vehicle within \( n \) seconds of the crossing, where \( n \) is the length of the warning, then the stage change cannot occur for \( n \) seconds. This will result in extra delay for the vehicle and the pedestrian (if the pedestrian waits for the invitation to cross).

The situation will be worse when the pedestrian chooses to cross without waiting for the delayed invitation to cross as vehicles will then be forced to stop for no reason. Much work has gone into the design of Puffin crossings to prevent this situation, but, if a warning to stop has been given, then the signals must change to prevent the warning being ignored in the future. Therefore, some of the efficiency of the Puffin crossing will be lost, a severe retrograde step. It is not considered sensible to attempt to calculate the cost of the extra delay as there will be large variability between sites depending on the vehicle and pedestrian flows and particularly because the effect will depend on pedestrians’ response. The increase in delay will depend on the extent to which pedestrians are prepared to wait for the delayed invitation to cross. It should be noted that the number of signal controlled pedestrian crossings is large. In the West Midlands there are about twice as many crossings as signal controlled junctions under UTC control.

7.2.2 Environmental

There will be a small benefit from those drivers who choose to use the information to provide an opportunity for an earlier, more gradual deceleration, but there will be an increase in emissions due to longer idle times for those who stop who would not otherwise stop. In addition there will be some increase from drivers accelerating and continuing at high speed to avoid stopping and a decrease from the same vehicles not stopping. The overall changes are expected to be too small to justify detailed estimation.

The dominant effect will, however, be an increase in emissions due to the extra delay from less efficient control. An increase of a similar size to the reduction calculated in section 6.2.2.

7.2.3 Safety

Warning of the start of the amber period is designed to reduce the amount of red running at traffic signals and reduce the probability of a side impact in the junction due to red running. However, only 19.4% of fatal and serious accidents and 11.6% of all slight accidents at traffic controlled crossroads in urban areas are side impacts (Hall, 1996). Experiments with the TRL simulator and some on-road experience in countries that use some advance warning flashers (Federal Highway Administration, 2003) show mixed reactions by drivers to advance warnings.

The conclusion from the TRL simulator trial was that advanced warning of a change to amber should not be used because of the probability of increased shunt accidents and that drivers who chose to continue showed less caution than when there was no warning and accelerated through the junction. Of particular concern was that drivers who continued through the junction made their decisions before those who chose to stop. That is a driver could decide to proceed and commit to accelerating through the junction before the driver in front decided to stop.

An advanced system including external vehicle control that could respond to the stopping information by calculating the required deceleration to stop and the opportunity to continue could remove the uncertainty in the response to the advanced information; the system would decide and implement the decision without the driver’s intervention or dilemma. Such a system is considerably further in the
future than an information system, because the safety and acceptability of external vehicle control will present considerable obstacles to implementation. Considerations of the benefits of external vehicle control are considered later in the context of preventing red running.

To provide safe operation, a warning system would have to be consistent. That is it would have to warn of an impending change at all signals, including mid-block pedestrian crossings. As described above when investigating the delay changes, warning of a change at pedestrian crossings would reduce the efficiency of those crossings at some times. Pedestrians could become confused as to what to expect to happen at crossings. Sometimes the crossing would react promptly to a button press with a car some considerable way off, when that car is not equipped for cooperative signalling, and at other times there would be a delay in the response, when the car is equipped. Uncertainty about when the signals will change and how much time will be saved by crossing against the signals is likely to result in an increase in unsafe pedestrian behaviour. Also as noted above, some of the efficiency of Puffin crossing operation will be lost. These adverse effects at pedestrian crossings appreciably strengthen the arguments against an in-vehicle warning of loss of right-of-way which would have to be universal.

Those countries that have implemented warning flashers have generally done so at specific locations for specific reasons. If a warning is justified at a specific site, then it should be provided to all drivers by use of dedicated signs and not just to a subset of drivers who have purchased special equipment.

### 7.2.4 Social and accessibility

Some drivers would enjoy smoother driving and removal of stress caused by not being presented with amber when in the dilemma zone. Others would be the victims of increased shunt accidents.

### 7.3 Effects of fitment level

When drivers of equipped vehicles slow down, some drivers of other vehicles would follow suit, but others may be taken by surprise, or decide to overtake the slowing traffic. Either of these effects would be likely to increase the number of accidents when approaching a junction just before a signal change. It is unclear how the variability in drivers’ actions overall would be affected by the number of drivers reacting to in-vehicle information.

### 7.4 Data needs

vehicle position and speed
stop at signals in x metres message to vehicle

### 7.5 Conclusions

It is considered that the disbenefit of an increased probability of shunt accidents, increases in delay and degraded performance of pedestrian crossings outweigh potential benefits.
8 Information to vehicles about start of green

8.1 Concept

Drivers waiting at traffic signals could be informed that the signals are about to change in their favour. One objective would be to provide conditions for more relaxed driving. Drivers waiting at signals would not need to concentrate on the signals, anxious to react quickly to the starting amber, but would be able to relax, knowing that they would be alerted a few seconds in advance. In addition, the in-vehicle indication would indicate which movements were about to be given green, when not all movements at the stopline start at the same time.

8.1.1 Policy issues relevant to this concept

The policy issues relevant to this concept are included in section 2.2.7, Inform drivers and / or vehicles of coming signal changes

8.2 Benefits and disbenefits

8.2.1 Congestion / delay

Little change in delay is anticipated, but there may be a marginal reduction in delay due to fewer late starts by inattentive drivers. It is not considered that any reduction would be large enough to be quantified.

8.2.2 Environmental

Little environmental effect is anticipated. There could be some occasional slight reduction in emissions from avoiding some rapid acceleration as drivers try to compensate for their slow response to the start of green. Conversely, some drivers might react to the early warning by pressing the accelerator, to be ready to start moving, earlier than without a warning. Overall it is not considered that any change is quantifiable.

8.2.3 Safety

There are potential adverse effects from driver information systems. Work by TRL examining the effects of the starting amber (red and amber indication) has shown that many drivers treat the starting amber as an indication to start moving. In fact red and amber means stop, just as red alone does, but does indicate that the green will start shortly and drivers should prepare to move. Video recordings of a selection of stop lines showed that a third of vehicles that had been waiting behind the stopline had crossed the stopline before the start of green. It is a concern that some drivers may react to an in-vehicle early warning of the start of green by starting to move and crossing the stopline to enter the junction further in advance of the start of green than at present.

Part of the study of changes to the starting amber duration used the TRL driving simulator to investigate drivers’ reactions to reducing the starting amber to 1 second or eliminating it altogether. The results showed that drivers did react faster with less warning of the start of green, but not by as much as the reduced starting amber. From this result, drivers would be expected to react in a more relaxed manner to a longer warning, but to start to move somewhat sooner relative to the start of green. It is expected that there would be some increased risk from drivers starting to move earlier if they received early warning of the start of green. There is not sufficient information to quantify the risk, both in terms of how much earlier drivers are likely to start to move and the increased accident risk of a change in the time when drivers start to move. Evidence from the video recordings of
starting behaviour showed that drivers delayed their start when they could see potential conflicts in
the junction due to opposing vehicles having difficulty clearing the junction. However, not all
situations that could result in accidents due to early starts will be obvious to drivers.

Where different movements at signals are signalled separately, the starting warning would be adjusted
to specify which movements are about to gain right-of-way, resulting in a reduction of the number of
drivers starting to move in error when an adjacent lane receives right-of-way. The warning could, in
fact, be restricted to operate only when there was a danger of drivers being unclear of which
movements were about to be permitted. Studies of experimental amber arrows (Swain 1997) showed
that some drivers start to move in error when there are separately staged movements that share a
common stopline. The objective of the study was to see whether presenting drivers with an amber
arrow (together with a full red) would reduce the numbers of drivers starting to move in error when
the movement that they wished to make was prevented by a red signal. For instance right-turning
vehicles starting to move when only the ahead and left turn movements are permitted. The false start
rate varied considerably between the 17 approaches studied as did the effect of changing from a full
amber to an amber arrow. Overall 1.6% of drivers waiting at the stopline to make a movement that
was not permitted to start as early as other movements from that stopline went through the junction at
the start of the wrong stage. The proportion dropped to 0.7% after installation of an amber arrow.
These overall figures mask large variation between sites, indeed at some sites the infringement rate
increased with the amber arrow.

There are no data available on the number of junctions where separately staged movement share a
stopline. The number is, however, likely to increase with the need for increasingly complex phasing
and staging arrangements as traffic volumes grow. As an indication of the potential benefits that
could result from better information about which movements are about to start we can use the data on
junctions accidents in section 11. The total cost of injury accidents at signal controlled junctions is
about £740M per annum. It is not expected that providing information on which movements are to
start would prevent a large proportion of these accidents. For indicative figures we would suggest a
saving of around 1% of junction accidents with an upper limit of 5%. The likely benefit of reducing
accidents associated with false starts at shared stopline is, therefore, estimated to be:

Best estimate of benefit of reducing accidents due to false starts ~ £7M

Benefit definitely expected to be no more than £35M per annum

8.2.4 Social and accessibility

Drivers could potentially relax more when waiting at a red signal knowing that they will be alerted to
the forthcoming green and they do not have to concentrate on the traffic signals to be alert to the start
of green.

8.3 Effect of fitment level

It is not anticipated that there should be any significant correlation between drivers who purchase /
use fitted vehicles and a greater or less than average propensity to make false starts at signals with
shared stoplines. Therefore, the benefits are predicted to be linearly related to the use of fitted
vehicles, with no minimum threshold that needs to be crossed before benefits accrue.

8.4 Conclusions

There are potential benefits from giving drivers information about which movements are about to
receive right-of-way when separately staged movements share a stopline. General information about
the start of green is not recommended at present as the benefits are expected to be small and there is a
concern that the information could be abused resulting in a greater accident risk. There is insufficient
knowledge at present to quantify the increased accident risk. Further research into the behavioural
response to an early warning would be needed before the technique could be recommended for
general use, rather than just to warn that only certain movements are about to be permitted.

8.5 Data needs
Indication of movements that are to receive right-of-way in x seconds. The information would only
be delivered to drivers that are stationary on the approach to the signals.
9 Green wave information to the vehicle

9.1 Concept
With fixed time coordinated signals and knowledge of the queue ahead it is possible, in under saturated conditions, to calculate a speed at which a vehicle can expect to pass through the next signals without delay.

9.1.1 Policy issues relevant to this concept
The policy issues relevant to this concept are included in section 2.2.7, Inform drivers and / or vehicles of coming signal changes.

9.2 Benefits and disbenefits

9.2.1 Congestion / delay
To provide useful information to drivers on the speed to adopt to pass through traffic signals as part of a green wave, there must be a high probability that following the advice will result in passing through the next signals without delay. A high probability requires the vehicle’s predicted arrival time to be before the end of green. Therefore, the end of green should not be advanced to an earlier time as the vehicle is on the link. This requirement severely restricts the freedom of a system such as SCOOT to respond to current traffic demands in the most efficient manner.

In addition, there will be some loss of capacity if the green waves are designed to avoid slowing down to join the back of a moving queue discharging from the signals. Capacity is maximised if there are always vehicles waiting to discharge throughout the green. Starting the green sufficiently early that the initial queue will definitely discharge before the arrival of the main platoon of traffic reduces the capacity of a junction.

A more practical option would be to warn drivers to slow down to reduce their queuing time at the next junction. A small reduction in speed along a link could result in avoiding coming to a complete halt in the queue for the next junction. It is unlikely to be acceptable to give the opposite advice, that is, to speed up to avoid missing a green. If drivers are travelling slowly it must be assumed that there is a reason for the low speed and they should not be pressured into ignoring the reason.

To provide green wave information requires:
- The traffic control system not to advance the end of green to a link when a vehicle is approaching at the recommended speed to prevent stopping a vehicle that is following the system recommendation.
- The traffic control system not to delay the start of green to a link when a vehicle is approaching at the recommended speed to prevent stopping a vehicle that would expect a green wave from following the recommended speed.
- The signals to operate with sufficient spare green to allow good progression of the front of the platoon, that is, not to be significantly delayed by the end of the standing queue at the start of green.

All these requirements reduce the efficiency of the traffic control system. In particular the last condition will probably not be feasible on many links in peak periods. The first two requirements will remove much of the freedom of the SCOOT split optimiser, but not all. The last will require a higher than optimal cycle time. As a first approximation to the combined effect of the two restrictions it is assumed that the delay will increase to that typical of good fixed-time control, rather than traffic-responsive SCOOT control – an increase in delay of 12%. This increase will only be effective outside
the peak periods, as insufficient capacity is available for green waves during the peak periods. It is considered that such an increase in delay is unacceptable.

To estimate how often it might be possible to run green waves on major routes, SCOOT data for Edgware Road was examined. It is considered that green wave control with a realistic prospect of most main road drivers receiving a green wave through several junctions requires those junctions to be operating at 80% saturation or, preferably, less. On the selected May weekday, the average proportion of time that a link was not more than 80% saturated, averaged over all links for the period 07:00 to 20:00, was 77%. However, there was considerable variation between links; four of the Southbound links were each more than 80% saturated for half the period or longer. It would not have been possible sensibly to operate green waves southbound on this day. Green waves could have been operated northbound over part of the route, as far north as the approach to Marylebone Road, for much of the day, but not during the evening peak.

If all vehicles were equipped with and using route guidance, then more advance information on demand would be available allowing good decisions on signal timings to be made in time to give green wave information. There would still be a loss of capacity to provide conditions where the first vehicles in the approaching platoon are not slowed significantly. In practice the level of use of route guidance systems will be limited. It is unlikely that drivers will all switch on route guidance for familiar journeys where there is little opportunity to divert round unusual sources of delay. A new signal control algorithm would have to be developed to use the combination of route guidance and detector information. Based on the experience of developing existing algorithms, a development cost of several million pounds is expected to produce an efficient system.

### 9.2.2 Environmental

In principle it is possible to reduce harmful emissions from vehicles by operating at a slower constant speed rather than cruising at a higher speed and then stopping at signals. During the environmental assessment of the Gloucester Safer City project (Boulter 2000) estimates were made of the savings in emissions that would be made if drivers drove at a constant speed equal to the achieved average speed of driving through the traffic calmed area.

The achieved average speeds were in the range 33 to 49 km/h (20 to 30 mph) for the different routes. In Gloucester the average savings in emissions expected if drivers drove at a uniform speed are shown in Table 9-1.

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>CO₂</th>
<th>HC</th>
<th>NOₓ</th>
</tr>
</thead>
</table>
| Such reductions would be a considerable benefit in terms of improved air quality and reduction in greenhouse gas. These benefits are, however, overestimates of what could be achieved as they ignore the effects of less efficient control and extra delay detailed above.

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>CO₂</th>
<th>HC</th>
<th>NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10%</td>
<td>5%</td>
<td>-1%</td>
<td>16%</td>
</tr>
</tbody>
</table>

### 9.2.3 Safety

There is a possible reduction in shunt accidents, but it is unlikely to be significant as most such accidents are associated with stopping at the end of green, rather than with joining a queue of stationary vehicles.
9.2.4 Social and accessibility

There would be opportunities for more relaxed driving when the green waves are able to operate plus a feel good factor from helping to reduce harmful emissions.

9.3 Effect of fitment level

No detailed analysis of the effect of fitment level has been undertaken as the concept is not recommended, but it should be noted that on roads with limited overtaking opportunities a relatively low proportion of vehicles equipped and following the speed advice will result in a much larger proportion of vehicles operating at the green wave speed.

9.4 Data needs

Positions and speeds of all vehicles along a link
Recommended speed transmitted to each vehicle

9.5 Conclusions

The extra delay from less efficient operation is expected to be unacceptable. The theoretical benefits of lower emissions from not stopping rely on drivers adopting recommended low cruising speeds. Using information from route guidance systems could reduce the increase in delay, but would require a high market penetration and a very expensive control algorithm development. Even using route guidance information it would not be possible to provide green waves in saturated or oversaturated conditions.
10 Use of vehicle stopping information

10.1 Concept

If vehicles approaching the stopline as the signals change against them can confirm that they will stop before reaching the stopline and that there are no vehicles, equipped or unequipped, in front, alongside, or behind that have not also indicated that they will stop then the intergreen could be shortened on confirmation from the last vehicle to cross the stopline on when it will clear the conflict zone.

The potential implementation of this concept is someway in the future because of the need to ensure that it is safe to shorten the intergreen. That is the equipped vehicle approaching the signals must be able to confirm that it will stop and the driver cannot override the stop. Therefore, drivers will have to be willing to surrender some, at least, of their control of the vehicle to an automatic system. In addition, there will need to be confirmation that no other vehicle will continue through the junction, on any approach that is losing right-of-way. It is likely that advanced infrastructure based sensors would be needed to check for unequipped vehicles. In-vehicle sensors would need to be told which directions were losing right-of-way and could have difficulty in sensing all the relevant road space. The infrastructure sensors would have to accurately sense at least position and speed.

10.1.1 Policy issues relevant to this concept

The policy issues relevant to this concept are included in section 2.2.4, Modify signal timings in response to information from vehicles on their projected behaviour.

10.2 Benefits and disbenefits

10.2.1 Congestion / delay

The intention is to reduce delay by shortening the intergreen when it is safe to do so. Intergreen timings are designed to give a safe clearance between conflicting movements; sometimes it could be possible to shorten the period. The potential reduction in the intergreen will depend on the width of the junction and the speed of the clearing vehicle. The recommended settings (see TA 16/81) allow for conflicting vehicles travelling at about 20 mph. Where the clearing vehicle is moving faster and the starting vehicle is starting from rest, a saving can be made.

Consider an “x” distance, as defined in TA16/81 of 10 metres and a clearing vehicle travelling at 30 mph.

\[
\text{Time to cover the 12m from the Z detector to the stopline} = 0.9 \text{ s}
\]

\[
\text{Extension from Z detector expires 1.5 s after the vehicle leaves the Z detector}
\]

\[
\text{Vehicle covers “x” metres in 0.8s}
\]

In this example, if it can be confirmed that no other vehicle will enter the junction from the links losing right-of-way and that the starting vehicle will not be travelling faster than 30 mph, then the intergreen can be safely shortened to 2 seconds from the normal 6 seconds. With wider junctions, the calculation will yield a slightly larger potential saving, e.g. reduce the intergreen from 8 seconds to 3 for an x distance of 36m. The savings will be less for vehicles travelling slower than 30 mph. Allowing for slower speeds a typical potential shortening of the intergreen of 3 seconds will be used to estimate benefits.

The intergreen can only be shortened when there is a clear gap behind the clearing vehicle so that any following vehicles can stop reasonably comfortably. With system D detection a gap change will only occur when the gap between vehicles is 1.5 seconds greater than the time taken by the first vehicle to...
travel from the z to the x detector, typically 28 m, that is slightly under 4 seconds at 30 mph. To estimate the probability of being able to reduce the intergreen in any cycle we need to estimate the probability of a gap of greater than 4 seconds occurring in an appropriate part of the signal cycle.

A gap is only relevant if it occurs outside the red time for the approach and the time taken for the queue on the link to disperse. With reasonably efficient timings no more than a quarter of the cycle would be expected to be relevant for gap changes on average. The probability of a gap will be highly dependant on the flow. For roads that are green simultaneously in both directions, it is the two-way flow that is relevant. Assuming a Poisson distribution, the probability of a gap of at least 4 seconds can be calculated. As gaps are only relevant in one quarter of a cycle, the probability of a useable gap is one quarter of the overall calculated probability. The calculated probability is plotted in Figure 10-1.

![Probability of a useable gap](figure)

**Figure 10-1: Probability of a useable gap as a function of two-way flow**

Opportunities for reducing the intergreen time will occur predominantly on the quieter roads, or quieter times. The probabilities in Figure 10-1 do not include the probability that there is a vehicle waiting on the conflicting road that will be able to take advantage of a shortened intergreen. Therefore, the probabilities at the lowest flows, at least, are optimistic.

As noted above in section 7.2.1, the total number of traffic signals in the UK is not known, but the number of signals operating under isolated control is believed to be similar to, but probably somewhat less than, the number under UTC. Extrapolating from the UTC figures for London, West Midlands and Greater Manchester, the total number of signals in the UK, is estimated to be around 12000, with possibly a similar number of pedestrian crossings.

The probability, averaged over the whole day, of a useable gap and, simultaneously, a conflicting vehicle waiting for a green signal will be taken to be 1% at typical signals. This estimate looks low from Figure 10-1, but is believed to be realistic when allowing for the probability of a waiting conflicting vehicle at the quiet times. We also need to estimate the number of intergreens during the day. An average of 60 second cycle and two-stages gives 120 intergreens per hour. Quiet junctions can operate at lower cycle times, but because of lack of demand will also have long cycles. Busy junctions with more stages will have longer cycle times. Overall 120 intergreen per hour seems reasonable. The potential saving, assuming one vehicle waiting and an average cycle time of 60s, of reducing the intergreen by an average of 3s is therefore:

\[
\text{Potential delay saving} = 0.01 \times 3 \times 12000 \times 120 \times 24 \times 365 \text{ vehicle-seconds per annum}
\]
\[
\approx 105000 \text{ vehicle-hours per annum}
\]
Using the standard value of time, this equates to about £1.5 M per annum, a low sum for the effort that will be required to ensure safe operation. The estimate could be increased by including mid-link pedestrian crossings, but the saving to be postulated would be more difficult as some pedestrians will cross in the gap without waiting for the signals to change. The probability of a useful gap may also be greater than the 1% assumed here. Overall the potential benefit is estimated to be in the range:

Potential delay saving due to reducing intergreens = £1.5M to £5M per annum over the UK

10.2.2 Environmental
There would be a small reduction in emissions from the reduction in the time vehicles spend idling at red signals.

10.2.3 Safety
A more responsive traffic control system that started the green as early as possible would be expected to have some safety benefits in terms of reducing incentives for drivers to red-run or to anticipate the start of green to reduce their delay. However, the expected level of the changes and the probability that traffic will be very light with short delays when the intergreen is shortened means that little practical effect is anticipated. Conversely it is not anticipated that the shortening of the intergreen will be sufficiently frequent that drivers will come to expect it resulting in an increase in accident risk when it is not possible to shorten the intergreen.

There could be safety benefits at pedestrian crossings if pedestrians see that the signals normally change rapidly when there is an opportunity to cross. Pedestrians may be less inclined to cross against the signals. Developments of MOVA to provide a very responsive control of Puffin crossings are already providing some of these potential benefits to pedestrians.

The main safety issue is, however, the need to ensure that the intergreen is only shortened when it is appropriate. That is, the system must be certain that all vehicles losing right-of-way will stop and that the last vehicle will clear the conflict point before conflicting vehicles arrive there. As described above, sophisticated detectors are likely to be needed to give sufficient confidence.

10.2.4 Social and accessibility
There would be less frustration for pedestrians waiting to cross at junctions and stand alone crossings.

10.3 Effect of fitment level
The concept is likely only to be valid at a very high fitment level.

10.4 Conclusions
Small, but valuable, benefits are predicted. However, the concept would only be feasible with a high fitment level and extra infrastructure in the form of sophisticated detectors on each approach to junctions and mid-link crossings.

It is unlikely that such a system will be viable in the medium-term future.

10.5 Data needs
High integrity information with high timeliness
Position and confirmation of stopping from all relevant vehicles
11 Response to red runners

11.1 Concept

When a vehicle fails to stop for a red light there is a danger of a collision in the junctions with vehicles that have entered the junction legitimately at the start of their green. The normal intergreen period is designed to prevent such collisions when drivers obey the lights, but will not be long enough to protect all red runners and their potential victims. Intelligent traffic signals could take information from vehicles about red running and use it to extend the intergreen to provide extra protection against mid-junction collisions. Vehicles would have to be informed of the status of the traffic signals and calculate the probability that they will red run.

Although the intention would be to reduce accidents, the action would, in effect, condone illegal driving behaviour. Therefore, it is considered that it would not be practical to extend the intergreen for red runners without simultaneously acting to detect the illegal driving. The actual mechanics of preventing red running are considered in the following section. The benefits of the combined system of automatic enforcement and extension of the intergreen are evaluated here. Similar benefits would be expected from external vehicle control preventing red running.

11.1.1 Policy issues relevant to this concept

The policy issues relevant to this concept are included in sections 2.2.1, Modify signal timings to cater for individual (probably bad) driving and 2.2.2, Take enforcement action on system information.

11.2 Benefits and disbenefits

11.2.1 Congestion / delay

Little change in delay is expected. Red running is not a frequent occurrence; an occasional few extra seconds of all-red time would not be expected to affect total delay significantly. In addition, the normal reaction to red-running is for the starting vehicles to observe the problem and wait until the offending vehicle has passed. Work at TRL on possible changes to the starting amber analysed the behaviour of many vehicles at the start of green. When vehicles were still in the junction during the starting amber, it was observed that drivers started to move later than when the junction was clear. Although in the situations observed the vehicles had entered the junctions legitimately and been delayed from leaving; red runners would not necessarily be so obvious to the drivers of starting vehicles. The objective of the system is to reduce accidents in the junction. When it is successful, there will be a reduction in delay by avoiding the disruption caused by an accident.

The concept would be applicable to both isolated and coordinated junctions. In both cases there would need to be direct vehicle – controller communications and implementation in an intelligent controller. Routing the information to a UTC system to make the decision would introduce potentially unacceptable communications delays.

11.2.2 Environmental

The environmental benefits would be associated with the reduction in accidents and the reduction in consumption of resources in repairing damaged vehicles and infrastructure and in emergency services and breakdown vehicles responding to the accidents. As noted above, the delay savings would not be significant and so no significant effect on emissions from vehicles is expected.
11.2.3 Safety

The main anticipated benefit is the safety benefit from reduced accidents. It is assumed that some form of enforcement action would be taken to avoid the probability of drivers responding to driving an equipped vehicle by assuming that they can safely red run for a few seconds with impunity. Analysis of the effects of red-light cameras provides information about the likely accident reduction of protecting against the junction accident risk from red running. Unfortunately, most of the published material is on the effects of enforcement cameras and does not differentiate in detail between the effects of red-light cameras and speed enforcement cameras. One study dedicated to red-light cameras was conducted by the Scottish Office (Halcrow 1996). That study estimated that 17% of the accidents at traffic signals in Glasgow were due to red running and that red-light cameras reduced those accidents by 15%. A saving of 15% of 17% = 2.6% of accidents at traffic signals. Data on the total number of accidents at traffic signals are not available without special analysis of the STATS19 data. However, Hall 1986, stated that there were 19,400 personal injury accidents at traffic signals in Great Britain in 1984.

The total number of accidents has decreased since 1984, from 253,183 to 214,030 in 2003. Therefore, the total number of accidents at traffic signals is estimated to be:

\[
\text{Total number of accidents at traffic signals} = 19,400 \times 214,060 / 253,183
\]

\[
= 16,400
\]

Applying the figures from the Scottish Office study to the total number of accidents at signals provides the estimate of the potential accident saving by universal use of red-light cameras

Reduction in number of accidents from universal use of red-light cameras = 425 per annum.

Use of intelligent vehicle and signal technology would be expected to be at least as effective as red-light cameras with a high level of fitment. Drivers would know that they would be prosecuted; there would be no equivalent of the possibility that there might not be a camera in the housing. In addition the extension of the intergreen would provide extra protection. The upper limit of the benefit would be to prevent all the 17% of accidents at traffic signals that were estimated to be due to red running.

Upper limit of accident reduction = 2788 per annum

The average cost of an injury accident is £45k (Hirst, et al. 2004). Therefore, the potential saving from extending the intergreen during red running combined with enforcement action to automatically prosecute or prevent red-running is estimated to be in the range:

Benefits of actions to improve safety related to red running actions = £19M to £125M

There are no figures available on the potential for increased shunt accidents caused by red-light cameras and the above figures assume no increase. To obtain the benefits predicted requires all vehicles to be equipped, in which case it is expected that all drivers would be likely to aim to stop for red lights and so there should not be a large increase in shunt accidents.

11.2.4 Social and accessibility

The social benefits from reducing accidents are included in the standard economic assessment. No further social benefits are anticipated, however, the social acceptability of automatic enforcement using equipment in the offender’s vehicle, or of external vehicle control is a serious issue. It is not proposed to try and evaluate the social cost as by the time the concept is feasible, the public attitude to automatic enforcement systems will have almost certainly changed. Whether the change will be in favour of automatic systems or a hardening of objections is hard to predict. What can be said is that it will probably be necessary to emphasise the extra protection afforded to users by the extension of the intergreen, if a driver should make a mistake and run a red light. The cost of that protection will be prosecution for the offence.

There are no obvious effects on accessibility.
11.3 Effect of fitment level

At first sight, the benefit of the system will be in direct proportion to the number of vehicles fitted and the number of junctions equipped. In practice, the relationship will not be exactly linear as the first junctions to be equipped will be the major ones with particular problems from red running and the benefit from fitting an individual vehicle will depend on the use of the vehicle. Intelligent vehicle systems have so far tended to be offered first on the more expensive cars in a manufacturer’s range. Such vehicles, particularly on first ownership, are likely to be used more intensively than the average, potentially increasing the safety benefit. However, if use of the system will result in automatic prosecution of offences, then those most likely to offend are likely to avoid purchasing such vehicles. At low fitment levels there may be an increase in shunt accidents if behaviour changes such that drivers of equipped vehicles are more likely to stop when signals change to amber than currently and other drivers do not expect such behaviour.

There is, however, no critical level below which the system is ineffective. Therefore, as a first approximation it is recommended that a linear relationship between fitment level and benefit should be assumed.

11.4 Assumptions and risks

The main risk is the user and political acceptability of automatic enforcement. Without the enforcement, is it acceptable to condone bad driving to protect others as well as the bad driver from the consequences of their actions?

If automatic enforcement is accepted how will the system be approved? The enforcement evidence will include information and identification from the vehicle. It will be essential that the identification and offence can be validated and be proof against drivers interfering with the vehicle equipment after offending.

Any conditions imposed on the first user of a system to accept enforcement would need to be passed on to subsequent vehicle owners.

11.5 Data needs

Accurate vehicle location in the vehicle

Stopline position and signal change time transmitted to vehicle, if the calculation of red running is done in the vehicle

Speed, acceleration and position transmitted to the infrastructure at frequent intervals as the vehicle approaches the stopline if the calculation is done in the infrastructure. The demand for the data could be switched on by the infrastructure for all vehicles within x metres of the stopline at the end of green, start of amber.

The timeliness requirement is high: the confirmation of the red running needs to be late in the intergreen to confirm that it will happen, but the information needs to reach the controller before the next starting amber.

Data needs will be higher if the calculation is done in the infrastructure rather than in the vehicle. Speed and acceleration will be needed at frequent intervals. More detailed calculations will be needed to determine the minimum frequency, but at this stage it would seem sensible to allow for updates every 0.1s.

11.6 Conclusions

The analysis has assumed that extending the all-red to increase the intergreen when an equipped vehicle runs a red light will be used as a safety back up to a system of automatic enforcement or external vehicle control. The benefits have been estimated for the package and show a valuable
reduction in accidents and associated costs. No allowance has been made for a potential increase in shunt accidents at low to moderate market penetration levels. Political acceptability as well as technical feasibility is likely to be a significant factor in implementation.
12 Prevention of red running

12.1 Concept

There is a danger that driver information systems such as advance notification of a change of signals may encourage drivers to take the risk of red running. Therefore, in order to achieve the lowest possible number of road casualties, as is the aim of the Swedish Vision Zero, it may be necessary to take control of the vehicle, where a driver is likely to cause an accident. Prevention of running red lights is one potential application of external vehicle control, but it is unlikely to be the first modification of vehicle performance enforced from outside the vehicle. External speed limiting, where the driver retains control, but is unable to accelerate to above the speed limit, is less intrusive than external control, but is seen as politically unacceptable at present, is likely to become acceptable before full external control.

The objective of this section is to raise the possibility of external control and how it would fit in a cooperative signalling system. To operate the vehicle would be informed by the infrastructure that it should stop at the traffic signals at a given location. The vehicle would then implement the stop, first checking that it could do so with an acceptable level of braking. In addition to obeying the instruction to stop at the stopline, the vehicle would have to sense any other vehicles in front of it and stop behind them.

12.1.1 Policy issues relevant to this concept

The policy issues relevant to this concept are included in section 2.2.3, Take external control of vehicles to enhance safety.

12.2 Method

Stopping an isolated vehicle at a specific location (the stopline) when its position and speed are known and the maximum required deceleration is well within the capabilities of the vehicle is relatively easy. The vehicle systems would need to know the performance of the vehicle braking system to determine the braking pressure required and would also be expected to check that the required stop is being achieved. However, on a real road there can be other vehicles around, therefore, the stopping point may not be at the stopline and it may be undesirable to brake hard because of the behaviour of a following driver.

External vehicle control will need considerable cooperation from the vehicle that is being “controlled” to manage the interactions with other vehicles if external control is allowed in conditions where not all vehicles are externally controlled. Systems such as “stop & go” are being developed to automatically stop vehicles behind others, but with these the driver still has ultimate control and the system is part of a driver assistance system, Adaptive Cruise Control (ACC), designed to assist the whole driving task, not just cut in to take over when approaching signals that are changing from green.

Where all vehicles are equipped for external control, it is likely that vehicle to vehicle communications will be used rather than each vehicle sense the presence and actions of others without any direct information from the other vehicles. The problems with sensing the presence and actions of other vehicles, including cyclists, are much greater than sensing the behaviour of the vehicle itself. Therefore, considerable developments will be required in vehicle mounted sensing systems and the interpretation of their outputs, or in equipping all vehicles with appropriate vehicle-vehicle communications, before external vehicle control, which cannot be overridden by the driver, becomes feasible.

It is likely that if the system were introduced, then it would always intervene to stop the vehicle as soon as the instruction was received from the infrastructure. Delaying to see whether the driver was
going to stop would result in higher than necessary braking whenever the driver did not respond. In addition there could be confusion on the part of the driver as to what to do, whether to brake manually or wait for the system to act.

12.3 Benefits and disbenefits
The benefits and disbenefits of preventing red running will be at the upper limit of those calculated in the previous section on alleviating the effects of red running.

12.4 Effect of fitment level
It is not envisaged that any form of external vehicle control would be implemented until drivers are happy with the concept. To gain that confidence will probably require extensive experience of driver assistance systems such as collision avoidance, speed limiting, lane departure warning etc. If a system is developed that relies on vehicle-vehicle cooperation to control stopping behind other vehicles, then a very high fitment level would be required before the system could be implemented. If the system depends on in-vehicle sensors to detect other vehicles and their behaviours then there is no obvious reason why a minimum market penetration would be required before a system could be implemented; it should not be a surprise to other drivers when a vehicle stops for a red signal. However, because of the need for driver familiarity and acceptance of automation of some driver tasks, it is likely that some automation will be a standard feature of virtually all new vehicles when external control to prevent red-running is introduced. Therefore, it could be a relatively simple modification to enable the system on new vehicles leading to a rapid increase in market penetration.

12.5 Data needs
The data communication needs from the infrastructure are relatively low volume, location of the stopline and time of start of red, but high timeliness and integrity. Vehicle-vehicle communications will be satisfied by the requirements for other vehicle following systems that will already have defined the needs for such communications.

12.6 Conclusions
This type of intervention is unlikely to be acceptable to society for some time. As noted above, it will also require considerable technical development to allow for the interactions between vehicles. External vehicle control of this type could be included in measures aimed to eradicate deaths in road accidents, the aim of the Swedish Vision Zero concept. The analysis shows that cooperative signalling systems would be compatible with external control, but only with the addition of considerable in-vehicle intelligence to sense and respond to other vehicles or with comprehensive vehicle-vehicle communications. Detection of cyclists and possibly motor-cyclists will be required by in-vehicle systems even with comprehensive vehicle-vehicle communications.
13 Probe vehicle information

13.1 Concept

Vehicles equipped with accurate location equipment can act as probe vehicles and provide good information about the performance of the network. Such information will enable the signal control system to monitor its achieved performance against its objectives. Discrepancies between objectives and performance may indicate errors in the way that the control system models and predicts the results of its actions. Probe vehicle information can be used in several ways:

- To compare the actual vehicle delay with that predicted by the control system
- To compare system parameters such as saturation flow and journey time with the values achieved by vehicles
- Incident detection
- Improved modelling, particularly for a supervisor system to respond to incidents
- Respond to road conditions, considered in section 14
- Respond to downstream problems (exit blocking), considered in section 15
- Improvements to operation of temporary traffic signals, considered in section 16

13.1.1 Policy issues relevant to this concept

There are no significant policy issues involved with the use of probe vehicle information to increase the efficiency of traffic control, provided adequate safeguards are in place to avoid the identification of individual vehicles or drivers.

13.2 Method of calculating Saturation Flow

Providing more accurate values for traffic parameters will allow traffic control systems to control traffic better and reduce delay. One of the critical parameters is the saturation flow, but it is known that saturation flows can vary during the day due to various factors such as:

- Different lane use by time of day, e.g. all lanes used in the peak, but queuing predominantly in lane 1 at quieter times
- High proportion of HGV at some times of day
- Obstruction by parked vehicles

Calculation of saturation flow will be easier when virtually all vehicles are equipped than when only a small number are. The calculation will be more difficult on multi-lane and flared approaches than with simple single lane approaches. A first approach will be to assume that the typical separation of vehicles in a queue is 6 metres. The position of a stationary vehicle at the start of green will then indicate the number of vehicles ahead of it. Measuring the time of that vehicle to cross the stopline will provide an estimate of saturation flow. The data for individual vehicles would be accumulated and the best fit in terms of saturation flow and start lag calculated. The infrastructure would have to define the approach and position of the stopline to approaching vehicles and instruct them to return the information about stopping position and time of crossing the stopline.

A major factor in the variability of saturation flow at sites with flared and multi-lane approaches is the use made of the different lanes. Unfortunately, at low fitment levels, there would be too few probe vehicles to rapidly build up an estimate of the effect of varying lane usage on the effective saturation flow.
This method assumes no exit blocking; cycles where a downstream detector indicates exit blocking would be ignored. Alternatively if there is no information on exit blocking, then all the data should be included to produce a smoothed, running average effective saturation flow.

For high fitment levels, it will be possible to calculate the saturation flow more accurately. Data from individual vehicles of the time that they cross the stopline will be analysed to calculate the average inter-vehicle gap, a direct measure of saturation flow under saturated flow. Data will be used up to the first occurrence of a “critical gap,” a value of inter-vehicle gap that indicates the end of saturation flow. An unequipped vehicle in the queue will give rise to a critical gap between equipped vehicles, resulting in a loss of efficiency of the method, but not a deterioration of the accuracy. Exit blocking will be detected by an excessive time to reach the stopline from a vehicle’s starting position in the queue. A consistent high value during part of a green will indicate exit blocking and an effective saturation flow calculated.

The calculation of saturation flow may have two aims:

- A smoothed average value that may vary during the day
- A current effective flow when there appears to be partial exit blocking

The latter value will be more easily calculated with a high fitment level.

13.3 Benefits and disbenefits

13.3.1 Congestion / delay

Work within the SCOOT development project produced the Saturation Occupancy Flow Technique (SOFT) to estimate the saturation occupancy (the SCOOT equivalent of saturation flow) on individual links. That technique is applicable to around 50% of links in a typical SCOOT network. Figure 13-1 and Figure 13-2 show variations in the saturation occupancy during a Friday and a Saturday. The validated value is correct as an average value, but variations of 1 or 2 units in 18 are common. These values are for a two-lane link, where variation in saturation flow is likely to be greater than on a single lane link.

Figure 13-1: Example of weekday variation of saturation occupancy
Figure 13-2: Example of weekend variation of saturation occupancy

The SOFT data provide information on the variability of saturation flow, but not on the effects of those variations. Calculations of the effect of incorrect saturation flows were made by applying the signal timing programme included in the original TRL Bundle of traffic engineering programmes (www.trlsoftware.co.uk) to a simple 4-arm junction.

Figure 13-3: Percentage change in delay v side road saturation flow

Figure 13-3 shows an example of the results for the whole junction and the main road and side road separately. The main and side road results are for just the direction with the higher flow on each type of road, the dominant flow on each road. The conditions used were:

Main road dominant flow = 900 vehicles per hour
Side road dominant flow = 600 vehicles per hour
Assumed saturation flow = 1800 vehicles per hour on each approach
Actual main road saturation flow = 1800 vehicles per hour

Signal timings were calculated using a saturation flow of 1800 vehicles per hour. The saturation flow on either the dominant main road or dominant side road approach, or both, was then changed and the delays calculated using the timings optimised for saturation flows of 1800 vehicles per hour. The timings were then optimised for the actual saturation flows and the delays recalculated. The benefits of using timings based on the actual saturation flow were then calculated.

It can be seen that optimising signal timings based on an overestimate of the saturation flow (1800 rather than 1750 or 1700 vehicles per hour) has more serious consequences than using an underestimate in this example. In addition the effect of an error on one link may not change the overall delay at the junction by a large amount, but can cause large discrepancies between the delays on the different arms. When the green times are based on an underestimate of the saturation flow on a link, that link benefits from extra green, but opposing links suffer a loss of green and increased delay. Such differences cause dissatisfaction to motorists, but it is hard to quantify the disbenefit of the imbalance in delays.

Figure 13-4 shows the effect of an error in the main road saturation flow. In this case the consequences of an underestimate are worse than those of an overestimate. The reason for the difference is that the side road green is short relative to the main road and so an error that results in a shorter green for the side road is likely to increase the delay to vehicles on that link more than a similar shortening of the longer main road.

These calculations of the effects of optimising traffic signal timings based on an erroneous value of saturation flow show an increase in delay of 2% due to an error of 50 vehicles per hour in a saturation flow of 1800 per hour. Use of a simple simulation is likely to overestimate the effect of a small error. In reality the saturation flow will vary from cycle to cycle, because of the headway left to the vehicle in front by individual drivers. In addition the data from vehicle detectors in a real system is not perfect. For instance, for SCOOT it is possible for vehicles to enter or exit a link between the detector and the stopline and a single detector loop can be installed over two lanes giving some errors due to masking of one vehicle by another. SCOOT is not sensitive to the average effects of these problems.
with vehicle detection, as it works in terms of saturation occupancy, the saturation flow measured in
SCOOT’s demand units as measured by the detector on that link. The saturation occupancy also
allows for the average proportion of vehicles that enter and leave the link between the detector and the
stopline.

Looking at the graphs in Figure 13-1 and Figure 13-2 shows that a change in saturation occupancy of
10% is quite possible over time. The simple calculation of the dependence on the accuracy of the
saturation flow would imply large increases in delay from such changes. However, many junctions in
a SCOOT network will not be operating as close to saturation as the example used in the simulation
above, because their cycle time will be controlled by the critical junctions in the region. In addition
the variability of drivers’ behaviour will mean that it is not possible to calculate an exact saturation
flow in each cycle. Therefore, the benefit of typical variation in saturation flow is estimated to
average a few percent.

To estimate the likely benefits of using probe vehicle data to calculate saturation flows, however, we
need to consider several factors:

- SCOOT’s own estimation of saturation flow (SOFT) is applicable to about half the links in a
  controlled area
- A method to estimate saturation flow on-line is being developed for MOVA
- System D VA does not use saturation flow in its day-to-day operation, but is not as efficient
  as MOVA

It would seem sensible to reduce the predicted saving in delay at SCOOT and MOVA controlled
junctions to 1% due to extra capability to estimate saturation flow from probe vehicle data in the light
of the other developments. Probe vehicle information could also alert signal engineers to the need to
retimes system D and fixed time UTC junctions, and provide much of the traffic data needed for the
off-line programs (TRANSYT, OSCADY, LINSIG) used to calculate the new timings. Considerable
improvements would be expected at those junctions, but even with probe vehicle data, only a
proportion are likely to be modified in any year. Therefore, an overall reduction of 1% of delay is
suggested for the use of probe vehicle data, saturation flow for SCOOT and MOVA, delays and
general traffic information for other systems. In section 7, the cost of increasing delay by 1% was
estimated to be at least £60M.

Estimate of benefit of improved estimation of saturation flow > £60M per annum

The objective is to improve signal control and hence reduce delay and congestion. As stated in
section 6.2.4, reductions in delay may be taken to improve the service provided to particular groups of
travellers, without an overall increase in delay. Detection of incidents and improved response to
incidents will also reduce delays.

**13.3.2 Environmental**

As for other methods of reducing delay, there will be a consequential reduction in emissions from
vehicles if delays are reduced.

**13.3.3 Safety**

Good monitoring of the performance of the control system, its modelling of traffic and parameter
values will provide better knowledge of vehicles approaching the junction and so allow the control
system to reduce the probability of signals changing at an awkward time for an approaching driver.
Early detection of incidents and appropriate action will reduce the potential for secondary accidents.
Improvements in safety are likely to be too small to justify the effort to trying to quantify them.
However, it is important to note that improvements rather than deterioration in safety is anticipated.
13.3.4 **Social and accessibility**

No large effects are predicted; the reduction in delay will not significantly affect accessibility.

13.3.5 **Setting up and calibrating system**

Currently considerable effort is required to set up and calibrate SCOOT and MOVA systems to ensure that all parameters are set accurately. Probe vehicle data will not be able to replace all the manual input, but would be expected to save several person-hours per junction. A saving of one hour per approach should be possible, resulting in saving half a person-day at a four-arm intersection.

13.4 **Other parameters**

The above discussion has concentrated on saturation flow as the main parameter that is often in error. SCOOT also uses the free running cruise time from the detector to the stopline. Probe vehicles will be able to supply a value for the cruise time in undersaturated conditions by measuring the cruise speed along the main part of the link before slowing because of queuing for the junction. No quantitative estimates of the effects of cruise time on delay are available, but the journey time is not as likely to be in error, or as critical, as the saturation flow. An extra delay benefit of 10% of that due to improved estimation of saturation flow, i.e. about £5M per annum, is postulated.

MOVA also uses a cruise speed, although a lower value than would be used in equivalent circumstances by SCOOT. Recent work, Kennedy et. al. 2005, suggests that an accurate value of the cruise speed in the MOVA dataset for a junction may contribute to improved safety at high-speed sites. It was not possible to separate out the effect of cruise speed from the other parameters, but from the evidence in the paper a reduction in junction accidents of at least 15% due to accurate cruise speed seems reasonable. What is not known is the proportion of high-speed sites where the cruise speed is sufficiently in error to affect the accident probability.

There are about 1000 MOVA sites in the UK, a reduction of 5% of accidents (assuming errors in the cruise speed at one third of links) at half these junctions (not all installations are at high-speed sites) would produce a saving of over £1M, assuming an average number of accidents per junction and the average cost of an accident at traffic signalled junctions. Both these estimates are likely to be too low as MOVA has been preferentially installed at the busiest sites and accidents at high-speed roads are likely to be more severe than the average. A saving in accidents of £2M or more, because of increased number of sites under MOVA, by the time that cooperative signal systems become possible is predicted.

Comparing actual journey time with that predicted by the control system should allow some further improvements. However, that would be conditional on the development of a new control system, or major revision of existing systems to use the information.

13.5 **Effect of fitment level**

Cruise time measurements will be possible at low fitment levels; it will take some time to accumulate good data, but there is no minimum market penetration required. Saturation flow will also be calculable at low fitment levels, but realistically only on single lane approaches without significant flaring at the stopline. Market penetration of over 50% will be required to make the headway method of calculating saturation flow feasible and this method is required for flared stoplines and multi-lane approaches.

Typical manual measurements of saturation flow would require measurement over 10 cycles under fairly heavily trafficked conditions, with 10 or more vehicles each cycle crossing the stopline at saturation flow. The proposed method for measuring single lane saturation flows at low penetration levels only requires one vehicle per cycle, but that vehicle needs to be in the queue at the start of...
green with at least 4 vehicles in front of it so that the results are averaged over the reactions and
behaviour (following distance in particular) of a representative number of drivers.

To estimate the probability consider an approach with 900 vehicles per hour, one every 4 seconds on
average, a cycle time of 80 seconds and an effective red time of 30 seconds. Then with uniform
arrivals it will be 20 seconds after the start of effective red before the fifth vehicle joins the queue. On
average, to be a suitable vehicle for estimating saturation flow an equipped vehicle will have to arrive
between 20 seconds after the start of effective red and the time when the back of queue starts to move.
With a typical starting wave of 12 ms\(^{-1}\) there will be a period of 10 seconds in which a vehicle could
arrive. N.B. 10 seconds is an upper limit of the estimate as, on average, the back of queue will start
moving as the 10\(^{th}\) vehicle joins the queue at 40 seconds after the start of effective red. The result is
that only an average of a quarter (those arriving in 20 seconds of the 80 second cycle) of the equipped
vehicles will furnish a useful estimate of saturation flow. With good coordination, the proportion will
be considerably reduced.

On this link with a 10% fitment level 2.5% of the vehicles will provide a good estimate of saturation
flow. For 10 samples that represents a total of 400 vehicles, or nearly half an hour to accumulate the
data. The conclusion is that at low fitment levels, about 5% to 20% it will be possible to measure
average saturation flows by time of day, but not respond to any variations on a timescale of
appreciably less than 1 hour.

13.6 Data needs

The data is to be used in the infrastructure, in the traffic signal control system to monitor its
performance and parameters. It will, therefore, be logical for the control system to define the
locations where it needs vehicles to report their arrival time and journey time from the previous
monitoring point. The set of monitoring points, to include all possible routes, will be transmitted from
the infrastructure as vehicles approach each junction. The timeliness requirement for transmission of
the observation points to vehicles is moderately high, but the subsequent information transmission
from vehicles has low timeliness as the data will be averaged before being used to monitor system
performance and update system parameters.

13.7 Conclusions

Monitoring traffic signal control parameters via probe vehicle data is likely to lead to benefits of
about £60M per annum in terms of reduced delay and also of £1M to £2M in reduced accidents. A
large proportion of the benefits will be available with only a small market penetration.
14 Response to information about slippery roads

14.1 Concept

Weather conditions affect the road surface, which will become more slippery when wet and much more so when icy or covered in snow. In principle probe vehicles could report the change in conditions and the control system make appropriate changes. There are two principal effects of adverse conditions:

- Reduction in saturation flow and increase in cruise time due to change in drivers’ behaviour and vehicle performance
- Increased accident risk from reduction in grip and inadequacy of drivers’ change in behaviour

The appropriate responses to the two effects are different. In the first case the appropriate action is to modify the control algorithm parameters, in the second it could be to increase the intergreen to reduce the possibility of accidents in the junction. However, accidents within the junction are not as common as shunt accidents on the approaches and these accidents are likely to increase in adverse conditions. Increasing the intergreen could increase shunt accidents if some drivers realise that intergreens are longer in the rain and so are less likely to try to stop. Other drivers will be more cautious in the wet. If a driver who is less inclined to stop comes up behind a more cautious driver at the wrong time, then an accident is likely. Ideally action would be taken to reduce the probability of shunt accidents on the approaches to the junction; unfortunately it is not clear what this action should be. A warning could be issued via the in-vehicle HMI to warn of slippery conditions which could help, but could also increase the difference between the behaviour of different drivers with adverse consequences. Any net safety improvements would appear to depend upon the implementation of external control of vehicles to cause all to stop in turn. Similar advantages should be delivered from the provision of automatic cruise control (ACC), which should reduce the risk of shunt accidents.

14.2 Method

Adverse conditions will result in modified driver behaviour, slower speeds, drop in saturation flow etc. and a change in the use of vehicle systems, windscreen wipers and lights, in addition driver assistance systems, such as the Electronic Stability Programme (ESP) and anti-lock brakes (ABS) may become more active. All these changes are potential indicators of a change in conditions that could trigger action in the signal control algorithms.

In section 13.5 it was shown that to provide estimations of current saturation flow requires a high vehicle fitment level of more than 50%. Therefore, in the early days of cooperative vehicle signalling systems direct measurement of the effect of adverse weather on saturation flow will not be possible. Vehicle manufacturers have treated data on the action of driver assistance systems such as ESP or ABS as commercially confidential. Consequently it has not been possible to estimate the probability of these systems providing information on road surface conditions. However, it appears unlikely, particularly for ABS, that the in-vehicle systems would be activated sufficiently frequently in normal driving to give a reliable measure of current road condition. Long term monitoring of road surface deterioration may well be possible, but not detecting the effect of recent rainfall.

Information from windscreen wipers will provide information on moisture in the air, either rain falling, which will wet the road, or spray rising from wet roads. Use of headlights in daylight will help confirm adverse conditions. Outside temperature readings could indicate the probability of ice being detected. A sample of 6 vehicles all with their wipers on would indicate a need for wipers to be in use with a probability of more than 95%. Therefore, a minimum sample size of 6 vehicles will provide good confidence that wipers are needed and the road surface is unlikely to be dry under those conditions. If wipers are to be used as the indicator, the efficiency of the test is greatly increased as all vehicles in the area can be used, not just those on a particular link.
The test for wet conditions will depend on the proportion of vehicles with windscreen wipers operating. Unfortunately, the proportion cannot be obtained purely by exception reporting. If vehicles only report when wipers are switched on there will need to be some extra mechanism to provide an accurate measure of how many have them switched off. When wet weather has been confirmed, then the exception reporting will be switched to vehicles that have wipers off. There are several potential mechanisms:

- A poll of vehicles to obtain the status of their vehicle systems, wipers, lights etc.
- Methods dependant on vehicles reporting when passing census points:
  1. All vehicles passing census points will need to report the status of the equipment in the vehicle
  2. All vehicles passing census points to register their presence with the system at the points. The system would then have to keep a record of the number of vehicles in each section
  3. All vehicles passing census points to register their presence and provide exception reports

There will be a need for short range communications as some cooperative signalling functions require direct vehicle to controller communications. These communications could form the census points; they would not have to be created specially. Therefore, as census points will be there for other purposes, there is no need to go the expense of developing a polling system.

Considering the census point methods:

- The first requires the most data to be transmitted
- The second is subject to error as privacy conditions will probably rule out recording vehicle identifiers and simple in and out counts will be subject to error as there will be sinks and sources of traffic between census points, on-street parking for example.
- The preferred option is, therefore, the third census option, for all vehicles to register and pass exception information at census points with simple periodic area wide broadcasts of the normal data against which exceptions are to be reported.

In an urban area a group of 5 junctions would cover a fairly compact geographical area where weather conditions would be expected to be the same. With only 1500 vehicles per hour passing through each junction that would provide a total of 7500 census readings per hour, if just 1% of vehicles were equipped then it should be possible to confirm wet conditions in 10 minutes. Although six vehicles with wipers operating and none without would give confirmation, the check would have to use a rolling sample and so require results from more than 6 vehicles.

14.3 Benefits and disbenefits

14.3.1 Congestion / delay

There is a limited amount of information on the effect of adverse weather conditions on the behaviour of drivers. Gillam and Withill (1992) estimated an increase in SCOOT link journey times, the free flow cruise time down the link, of about 10% in ‘wet’ conditions and Hounsell (1989) found a reduction in stopline saturation flow of 6% under ‘wet’ conditions. Such changes in vehicle performance should be reflected in control system parameters. Gillam and Withill did make some limited trials of manually modifying parameters and reported indications of an improvement, but they did not have sufficient resources for a full trial.

Estimates were made in the section 13.3.1 of the effects of inaccurate saturation flow and journey time data. For the effects of bad weather we also need to estimate the proportion of time that the
roads will be affected. Rain does not fall uniformly over the country; it is considerably more likely in the West and over high ground. Directly relevant information is not available, but the Meteorological office web site does give average rainfall graphs for the country showing the average number of days in a month when more than 1mm of rain fell. Looking at these graphs and making a quick visual population weighting suggests an average of about 10 such “wet” days per month. However, 1mm is not a great amount of rain and would certainly not result in wet roads for the whole day. Significantly poor weather during peak periods probably affects between 5 and 10% of commuter journeys and that range will be taken as an indicator of the probability of affected journeys.

All links in an area are likely to be equally affected by rain. That is the reduction in saturation flow will not affect the relative demand for green time between opposing links at a junction. It will, however, increase the degree of saturation of the junction if the cycle time is not increased. This increase in saturation will only have a significant effect at the critical junctions in the network, those that are controlling region cycle times. An increase in saturation of a junction from SCOOT’s target of 90% to 95% due to a 5% change in saturation flow would be expected to produce an appreciable increase in delay, 10% or more. However, this increase would only be at 5 to 10% of junctions, assuming the equivalent of two critical junctions in a region of 20 junctions. The overall increase in delay is, therefore estimated to be of the order of 1%.

Assuming an occurrence of conditions that would cause such a large effect for 5 to 10% of journeys produces estimates of the benefits of modifying signal control parameters in response to bad weather of

\[
\text{Benefit of reduced delay} = £2.5\text{M to £5M per annum}
\]

As in section 13.3.1, these benefits assume that all signals are controlled by algorithms that can use on-line saturation flow data. At present only a limited number are and the immediate benefits from provision of improved saturation flow values would be no more than half the values quoted above.

The second response to bad weather information is to try to reduce the increase in accidents caused by adverse conditions. As noted above, the form of the response is not clear as increasing the intergreen although expected to reduce the number of accidents in the junction, may not result in an overall reduction in accidents if drivers respond in such a way as to increase shunt accidents. Increasing the intergreen will result in extra delay to vehicles; the effect will depend on the degree of saturation of an individual junction. As an example, the test junction used in the calculations of the benefits of responding to a change in saturation flow showed a 10% increase in delay for a 2 second increase in the intergreen.

Increasing the intergreen in poor weather to try to reduce junction accidents is likely to increase delay by more than the reduction due to using better optimisation parameter values. The combined effect is uncertain, but a value about half as large as the benefit due to better saturation values is believed to be a reasonable figure.

\[
\text{Net disbenefit of increased intergreen and better saturation flow} \sim £1\text{M to £2M per annum}
\]

14.3.2 Environmental

As with other elements of the system, changes in delay will result in changes in the emission of pollutants.

14.3.3 Safety

It has been clearly established that slippery road surfaces contribute to accidents and there is a large scale programme of routine skid measurement to determine when roads need resurfacing. The accident risk on poor surfaces is particularly high in wet conditions. Approaches to signal controlled junctions on high speed roads are amongst the locations where poor surfaces are particularly undesirable.
At the start of the project, it was expected that one technique to be used by cooperative traffic signalling systems would be to respond to wet weather by extending the intergreen in wet weather to reduce the probability of junction accidents caused by drivers failing to stop and sliding into the junction due to lack of friction. Work through the project has looked at the evidence on the effects of long intergreens, see section 11, and found potential problems with long or unpredictable intergreens. In addition, as described above, increasing intergreens leads to significant increases in delay.

The analysis in section 14.2 shows that, without high fitment levels, the information on road condition will come from the use of windscreen wipers, not direct measurement of the coefficient of friction from in-vehicle systems such as ABS, nor from information on modified driver behaviour. In view of the doubt over the effectiveness of increasing the intergreen to reduce the overall accident rate and the increase in delay, it is not proposed to take action to increase the intergreen on the evidence of windscreen wiper use alone. Also no method of reducing the risk of shunt accidents has been devised. Messages of the type, “It is wet take extra care” are not likely to be effective as drivers may be annoyed as they know it is wet and that is why they have switched the wipers on.

### 14.3.4 Social and accessibility

None obvious

### 14.4 Effect of fitment level

The analysis in section 14.2 shows that information from the use of windscreen wipers etc. will be significant at low market penetration, but other measures based on changes in driver behaviour will not be measurable except at high fitment levels. Provision of direct data on road conditions from systems such as ABS or ESP is uncertain as the motor industry is unwilling to discuss the possibilities citing commercial confidentiality.

### 14.5 Data needs

Wiper and headlight information as discussed in section 14.2.

### 14.6 Conclusions

Adjustment of the traffic signal control parameters is potentially valuable and does not need high market penetration. Unfortunately, it has not been possible to design a reliable method of responding to information on adverse road conditions to reliably reduce the accident risk. Improvements are much more likely if external control of vehicle speed and ultimately stopping is implemented. Lower deceleration rates could be used, with earlier intervention by the system in slippery conditions.
15  Response to downstream problems

15.1  Concept
Downstream problems that cause some degree of exit blocking can seriously impair the operation of traffic signal controlled junctions. Most traffic control systems have difficulty in accurately detecting the extent of any exit blocking. Exit blocking can occur routinely or because of a particular cause, e.g., inappropriate parking, an accident, road works etc. Information collected over a period may be analysed to help understand the nature of routine blocking and to identify solutions which may include re-optimisation of signal timing, particularly over the critical coordination between junctions. For occasional exit blocking it is not important; it is the effect on the discharge from the junction that the control system needs to respond to. Probe vehicle information could provide information on exit blocking to be used by the signal control algorithm.

15.2  Method
There are two possible mechanisms for using probe vehicle data to detect exit blocking:

- Measure changes in the achieved saturation flow using the methods described in section 13.2
- Use information from probe vehicles about unexpected delay in reaching the stopline after the start of green

The first method is preferred as it measures directly the reduction in throughput caused by the exit blocking. Unfortunately as described in deriving the method of measuring saturation flow, it is only possible to get quick updates to the saturation with a very large proportion of the vehicle feet fitted with the system. Therefore, the second method needs to be considered for lower market penetration levels.

The method of measuring saturation flow at low market penetration relies on estimating the number of vehicles ahead of the probe in the queue at start of green and measuring the time from start of green for the probe to cross the stopline. With medium market penetration levels the sampling rate will be sparse in terms of the position in the queue of probe vehicles, and for low penetration rates there will be greens without a useable probe vehicle in the queue. The result of this undesirable sampling rate will be that it is not possible to give a reliable estimate of effective saturation flow in any individual signal cycle. A smoothed average effective saturation flow will have to be calculated and used. It is suggested that the effect of exit blocking should be set to zero following two cycles in which probe vehicles in a good position to detect exit blocking have not detected any and that no significant exit blocking has been detected in any intervening cycles.

15.3  Benefits and disbenefits

15.3.1  Congestion / delay
Reduction in delay could be achieved by including good information on exit blocking in the signal control optimisation. Further improvements might be possible from using the exit blocking information to target measures, such as parking enforcement or obstruction removal, to remove the cause of the exit blocking.

Examination of SCOOT data for the Edgware Road area of London showed that SCOOT had registered exit blocking in 8% of the cycles, averaged over all links, from 07:00 to 20:00. This region is a busy area of London, constituting part of the ring road. It is not possible from the basic SCOOT message on the occurrence of exit blocking to estimate how long the exit blocking lasted, only that the link was exit blocked for some time in the cycle. Normally there are limited opportunities to mitigate the effects of exit blocking. Where possible green can be given to vehicles with routes that do not go
down the blocked link and the signal timings can be optimised allowing for the effect of blocking. However, exit blocking usually means that there is insufficient capacity on a link that a large proportion of the traffic wishes to use and, therefore, it will have serious effects even with the best signal control. Demand management measures are probably required to make a large reduction in the adverse effects.

The SCOOT data for Edgware Road show that in a busy area of London exit blocking can affect an appreciable number of signal cycles (8%) when averaged over a long working day. It would seem reasonable to assume that nationally an average of a few percent, 1-2% would be affected over the working day. Where a link is operating near saturation the effects of exit blocking can be large. The test junction that was used to consider the effects of errors in the saturation flow showed an increase of 20% in delay when the lost time on the dominant direction on the main road was increased by 4 seconds, that is assuming that exit blocking caused a complete loss of flow for 4 seconds of green time on the dominant flow on the main road.

It can be seen that exit blocking is potentially a cause of large delays; increases in delay of 20 to 40% in affected greens on busy links would be far from exceptionable. However, existing control algorithms, SCOOT and MOVA have some automatic alleviating techniques built in. In addition in a coordinated network, traffic engineers can use the congestion management features to reduce the problems caused by exit blocking. Probe vehicle data could provide information for targeted enforcement activity to reduce the effects of exit blocking and to enable optimisation of signal timings based on good estimates of effective saturation flow. It is likely that improved information on exit blocking and consequent signal timing optimisation could reduce delays by about 5% over the working day at very high market penetration rates. Using the delay costs estimated in section 7.2.1 a reduction in delay of 5% over the working day gives:

\[
\text{Benefit of improved control in the presence of exit blocking} \approx \£180M
\]

It should be noted that this estimate is not solely due to the effects of changes in signal control from cooperative traffic signalling, but includes the effects of using the probe vehicle information on exit blocking to instigate other measures, such as targeted enforcement to reduce the occurrence of exit blocking.

15.3.2 Environmental

As with the other concepts, reduction in delay would result in reduction of emissions of pollutants. The precise reductions would depend on the details of how the delay is reduced. Making the same assumptions as in section 6.2.2 would suggest potential reductions as shown in Table 15-1.

<table>
<thead>
<tr>
<th>CO</th>
<th>CO₂</th>
<th>HC</th>
<th>NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>4100</td>
<td>9</td>
<td>1.8</td>
</tr>
</tbody>
</table>

15.3.3 Safety

No major effects expected. Reduction in congestion may result in some reduction in accidents, but the evidence on the relation between congestion and accidents is not strong enough to predict any change.

15.3.4 Social and accessibility

No major effects expected.
15.4 Effects of fitment level
Full benefits depend on a high market penetration to provide good current estimates of saturation flow. At low penetration levels information will be available to identify problem links that are frequently exit blocked to allow targeted action to remove or alleviate the blockage. The SCOOT system detects exit blocking when there is a stationary queue downstream of a junction for several seconds (provided the detector on the downstream link is in the normal position). Therefore, at low fitment levels the system will mainly be of advantage on links that frequently become obstructed and lose a considerable proportion of their capacity, without traffic normally coming to a full stop.

15.5 Data needs
As for estimation of saturation flows in section 13.6.

15.6 Conclusions
Large benefits are estimated, but there is considerable uncertainty in the estimates as it is often difficult to make large improvements to traffic flow by modifying signal control in response to exit blocking. Dynamic cycle by cycle control will only be possible when the fitment level is high. Other measures to remove the blockage are likely to yield more benefit when they are possible.
16 Temporary signals

16.1 Concept
The control systems of temporary signals are not as sophisticated as those of many permanent installations and too often considerably less care is taken in setting up the signal timing parameters. Probe vehicle information could give a good value of the travel time through the road works to provide a sensible intergreen time. It could also provide an estimate of saturation flow.

16.2 Method
Temporary traffic signals are normally vehicle actuated using microwave vehicle detectors (MVD). More sophisticated control would be expected to reduce delay, but the main problem appears to be with inaccurate setting of parameters, intergreen time and maximum times. The intergreen needs to be long enough to enable vehicles to clear the shuttle working section, but not excessively long resulting in unnecessary delay.

Probe vehicles could give a direct measure of journey time through the road works provided some method is provided to locate the ends of the shuttle working. Temporary signals are self-contained units, therefore, to operate cooperatively with vehicles they would have to be fitted with communications equipment to exchange data with equipped vehicles. Short range communications would seem the obvious method. The communications footprint could then be used to provide location information to vehicles. For example, the location of the traffic signals is 5m ahead of where you first receive this communications signal. The vehicle would then report its journey time through the shuttle working section. Allowances would have to be made for start up delays and for slower, unequipped vehicles. The signal control algorithm would then use the measured journey time to calculate the intergreen time.

A more sophisticated control algorithm would remove the need to set maximum green times. The starting point would be to refine the existing recommendations for maximum green times depending on length of the works. The system could then set the maximum green from the measured journey time. Further adjustments could then be made based on the ratio of flow of equipped vehicles in the two directions. The demand for green should be simply the ratio of the flows as with shuttle working both directions travel through the same section of road and, therefore, the saturation flow in the two directions would be expected to be the same. A further refinement would be to balance the delays to equipped vehicles in the two directions, provided that there are no other sources of significant delay close enough to the works to influence the delay to either stream.

16.3 Benefits and disbenefits

16.3.1 Congestion / delay
Work by TRL for DfT estimated that delay at temporary traffic signals is in the range of 2.44 to 18.99 million vehicle-hours per year. The large range was because of uncertainty in the number of temporary signals in use. The estimate from suppliers of signals was much higher than that derived from sample surveys in two counties. In calculating the delay, the researchers assumed that the traffic signals were set in accordance with the recommendations. Some temporary signals are, but experience suggests that many are not and that those that are badly set result in considerable unnecessary delay. Extra intergreen that causes signals to become over saturated can easily double the delay.

It is suggested that efficient timing would result in an average reduction of delay of at least 10% at temporary traffic signals. Converting the delay figures quoted above to a monetary cost using the standard value of time gives a cost of delay at temporary signals, assuming that they are set according
to the recommendations, of £35M to £270 per annum. Therefore, the predicted saving from using
probe vehicle data to set the signal timings is:

\[
\text{Estimated saving at temporary traffic signals} = £3.5M \text{ to } £27M \text{ per annum.}
\]

The delay may be valued more highly by the travelling public as the delays will be unexpected, at
least the first time that the works are encountered without warning.

**16.3.2 Environmental**

Reduction in emissions from reduced delay

**16.3.3 Safety**

Better adherence to temporary signals would be expected from improved operation and drivers not
sitting at red lights for long period without any opposing flow. Any such improvement in the respect
shown by drivers to traffic signals should result in improved safety. The effect could be particularly
valuable if there is a knock-on effect to maintain the credibility of all traffic signals, not just
temporary ones.

The figures on junction accidents analysed in section 11.2.3 show that a 1% reduction in junction
accidents would save over £1M per annum. Such a saving is unlikely from a change in behaviour just
at temporary signals, but could be saved if improved control at temporary signals prevented a general
deterioration in the obedience of traffic signals.

**16.3.4 Social and accessibility**

There will be less frustration for motorists from waiting at signals showing red for appreciable periods
when there is nothing moving the other way. There should also be less frustration from abuse of
signals that currently leads to motorists not being able to move on green because many vehicles have
ignored the red at the other end of the works.

**16.4 Data needs**

Location and time when passing signals at both ends of the works
Location when stopped in the queue on the approach to the signals
Stopping zone and location of signals transmitted from the signals to vehicles
The data volume is not high and the timeliness requirement is low as the data is averaged and used to
update parameters, rather than result in an immediate action.

**16.5 Conclusions and next steps**

Large benefits are possible, but temporary traffic signals will have to be made more sophisticated with
built-in communications and extra vehicle detectors if full optimisation of green timings is desired.
Coordination with adjacent junction controller would also offer significant potential advantages, as
exit blocking often occurs when closely located temporary and fixed signals are not coordinated.
17 Vehicle class information

17.1 Concept
Bus AVL systems are already being linked to traffic control systems to give priority to buses. The bus priority systems are more specialised than the general intelligent vehicle systems that we are considering as they include operational information such as adherence to schedule.

The principle of traffic signal control responding to the special needs of particular vehicles is relevant for us. There may be considerable advantage in extending the green by a few seconds to allow a fully laden HGV to pass through the signals rather than be stopped and then delay a queue behind it as it slowly accelerates at the start of the next green.

Emergency vehicle priority, using green waves and/or hurry calls, is currently provided at some junctions. With communications available between vehicles and junctions as the norm, emergency vehicle priority, activated by the blue lights, could be used at all junctions. With route guidance in the emergency vehicles, the control system could pro-actively modify the timings to clear out queues in front of the emergency vehicle.

For non-emergency vehicles, if vehicle occupancies are known, then the signal control could optimise on person delay rather than vehicle delay. N.B. the simple occupancy would not give the value of the occupants’ time, which is higher for working than for non-working time. Some estimates could be made by vehicle type, e.g. HGV drivers would be expected to be working, but average figures would have to be assumed for car occupants, unless the driver is prepared to pay for priority, which would give a useful measure of the perceived value of that individual’s time.

17.2 Method
For bus priority, there may be economies in not having to provide special communications systems from buses to signals, simply use the cooperative signalling system communications, but the specialised public transport priority system would be retained for intelligent priority linked to bus performance.

Priority for heavily laden HGVs could be given by an equivalent of the bus priority extension facility, where a qualifying vehicle approaching the signals at the start of red is granted a short extension to the green time to prevent it stopping.

Emergency vehicles would be given priority by changing the signals to green in advance of their arrival. Conceptually the system would be simple with exchange of route information from the emergency vehicle’s navigation system to signal control and then the appropriate signals set to green as the emergency vehicle passes a trigger point. The complications would be in the interfacing between the systems and defining the trigger points such that the queues are cleared in advance of the emergency vehicle, but not so far in advance that opposing vehicle drivers become frustrated.

Provision of universal vehicle to signal system communications would make it relatively easy to provide a green signal as an emergency vehicle approaches a junction, more extensive priority to clear out the queue in advance of the arrival of the emergency vehicle would be much more disruptive to traffic operations.

Optimising on vehicle occupants time would require a sufficiently high market penetration that vehicle detection information can be reliably converted into persons on individual links based on the current average occupancy of equipped vehicles on that link. The optimisation would then be simply a case of modifying the objective function.
17.2.1 **Policy issues relevant to this concept**

The policy issues relevant to this concept are included in section 2.2.6, Modify signal timings for different types of vehicles. There is an additional question as to whether it would be acceptable for individuals to buy priority. This should be at a commercial rate for the benefits gained. A charge of say £1 per minute saved would be consistent with the costs of a business executive’s time. But clearly the value to the individual may be much higher if they risk missing a vital opportunity, such as catching the train to a vital meeting. Of course there would be incidental benefits to adjacent vehicles travelling in the same direction, but disbenefits to others.

17.3 **Benefits and disbenefits**

17.3.1 **Congestion / delay**

It is not anticipated that there would be any significant effect on delays from the use of coordinated signalling systems communications for bus priority. However, there could be an effect on the provision of priority at more signals from removal of the need to provide dedicated communications from buses to signal controllers.

Provision of bus priority has not produced large disbenefits to other vehicles when it has been introduced in a controlled manner with the priority limited in the busiest conditions. Allowing fully laden HGVs to benefit from extensions under similar restrictions should not produce large disbenefits to vehicles on other links; it is only proposed to extend an existing green by a few seconds to avoid stopping a laden HGV at the end of green, not to recall an earlier green for HGVs. The net effect is likely to be little change in overall delay per vehicle assuming that most HGVs are on the major routes. (Modifying optimum timings slightly in favour of the main road is much less disruptive than modifying them in favour of the minor road.) Benefits to HGVs will be similar to those to buses, an average of around 2 seconds a vehicle, but much larger to individual vehicles that benefit from an extension.

HGVs predominantly use the main routes, therefore, they will be much more common at signals on these routes than at signals off such routes. There will also probably be buses receiving priority on the same routes. Experience with active bus priority in SCOOT shows that, typically, priority using extensions provides an average benefit of 2 seconds per vehicle, but somewhat lower with high flows of buses. Giving priority to both HGVs and buses will result in high flows of priority vehicles and a benefit of 1.5 seconds per vehicle will be used.

Taking a flow of 1 HGV per minute through a third of traffic signals for 10 hours per day Monday to Friday and 5 hours per day on weekends a saving of 1.5 seconds per vehicle produces:

\[
\text{Time saving to HGV} = 1.5 \times 60 \times 4000 \times 10 \times 6 \times 52 / 3600 = 0.31 \text{M vehicle-hours per annum}
\]

Assuming that the priority is well controlled and effectively neutral to overall delay, there will be a similar disbenefit to other vehicles. However, HGVs are much more expensive to operate than average vehicles. The value of the occupants time and operating costs for a car at low urban speeds is £14 per hour, whilst a large HGV is £29.20 per hour (TAG 2004). Therefore the benefit of limited priority to HGVs approaching traffic signals that are about to change from green is estimated to be:

\[
\text{Benefit of limited HGV priority} = 0.31 \times (29.2 - 14) \approx £5 \text{M per annum}
\]

Priority to emergency vehicles will reduce their journey times. Surveys at several junctions in London for the assessment of stage skipping for bus priority showed average junction delays of 20 to 60 seconds per vehicle. Emergency vehicles do not experience the same level of delay as other vehicles because of the way that they overtake queues and can proceed cautiously through junctions against the traffic signals. Therefore, a saving of at most half of the delay experienced by other vehicles, 10 to 30 seconds per junction, is postulated. The longest delays result from long queues to reach the junction, which emergency vehicles usually manage to overtake, therefore, the saving from
signal priority is likely to be towards the lower end of the range. Therefore, for an emergency route involving 6 sets of traffic signals a potential saving of 1 to 1½ minutes is expected.

The current response of vehicles to reduce delay to emergency vehicles is disruptive. Formalising this response by the action of the traffic signals will reduce some delay on the emergency vehicle’s route, but increase it on opposing routes.

No published information has been found on the disruption to traffic caused by emergency vehicles on which to base estimates of extra delay due to providing very high priority levels at signals. Consequently a quantitative estimate of the extra delay has not been made. It appears that the major consideration is that such high priority is known to be very disruptive and should be reserved for truly emergency situations. Agreement will be needed with the various emergency services on a code of practice for invoking priority that attempts to clear out the queue in front of an emergency vehicle. The conditions for invoking such priority will be much stricter than for providing a green signal when the emergency vehicle has fought its way close to the junction.

17.3.2 Environmental

There will be a reduction in emissions from reducing the number of heavily loaded HGVs that have to stop and start at traffic signals, but an increase in pollution from extra delay due to emergency vehicle priority.

17.3.3 Safety

There are likely to be safety benefits from providing formal priority to emergency vehicles in terms of both a faster response to the emergency and reduced accident risk at traffic signals on the way to the emergency. Figures quoted for the benefit of faster response are not always fully substantiated as exemplified by figures of extra deaths due to speed humps slowing ambulances. Accident figures at signal controlled junctions for emergency vehicles responding to an emergency are not readily available. However, a large reduction in accidents involving police cars was reported in London following the fitting of black box recorders; presumably driver behaviour is a major factor in accident risk.

There is some evidence that HGVs are less likely to stop at the onset of red than are cars (Baguley and Ray 1989). The reason is probably a combination of the poorer braking efficiency of HGVs and driver’s reluctance to stop a heavy vehicle. Selectively extending the green for HGVs at the end of red should reduce the incidence of such red-running. The greater level of red-running by HGVs than cars and the associated accident risk has not been quantified, considering the figures on the cost of junction accidents presented in section 11.2.3, a benefit of a few million pounds per annum looks possible. This benefit assumes that HGV drivers do not change their behaviour to assume that they will not be stopped. Some enhanced enforcement as suggested in section 11 would be strongly recommended.

17.3.4 Social and accessibility

Turning traffic signals green for emergency vehicles should result in less stress to both emergency vehicles crew and drivers trying to clear the approach to a junction to assist the emergency vehicle. There is potential for a reduction in stress for drivers deciding whether to stop for an amber signal and feeling intimidated by a following HGV.

17.4 Effects of fitment level

For the purposes of responding to specific classes of vehicles, the general market penetration level is not relevant. The benefits will scale with the number of junctions equipped, in a non-linear way, as the busiest junctions with the greatest delays are likely to be equipped first. However, there is no
threshold effect requiring a minimum level of equipped junctions or vehicles. Emergency vehicle crews would need to be aware that not all junctions may be equipped, and indeed that equipment can fail and drive appropriately.

17.5 Data needs
Position

Vehicle type, including current weight and speed for HGV, possibly occupancy for cars, emergency vehicle if blue lights in use

Timeliness is high as the data required are for current optimisation of the signals.

17.6 Conclusions and next steps

Cooperative traffic signalling systems offers the prospect of available communications between vehicles and signals. Emergency vehicle priority should be included in the system as the additional costs on top of the basic system will be small and there will be benefits to emergency vehicles from quicker journey times, savings of a minute or more would be expected on journeys through several sets of traffic signals.

Introduction of a variable scale of priorities should be considered.

Establishment of blue waves should give real advantages to the emergency services.
18 Virtual traffic signals

18.1 Concept

The concept is of a junction control system whose aim is to eliminate accidents. If we apply that objective to the concept of cooperative traffic control, then we must allow the control system to take control from the driver to prevent an accident, should the driver make a mistake. That control might then be applied to all junctions, and would need vulnerable users to be included within the system.

This ultimate cooperation between vehicles and junction control systems would require vehicles to became self organising, communicating with each other to determine optimum priorities at the intersection. If all vehicles had such a system then, ultimately there would be no need for traffic signals; all the instructions and possibly controls on whether to proceed and at what speed would be provided in the individual vehicles and to individual pedestrians. There would still be an external component to ensure that appropriate priorities were set to implement public policy.

All road users would need to have appropriate equipment. This would include bicycles, milk floats, tractors, horses etc. Ideally, all pedestrians would have a device, so that the drivers would be immediately alerted to a pedestrian crossing the road. Indeed pedestrian units could have a button to flag that they intended to cross the road and an indicator to tell them when it was safe to do so. The priority given to children could depend upon the location (near a school) and the time of day.

Essentially people would carry a Puffin crossing in their pocket and they would be expected to obey its instructions. Whilst it would not be possible to prevent a pedestrian from walking into the road, it may be possible to detect this activity and warn drivers, or control vehicles so as to avoid an accident.

The danger of such a system is that pedestrians could abuse this technology and simply walk across roads without worrying about their safety and the unnecessary disruption of traffic that would follow!

18.1.1 Policy issues relevant to this concept

This concept is for a very futuristic, potentially big brother system. As such it has not been studied in great detail, but analysed to test the compatibility of the other proposed elements of a system with the concept of a fully controlled travel environment.

18.2 Requirements

With physical traffic signals it is possible for an observer outside the car, or technology such as a red-light camera to observe abuse of the signals. With in-vehicle signalling, enforcement will require in-vehicle observation. As it is not possible to put a policeman in each car, the in-vehicle technology will have to include an enforcement element. That could be either observation and reporting of offences or automatic vehicle control. It is not important which option is selected to check compatibility of the systems proposed in the previous sections with virtual signals.

Control of pedestrian behaviour will be much more difficult. It will rely on all pedestrians fully comprehending the technology, how to use their individual device and understand its instructions. Having understood the instructions they would then be expected to obey them. It would not be possible to enforce obedience without access to an audit trail in the pedestrian unit and a method of comparing a pedestrian’s actions with the instructions. In the event of a collision in the carriageway, the comparison would be fairly simple: was a request to cross the road input to the unit? If so was the last instruction to cross or wait?

The system would have to be built to a high safety and integrity level and to allow for all the interactions between the many vehicles and pedestrians moving in the vicinity. In addition there would have to be a full audit trail to settle liability issues in the event of a problem.
The communications system would have to enable communication between all vehicles and pedestrians as well as with the infrastructure to allow the public policy input. Extensive confirmation capabilities would have to be built in so that each unit authorising a movement would have confirmation that it was permitted by all other relevant units. That they would not make a decision that would conflict for the duration of the authorised movement, including the effects of the momentum of the vehicle at the end of the manoeuvre.

Potentially the system could control the headway of all vehicles as well as their speed and manoeuvres. Essentially vehicles would be under automatic control even if the control was in the form of detailed instructions to the driver. In practice it may be difficult to provide detailed instructions to the driver in such a manner that he or she can also actively monitor the road. Lateral as well as longitudinal control will be required.

18.3 Relation to cooperative signal concepts

18.3.1 Demand management
Demand management would be made easier if individual vehicles had to obey system instructions. For instance, it would be possible to force rat running vehicles into a separate queue at a junction where they would be delayed compared with residents exiting their home zone. All vehicles would have to be equipped and so management of journeys would be technically simplified, but not necessarily any easier politically.

In principle it would be possible to restrict access to sensitive areas (eg. outside school during the daytime) to those vehicles that had a certain level of automated safety control. This might be implemented for a full Vision Zero capability, or perhaps for vehicles with ISA which would automatically limit the speeds when passing school gates etc.

18.3.2 Use of route information
Assuming all vehicles are fitted with route guidance systems as well as virtual signal systems, then the ability of an (automated) supervisor to calculate diversion routes for incidents will be enhanced, but, more importantly, it will be able to impose that diversion pattern on individual vehicles.

18.3.3 Information to vehicles that they will lose right-of-way
The ability of drivers to abuse information will be removed as the information that the signals are about to change would be replaced by an enforced instruction to stop at the forthcoming junction.

18.3.4 Information to vehicles about start of green
Again the opportunity to abuse information is removed and the concept becomes feasible, if the driver is in control, or irrelevant if the vehicle is under system control.

18.3.5 Green wave information to the vehicle
With full detailed control of all vehicles, journeys would become more predictable and so green waves could be devised that are reasonably efficient and vehicles could be controlled to travel at the required speed. The algorithms necessary to produce such green waves will still be expensive to develop, but development of a new control algorithm could be needed to take optimum advantage of virtual signals.
18.3.6 Use of vehicle stopping information
With full control the concept of fixed intergreens will need to be reconsidered. The use of information on the future behaviour of vehicles to optimise clearance periods will be a natural part of virtual signalling.

18.3.7 Response to and prevention of red-running
With full control or enforcement the problem of red-running should be effectively eliminated. If the driver control and enforcement route is taken, then there will still need to be the capability to extend the intergreen if a driver does red-run despite the certainty of prosecution.

18.3.8 Probe vehicle information
Probe vehicle information will be excellent as potentially every vehicle is a probe. As mentioned previously, virtual signals will require a major investment and part of that investment is likely to be to produce a new signal control algorithm to take advantage of the universal fitment and having all vehicles as potential probes.

18.3.9 Response to information about slippery roads
The response will be much more effective with full virtual signalling. Adjustments to vehicle speeds and saturation flows will be made on the basis of real performance as all vehicles will be probes. In addition it should be able to take effective action to prevent shunt accidents. It will be possible to enforce more caution on the approach to signals.

18.3.10 Response to downstream problems
Again the detection of exit blocking should be much improved and there will be scope for feeding the information back into route guidance systems, or a supervisor, to minimise the effects of the exit blocking.

18.3.11 Temporary signals
Universal fitment will enable accurate calculation of parameters, but in addition, the timings can be optimised each cycle because of the full information. For example, the clearance period could be extended for a bicycle, but shortened the next time because the cars were allowed to travel faster than average.

18.3.12 Vehicle class information
Again the large investment required for virtual signals offers an opportunity to develop new control algorithms that could incorporate special facilities for emergency vehicles and other specific classes of vehicles.

18.4 Conclusions
Universal equipment of vehicles with virtual signalling equipment and the requirement for vehicles to obey that equipment offers opportunities to further develop the concepts considered in this report. There are no conflicts between the concepts considered and virtual signals, but virtual signalling would be both a major investment and a major restriction on drivers’ freedom to control their vehicles or an intrusion on privacy as the vehicle would have to report every transgression of the virtual signal instructions.
Pedestrian adherence to virtual signals is likely to be problematic: the need to comprehend, carry and obey equipment.

All potential road-users in the area would need to be interconnected. Whilst priority can be established between two entities, with reasonable ease, prioritisation across a multitude of entities would create major challenges, not least because each road-user would be negotiating with a different set of nearest neighbours.

There would be an extremely high reliability requirement on both the equipment and communications systems. The driver of a vehicle with a failed unit would not know whether it was safe to proceed at every intersection on his route and would be a potential danger to pedestrians.
19 In-vehicle systems

Each of the use cases described in this report requires that there is an on-board unit in the vehicle that provides:

- A means to monitor and interrogate the vehicle’s internal information bus (CAN bus, K-line etc)
- A means to monitor the vehicle’s location
- A means to communicate information between the vehicle and traffic signal outstation control unit

Additionally, certain applications require:

- a means to communicate with the driver
- a means to take control of key vehicle parameter (brakes and accelerator). Note that this would have to be a system that the driver could not override.

The cost of a basic platform to be retrofitted to vehicles would be likely to cost in the region of £150 to £200 plus fitting and testing which might be a further £150 to £200, assuming that this is fitted as an after-market item. Overall the cost would be expected to be £300 to £400 fitted. These costs might be doubled to about £600 for a platform that could take control of some of the vehicle’s parameters.

Signalling on the CAN bus is only partially standardised and therefore aftermarket telematics platforms would need to be carefully configured. Clearly fitting these systems as original equipment will be much more cost-effective, with the manufacturer responsible for implementing and testing the individual monitoring and command capabilities.

Ideally the cooperative control of traffic signals might run as an application on a telematics platform provided for other applications. For instance full function Intelligent Speed Adaptation runs on a platform that has awareness of the precise location of the vehicle, and hence the speed limit that applies, as well as the location and speed of nearby vehicles, in order to determine the most appropriate speed for the vehicle to travel. ISA could be integrated into the cooperative control system, so as to automatically prevent red-running, jumping red lights etc.

Other developments that will support limited connection to the CAN bus, and external communications are:

- Electronic Fee Collection / Road User Charging
- Electronic Vehicle Identification
- Electronic Tachograph
- eCall / e112

Each of these new services is subject to European policies and directives. Indeed Directorate General Transport and Energy (DG TREN) has commissioned the eNlink consortium to develop the requirements specification for a Universal on-Board Unit that will support all of these applications. It is likely that the EU will mandate the fitting of this UOBU to all vehicles (private cars as well as trucks). It is vital that the UOBU is specified to also support the protocols and use-cases defined in this report.

It is likely that the directive might come into effect within 5 years, such that within 15 years we would expect 99% of vehicles on the road to be equipped with the UOBU. The UOBU will include the capability to download and configure new applications. This should enable an initial implementation of cooperative traffic control to be implemented, once the necessary critical mass for that application has been achieved. Functionality can then be increased by remotely controlled download, as higher levels of functionality can be supported with increasing penetration of suitably equipped vehicles.
Work in the Traffimatics project has already established the feasibility of extracting the relevant data from a vehicle’s CAN bus using a suitable adaptor as shown in Figure 19.1.

**Figure 19.1: Traffimatics project CAN bus gateway**
20 Location technology

There are two distinct techniques for determining location:

- Global Navigation Satellite System (GNSS) combined with map-matching technology to allow the precise context of the location to be understood.

- Short range radio systems act as “beacons” which serve the dual purpose of allowing a short burst of data transfer over a very short length of road, but in doing this the location of the vehicle is precisely known.

Considering the suitability of each system:

20.1 GNSS

GNSS is currently available as GPS. The average error of GPS is less than 10 metres, but the peak errors can be over 100m. GPS is currently being enhanced by the experimental EGNOS system, and the European Galileo system will become available in about 2010. These systems should deliver better performance in terms of:

- Accuracy (error that would normally be expected)
- Availability (no outage caused by satellite problems)
- Coverage (Geographical areas where the system works reliably)
- Integrity (Information to warn the user when the output is likely to contain errors)

A full service that uses both Galileo and GPS should give better than 3 metres accuracy with a good clear sky view. This would be sufficient for most applications but not for:

- The enforcement of red running use case, and
- Virtual traffic signals use case.

Enhanced accuracy would be needed for these services to operate adequately for these applications. The most appropriate technique is RTK, which is discussed below.

Of course the enhancement in accuracy overcomes only one of the limitations of GNSS. Coverage is a more important limitation, as there will be many urban junctions where the view of the sky is obscured by tall buildings. In these situations the GNSS may produce large errors. This problem can be overcome using augmentation, but this technique is not yet mature and the levels of performance that we can expect can only be estimated.

20.1.1 Real Time Kinematic (RTK) systems

Real Time Kinematic systems detect the precise carrier phase of the signal received from the satellite. This technique can lead to millimetric accuracy for static systems, and a few centimetres for moving systems. RTK requires that the device to be located has live communications with a nearby reference system, which is operating from a known position. The communications capacity is less than 1,000 bits per second, but it needs to be provided continuously. If less than 4 satellites are being received at any one time, or the RTK communications channel is lost, then the system will need to go through a re-acquisition phase. Reacquisition may take many seconds. This technique is still at the PhD research stage.

Because RTK also suffers from loss of contact with the satellites it is necessary to find some form of augmentation to maintain accurate knowledge of position and allow speedy re-acquisition.
20.1.2 Augmented systems

Augmentation techniques include:

- Downloading ephemeris data to the receiver as soon as it is turned on – this avoids the very slow initial acquisition process that can take many minutes.
- Pseudolites can be used to provide additional satellite type inputs to the receiver. There are blocking interference problems with the power levels if the user approaches too close to these devices, but they are generally effective, but expensive.
- Additional methods of estimating position can be combined with the GNSS data using Kalman filtering. Alternative sources of information might include:
  - Inertial navigation systems (Giro compasses and accelerometers)
  - Dead reckoning (eg using wheel rotation counting and compass)
  - Use of road-side beacons at known locations
  - Use of terrestrial positioning systems such as:
    - Loran C
    - Ultra WideBand (UWB)
    - “Cursor”
  - Provision of an on-board atomic clock (time is one of the variables that has to be solved)
  - Map matching, to constrain the range of possible locations

20.1.3 Recommended solution

It is clear at this point in time that GNSS would be a suitable location technology for many of the use cases, but not all. In particular, it would not be possible to forecast with absolute certainty that it can be developed so as to give the performance needed for systems where the information gathered is used to control the vehicle.

One possible approach would be to use the emerging UWB technology which should give centimetric accuracy, but in a fairly limited area (at least the area around the intersection). But again this requires the UWB infrastructure to be installed around the area of interest. More research work is needed here.

20.2 Radio beacon

Radio beacons have been used with mixed success by Transport for London, in implementing their Automatic Vehicle Location (AVL) system for controlling the running of London buses, and driving the Countdown bus information service. Radio beacons are essentially a specialist form of two-way radio communication system. The vehicle may simply send its identification, but can also send probe vehicle data. The polar diagram, see Figure 20.1, for such a system would normally be made deliberately small, so that the vehicle knows that when it is receiving information from the beacon it is located somewhere within the coverage range. Beacons have some disadvantages:

- They are not easily moved, and need to be sited at a point where they will be needed for the foreseeable future.
- They do not give any warning as the vehicle approaches. This means that, used in isolation they would not really be useful for enforcing red running. Whilst a command to stop as soon as the vehicle receives the beacon signal might be effective at stopping a vehicle travelling slowly, it would not be able to control a car that approached the beacon at speed, when the vehicle would travel beyond the beacon coverage range before it could be made to stop. A
second beacon in advance of the stopline would be required to command the vehicle to come to a stop x metres in front of the beacon, or sooner if the vehicle detects stopped or slow moving vehicles in front of it. The problem of sensing other vehicles will need to be solved however the stopping command is delivered to the vehicle.

An alternative approach might be to use another technology that provides a marker that can easily be recognised. Technology might include:

- Inductive loop in the road!
- Visible car code
- Infrared beacon

On the whole radio beacons are not considered to offer potential to be cost effective ways to determine location accurately. A sufficiently dense network of beacons would require a very large infrastructure investment.

Figure 20.1 shows the typical performance of CEN TC 278 passive 5.8GHz microwave and infrared based tolling technology. The communications range (and hence positioning range) for this configuration is about 9 metres (max). Note that a metalised windscreen will affect the path losses for a microwave signal, which will cause the calibration for positioning purposes to vary. With a system of this type it is feasible that the make contact and loss of signals points could both be used to confirm location.

**Figure 20.1** Polar diagram for tolling beacon technology (source Efkon AG)
21 Data communications

A number of communications technologies could be used to carry the necessary data transfer between the vehicles and the infrastructure (and occasionally between vehicles). These options will be explained below; however attention is drawn particularly to the CALM standard which has been developed specifically to meet the needs of cooperative vehicle highway systems and is described in section 21.6. This has the potential to deliver all the functionality required by cooperative traffic control systems.

21.1 Commercial Models

There are three aspects to costs of communications:

- Infrastructure Provision
- Mobile terminal provision
- Operational costs

There are two commercial models that can be applied:

- A private system can be installed on behalf of the stakeholders, who club together in some way to raise the capital and manage the provision, and then the ongoing operations and maintenance. Costs for this can be difficult to predict.
- A public system can be installed by a third party who recovers their investment by attracting users who pay a fee to receive service.
  - This has the advantages of
    - Spreading the risk – if communications demand is less than expected, the service operator is left with the challenge of cost recovery
    - The stakeholders do not need to run a major programme to implement the communications system
    - Capital expenditure is reduced
  - A public system has disadvantages
    - No direct control of performance of the network, eg improving areas of poor coverage
    - Higher operating costs

A hybrid is possible whereby a third party operates a private service on behalf of the stakeholders. Using this process there is an opportunity to adjust the sharing of risks. If the stakeholders are able to predict the demand accurately, and place long term contracts, it should be possible for the service operator to work on lower margins. The different technologies available tend to fall naturally into one of these models, some suit either business model.

21.2 Broadcast data

Broadcast data is insufficient on its own for most of the use cases considered for cooperative traffic signals systems. One possible use would be to distribute access rights information to a series of physical access control points, if decisions on which vehicles are to be allowed are to be made locally. However, it is recommended that such decisions are made by a centrally controlled service that has active dialogue with the controller and probably the vehicles trying to gain access. Possible bearers include:

- RDS TMC
• DAB
• Pager

21.3 Managed cellular network

There are essentially four managed network options.

• GSM / GPRS
• Third Generation Mobile (3G)
• Tetra
• GSM-R

GSM and 3G are managed as a publicly available service, with users paying a fee proportionate to the volume transacted. Costs have recently fallen significantly with transmission of 1Mbyte of data now costing less than £1. However, coverage is less than perfect, and whilst useful for the collection of floating vehicle data etc, would not be suitable for safety critical applications.

Tetra is operated by O2 Airwave, for the emergency services, and spare capacity can be accessed, subject to Home Office permission, on a secondary basis, subject at any time to pre-emption by the emergency services. The Airwave system provides a much more comprehensive coverage, as it must allow emergency services to work deep inside buildings. However, the fact that the network may be withdrawn for higher priority users makes it unsuitable for this application.

Tetra can also be implemented as a private network, on a self-managed (or contract managed) basis. However, it is unlikely that the costs would be significantly cheaper than buying managed airtime on GSM or 3G.

GSM-R is a special version of GSM that was developed for use on the railways. This is designed to be a private network operated on behalf of the user.

Deployment of GSM-R or Tetra as a network exclusively for transport information would be possible, but it would only work if adopted across the UK, which would require all the potential local authorities to agree to fund this. A UK-wide private network dedicated to transport would appear to be an unlikely prospect.

21.4 Short range communications

A number of technologies have been developed across Europe. These include:

• 2.45GHz Active Microwave
• 5.8GHz CEN278 Passive Microwave
• Infrared
• WiFi
• WiMax

2.45GHz active tags, 5.8GHz passive tags (CEN TC 278) and proprietary Infrared systems have been developed for road toll applications. 2.45GHz active tags are being phased out, mainly because of the interference in the 2.45GHz Industrial, Scientific & Medical (ISM) band.

WiFi is the term loosely applied to a range of wireless local area network (LAN) protocols that were initially designed by the IEEE 802 committee to operate within buildings to provide a wireless Ethernet that allows computers to be connected to the network for domestic or commercial purposes. These networks have since been made available as a managed network with coverage at hot-spots with service provided by companies such as BT and Cloud. Range is limited to about 100m with
interference sometimes causing problems, particularly outside. The time to establish a first connection is also a problem. These problems have been recognised and several new variants of 802.11 are being developed, which should overcome these problems. A particular example is the CALM standard that is described later in this section.

WiMax or IEEE 802.16 will provide a much higher performance, higher capacity and longer range (several kms) capability. This offers potential to provide connectivity to roadside infrastructure, instead of using fixed networks.

A key aspect of short range communications is that, because they only operate over a short range, they can also provide location information to the vehicle, or about the vehicle. WiFi coverage is somewhat unpredictable, whereas 5.8GHz communications can make use of a directional antenna which limits the area of operation to a zone that is defined by the antenna and its mounting arrangements.

Infrared is very flexible because an optical lens system is used instead of the antenna. Consequently the field of operation can be set by the optical field of view. A telephoto lens at low level can be used to provide a relatively long communications zone, perhaps for a vehicle approaching a junction. By mounting the lens at a greater height is it possible to ensure that only a small area of the road is visible, which would give a more accurate location update, but reduces the time during which data can be transferred.

21.5 Ad-hoc short range communications

Some of the problems of range, interference, and equipment faults can be overcome by using ad-hoc communications. Ad-hoc communications is an ideal protocol to use in a mobile environment. Ad-hoc communication would be used when a mobile terminal needs to communicate with an application on a server in the infrastructure (or even in another vehicle), but does not have access to a direct connection to that server. Communication is established by sending messages to one or more near neighbour terminals, which in turn forward the message, until a terminal that has access to the infrastructure is able to deliver the message to the infrastructure. There are many different routing schemes that are in use and many more in development and evaluation.

Ad-hoc communications are used by the military to provide a highly reliable, self organising network that automatically accommodates the destruction or failure of any part of that network. However, for transport applications there is a more important benefit, that the costs associated with a fully managed mobile network are avoided.

A number of radio protocols can be adapted to support ad-hoc operation

- WiFi has an ad-hoc mode
- ZigBee is new standard, that is designed to operate on an ad-hoc basis, primarily within the domestic environment
- Proprietary (eg Mesh Networks)
- CALM – is described in more detail below.

21.6 CALM – ISO TC204 WG16

CALM has been developed via a collaboration between CEN TC 278 and ISO TC 204, as TC 206 WG16. The objective is to provide a common mid-stack protocol that enables many telematics applications to be supported via a range of communications systems. An important feature is the local management and selection of communication system to be used when several systems are available. In principle, CALM would be able to understand the priority associated with each application, and be able to route urgent messages via GSM, should there be no lower cost alternative available at the instant that the message was originated. However, if a non time-critical messages (perhaps relating to
probe data reporting “normal condition”, then the message may be stored until a low cost connection becomes available.

The CALM Concept is shown in figure 21.1 and the physical communications media that are currently included within the scope of WG16 are listed below the figure. Additional media (such as Satellite) could be included if there are volunteers to work on the standard.

CALM Comms Scenarios

Figure 21.1 CALM communications scenarios. Source CALM Conference, Ulm Dec 2004

As can be seen a diverse range of physical communications media are supported, including:

- GSM / GPRS
- UMTS / 3G
- Active 60GHz millimetric microwave
- Active 5.8GHz
- Infrared
- DAB
- Satellite broadcast
Full details of the CALM architecture are beyond the scope of this project. However, the simplified CALM architecture in figure 21.2 shows the principle of supporting the ITS applications that have been defined in TC 204 over just 4 of the physical media is reproduced for the interested reader. It shows that reliable transport (TCP) transactions are supported as well as un-acknowledged datagrams using UDP.

**Figure 21.2: Simplified CALM architecture. Source CALM Conference, Ulm Dec 2004**

### 21.7 Recommended approach

All the applications called into play by the use cases described in this study should make use of the UOBU which is assumed to make use of CALM technology.

- For communications to and from the outstation traffic-control-unit it is envisaged that a short range system such as the new CALM M5 or active Infrared technology will be used. These systems will also provide some additional location information.

- Communications over a longer range, to contribute probe data etc will make use of ad-hoc communications technology, which will be able to use GSM / GPRS or 3G systems as a back-up.
22 Costs

The analysis of the individual components has concentrated on estimating the benefits as these are relevant to the individual components and in many instances difficult to estimate. The costs of the system are also required, but many of the costs are common to the system and do not change greatly on adding a new component. The major single cost that is required before any components can be introduced is the communications system. In addition there would need to be an in-vehicle system to provide vehicle data for transmission to the infrastructure and to process information from the infrastructure and present it to the driver. Much of this development would, again, be common to different components. Further in the future the information could be used to directly affect the vehicles’ control system, rather than be displayed to the driver. Such a development is unlikely to be made exclusively for cooperative traffic signalling; the signalling system would piggy back on other driver assistance system developments.

22.1 In-vehicle systems

With the introduction of the UOBU as a standard fitment to all vehicles at some stage in the next 5 to 10 years, we can discount the cost of any technology needed to support the use cases described. However, it is important that a small amount is invested to ensure that the cooperative traffic control requirements will be met by these developments.

22.2 Communications system

Figure 22.1 shows that use of “wireless access” (WLAN) technology is likely to cost only a fraction of the cost of GPRS and 3G (UMTS) data, n.b. the cost axis on the diagram is a logarithmic scale. This figure was prepared in 2002 and prices continue to fall.

For planning purposes, it can be assumed that costs of the required communications will fall to about £0.20 per Mbyte, based on the use of a CALM interface in a UOBU fitted to all vehicles.

This will allow applications to use the most appropriate technology available at the time.

Mobile Coms. Cost Trends

![Cost per Mbyte of competing mobile data services](image)

Source: Analysys Research, 2002

**Figure 22.1: Cost trends for mobile communications**
22.3 Control software costs

Many components can be introduced at a low cost as a modification to existing control. An alternative approach would be to produce a totally new control system based on the information available from equipped vehicles. Based on the cost of developing existing control systems, it is estimated that a totally new control algorithm would cost several tens of millions of pounds to develop and test to the point that one could be confident that it worked well in all foreseeable circumstances and represented an improvement over existing systems. By contrast to develop a component as a modification of an existing control algorithm would be expected to cost in the tens of thousands of pounds.

As an example, we can consider the use of information about slippery roads. That would need to take information from the vehicle about the use of windscreen wipers, a very low cost development, once the basic system to extract information from the vehicle’s data bus, process and transmit it has been created. Similarly, the response in the traffic control system will only require a link for the new system to the existing control algorithm that will change the appropriate parameters, journey time and saturation occupancy for SCOOT. The additional costs to add this functionality to a basic cooperative traffic signalling system would be very small.
23 Conclusions

Some of the ideas for cooperative traffic signal control identified in this study would appear to offer real benefits in improved efficiency of junctions and safety. However, many use cases would only deliver benefits when all vehicles are equipped to work in a cooperative way. The benefits, risks and recommendations are summarised in Table 23-1.

<table>
<thead>
<tr>
<th>Use-case</th>
<th>Benefits?</th>
<th>Risks?</th>
<th>Further study?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand management</td>
<td>Yes (value?)</td>
<td>Needs high % equipped</td>
<td>Yes</td>
</tr>
<tr>
<td>Route information</td>
<td>£8 to £80M</td>
<td>Drivers must set indicators &amp; use DRG</td>
<td>Yes</td>
</tr>
<tr>
<td>Loss of right of way</td>
<td>No</td>
<td>Confused drivers: more shunts, unless all vehicles controlled</td>
<td>No</td>
</tr>
<tr>
<td>Start of green</td>
<td>£7 to £35M</td>
<td>Must prevent early starts</td>
<td>Yes – User behaviour</td>
</tr>
<tr>
<td>Green wave speed</td>
<td>No, unless all vehicles are equipped and are controlled.</td>
<td>Reduced throughput: more shunts</td>
<td>No</td>
</tr>
<tr>
<td>Vehicle stopping</td>
<td>Only if combined with prevention (below)</td>
<td>Needs accurate vehicle position and speed data</td>
<td>Yes – Combined with enforcement (below)</td>
</tr>
<tr>
<td>Prevent red running</td>
<td>£19 to £125M from reduced accidents</td>
<td>Needs high % equipped. Very accurate location needed</td>
<td>Yes – policy issues and location system performance</td>
</tr>
<tr>
<td>Probe data</td>
<td>£60M from improved efficiency, excluding exit blocking</td>
<td>None</td>
<td>Yes – How do we gather and use Probe data?</td>
</tr>
<tr>
<td>Slippery roads</td>
<td>Depends on measures to reduce shunt accidents</td>
<td>Signalling Strategy changes unclear. Balance of advantages and disadvantages.</td>
<td>Yes – what strategies should be adopted?</td>
</tr>
<tr>
<td>Downstream data (exit blocking)</td>
<td>£180M mainly from use of improved strategies. Incremental provision is OK. Part of probe data, all efficiency</td>
<td>None</td>
<td>Yes – part of probe data analysis</td>
</tr>
<tr>
<td>Temporary lights</td>
<td>£3.5 to £27M</td>
<td>Requires temporary lights to be equipped with suitable short range communications</td>
<td>Yes – New algorithms needed. Interfacing to adjacent permanent signals is recommended</td>
</tr>
<tr>
<td>Vehicle class</td>
<td>£5M in efficiency, potentially major benefits for emergency services.</td>
<td>Only works when a very small minority of vehicles can claim a priority</td>
<td>Uncertain</td>
</tr>
<tr>
<td>Virtual signals</td>
<td>Yes, potentially over £3bn pa if road deaths eliminated</td>
<td>Policy, equipment levels, system performance</td>
<td>Yes – this is long term research, with potential short-term spin-off</td>
</tr>
</tbody>
</table>

The data requirements for the various use-cases are summarised in Table 23-2, which includes estimates of the required data accuracy using: 9m for the least critical, 3m for most requirements and 0.1m for critical systems.
Table 23-2: Summary of data requirements

<table>
<thead>
<tr>
<th>GNSS data</th>
<th>CAN Bus Commands</th>
<th>CAN Bus Status</th>
<th>Status from Additional sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Speed</td>
<td>Direction</td>
<td>Acceleration</td>
</tr>
<tr>
<td>Time</td>
<td>Throttle</td>
<td>Brake</td>
<td>Turn indicator</td>
</tr>
<tr>
<td>ABS operation</td>
<td>TC operation</td>
<td>Stabilisation</td>
<td>Headlights</td>
</tr>
<tr>
<td>Temperature</td>
<td>Wipers</td>
<td>Seat occupancy</td>
<td>Route guidance</td>
</tr>
<tr>
<td>Route guidance</td>
<td>Classification</td>
<td>Current load</td>
<td>Priority/urgency</td>
</tr>
<tr>
<td>Blue lights</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Response to route indication from vehicle**: 3m Y Y Y
- **Drivers informed of impending signal change**: 3m Y Y Y
- **Green wave information to vehicles**: 3m Y Y Y
- **Response to vehicle stopping information**: 3m Y Y Y
- **Automatic identification of Red Running**: 3m Y Y Y
- **Extending inter-green for red runners**: 3m Y Y Y Y Y Y
- **Prevention of red running**: 0.1 Y Y Y
- **Probe vehicle information**: 9m Y Y Y Y Y Y Y Y Y Y Y
- **Response to slippery roads**: 9m Y Y Y Y Y Y Y Y Y Y Y
- **Temporary signals**: 3m Y Y Y Y
- **Response to down-stream problems**: 9m Y Y Y
- **Vehicle class information**: 3m Y Y Y
- **Differential priorities**: 3m Y Y Y Y Y Y Y Y Y Y Y
- **Planned routes for emergency vehicles**: 9m Y Y Y Y Y Y Y Y Y Y Y
- **Virtual traffic signals**: 0.1 Y Y Y Y Y Y Y Y Y Y Y
In addition to the specific data requirements of individual use-cases detailed in the table, the project has identified the need for highway authorities to produce and maintain a detailed electronic inventory of the static infrastructure installed on our roads. Of particular interest to this project is the location, staging and phasing of traffic signals.

There are concerns about drivers abusing some of the features in the use-cases that we have considered. For example, drivers who receive advance notification of impending loss of green, may accelerate to try to get to the lights before the change, unless external vehicle control is used to prevent such actions. Further problems could occur with drivers of equipped vehicles behaving differently from those of un-equipped vehicles leading to the potential for more shunt accidents. Earlier work in TRL’s driving simulator showed that some drivers have a tendency to abuse the advance notice of a change in the signals, both by starting before green is indicated, or accelerating towards traffic lights, in order to get across before the lights change to red. Clearly this creates a safety risk. The risks of misuse can be reduced by two techniques:

- Using the in-vehicle systems to monitor behaviour and instigate automatic enforcement of infringements of traffic law
- Impose external control of the vehicle in relevant circumstances, e.g.:
  - prevent movement before the lights change to green,
  - force vehicles to drive at the required green wave
  - force vehicles to stop at red signals

As well as the technical challenges to implement such a scheme in a way that provides failsafe operation there is the need to secure the acceptance of drivers of systems that will reduce their freedom to control their vehicles.

However, both these technological and political acceptability problems will have to be overcome for other, nearer to market, CVHS systems such as Intelligent Speed Adaptation, where the driver must accept that the vehicle may prevent the driver exceeding the speed limit and in the future, possibly the safe speed that the vehicle calculates for the environment.

The total benefit from the provision of systems to support the full set of Cooperative Traffic Signal services described in the use cases in this report amounts to several hundred million pounds per annum.

These benefits may not be sufficient to justify investment in new technology provided exclusively to deliver cooperative traffic signals. A private capital spend of about £5bn (based on 23M cars each with £200 invested in on-board units, assuming these are fitted as original equipment). The budget would be twice these levels if remote control of the vehicle is to be enabled. In addition there would be the cost of the infrastructure side of the communications system. However, current practice results in a cost of £3bn per annum through loss of over 3,000 lives each year on UK roads. Environmental costs are in addition to these social costs.

Strong economic justification is expected within a 20 year timescale, assuming that the current plans within EU DG TREN come to fruition. DG TREN has commissioned the eNlink consortium to develop the requirements for a Universal On-Board Unit. Their objective is that eventually all vehicles will have a built in telematics platform that should be capable of supporting the functionality needed to provide cooperation for traffic control. The £5bn investment in vehicle equipment would no longer be relevant as a cost against cooperative traffic signalling. It is not clear at this time whether the DG TREN platform would also provide the ability to remotely control vehicles.

To be fully effective cooperative traffic signals would require the following pre-conditions:

1. High percentage of vehicles must be equipped
2. Policy must allow systems to cause vehicles to stop when they are considered to be likely to cause an accident
3. Accurate positioning
4. Low cost, reliable communications
5. New control algorithms for signal control to be developed

The pre-conditions imply that we face the classic challenge that there needs to be a complete step change to liberate the full benefits of the concept that we have studied but, the intermediate steps do not appear to offer cost effective incremental benefits. At first sight we might expect that this creates an insurmountable barrier to implementation. However, some of these pre-conditions will be met because of developments for other purposes, and this should present the opportunity to implement cooperative traffic control as a step change:

1. The DG TREN initiative to require all vehicles to have a Universal On-Board Unit – to support a diverse range of telematics applications - will result in vehicles being equipped with a telematics platform that should be able to meet the needs of cooperative road traffic signalling. Therefore, a modest investment is justified to ensure that these requirements will be met, otherwise an important opportunity will be lost.

2. Work to develop policy must be led by government. It seems likely that in 20 to 30 years time it should be possible to install the necessary control system into the entire fleet of vehicles, such that closed loop control of traffic might be implemented as a step change, rather then incrementally. Public acceptability of loss of freedom of control is likely to require a strong political commitment and a convincing information programme. Doubtless there will be some unforeseen problems to overcome.

3. The performance of GNSS systems will improve with the introduction of Galileo and the development of various augmentation techniques. Much of the development in industry and universities is working to generic targets – making improvements, rather then trying to achieve specific performance levels. It is very likely that the requirements for vehicle control will be met, but guiding and motivating research to achieve transport needs may accelerate that process.

4. Several competing low cost, reliable communications systems are being developed within diverse standards groups and as proprietary systems. Prices are expected to fall dramatically and service to improve.

5. Given that most of the pre-conditions that would enable cooperative traffic signals to be implemented could happen, it may be wise to invest in research into the development of algorithms for closed loop control of traffic. In 20 years time there really will be potential to install the necessary vehicle control applications into a fleet of vehicles that all have a suitable telematics platform.

It is recommended that the requirements for cooperative signal control are taken forward into related developments of in-vehicle telematics platforms, floating-car data gathering systems, accurate location technology etc, rather than invest in a dedicated capability. In this way it should be possible to phase in enhancements as the penetration of suitably equipped vehicles reaches levels at which correct operation of these advanced control systems is possible.


24  **Recommended follow-on actions**

There should be real benefits from the introduction of cooperative traffic control systems, but the value of these benefits would not justify the investment in dedicated systems to implement the functionality in all vehicles. However, there is potential to deliver real benefits by ensuring that future vehicle developments will support cooperative signalling systems at virtually no additional cost. New systems are unlikely to be designed in a way that completely supports the cooperative signal control, unless they have taken on board the specific requirements. The following specific follow-on activities are suggested:

24.1  **Floating-car data input to SCOOT**

A low-cost, quick-win way to improve SCOOT would be to develop a way to process floating car data and to import them into traffic control systems (SCOOT and MOVA), in order to increase efficiency. The data should also be used to monitor the network to identify problems not necessarily directly related to signal control, such as exit blocking junctions to enable traffic managers to take appropriate action. This would give a number of improvements such as:

- Easier system set up
- Better control of junctions where lane use varies during the day
- Better progression through SCOOT controlled junctions from accurate cruise times
- Reduced accidents at high-speed junctions controlled by MOVA
- Improved control of exit blocked junctions
- Evidence to target improvements at sites where exit blocking seriously reduces capacity

The value of these improvements has been calculated to be in the order of £180M. The benefits would be achieved by:

- Developing enhancements to the SCOOT software to take account of floating car data
- Pre-processing the floating vehicle / probe data to derive the statistics that will be needed by SCOOT
- Working with organisations that are already gathering floating vehicle data in order to create very low cost sources of floating car data that might be used to implement and evaluate improvements.
- To continue to review other potential sources of floating car data.
- To investigate other potential benefits from further analysing this source of data.

24.2  **Policy issues**

Several policy issues have been identified where the choice of a new control protocol to be used is constrained by the policy that government must set. These policy issues, which are spelt out in section 2, could be explored in more detail to evaluate the wider impact of these policies and the benefits versus the disbenefits of each option. The result would be to give government a background briefing which should be an important tool in resolving policy options.

24.3  **Threat analysis**

In this report we have considered the way that drivers might respond to additional information from the traffic control system. We have identified that a greater level of coaching and enforcement may be necessary to prevent abuse of the information on advance notification of change of right of way. However, there is an additional aspect that we have not considered in detail. That is the possibility of drivers (or hackers) causing mis-operation of the system by sending inappropriate messages. This might include:
• use of turn right indicators to force the lights to remain on green in his favour, so as to include a filter right sequence, which will also give a longer green for straight-ahead? Would that be an offence?

• Using a device to replicate the signals from a vehicle, so as to masquerade as a whole series of vehicles by sending information to the system so as to make it look as if there was a greater demand from a particular direction, so as to manipulate the operation for personal advantage, to support criminal activity, or for fun.

It is recommended that:

• the potential to disrupt the correct operation of traffic control systems is investigated so that it is understood fully, together with an analysis of the potential consequences of such action.

• A further investigation should be made into the security of potential communications networks for these applications, both existing and under development, given the context of the requirement for fast-connect operation. This may best be handled with a wider activity to make sure that all the requirements from cooperative traffic signal control would be captured (see next 2 recommendations).

24.4 Downstream requirements into future projects

It is recommended that the requirements for implementing cooperative control of traffic signals are taken forward and injected into projects such as the DG TREN Universal On-Board Unit requirements definition project that the eNlink consortium is working on. In this way it should be possible to ensure that any such systems will support the needs of cooperative traffic control without the need for incremental expenditure in the implementation of the on-board unit. It is not clear at this stage whether the UOBU will provide any kind of remote control capability. Certainly the project needs to consider how the UOBU might be incrementally enhanced to provide this capability. The following action plan is suggested:

• Register as a stakeholder in the UOBU project
• Meet with Faber Maunsell in order to ensure that our requirements are taken into account.
• Review the requirements documentation as this develops
• Provide additional information, as appropriate, to ensure that the platform will support traffic control applications
• Also consult with the ISA development team, to determine whether ISA can be combined with the UOBU in a way that could enable enforcement of compliance with traffic signals.

24.5 Enhancement of ISO TC204/WG16 standards

Section 3 of this report describes how ISO/CD22837 (Draft standard for “Vehicle probe data for wide area communications”) does not include all the classes of communications that have been identified in this study as being necessary to support Cooperative Traffic Signal Control. The structure of the ISO TC204/WG16 standard should be reviewed to clarify whether these will include the required communications capabilities, whether the standards as drafted would allow or prevent the inclusion of the necessary signals. From this analysis it should be possible to identify whether the standard should be modified or accepted in its present draft. Perhaps the most appropriate action would be to identify the need for an additional standard for “Communications for Vehicle to Infrastructure Cooperation”. It may be premature to create this standard, but requirements that arose elsewhere could be captured as input to this standard.

One particularly important aspect that CALM needs to investigate carefully is the security aspects of their fast-connect option. It is assumed that the standards group has developed the fast-connect
communications option for a specific set of requirements. The ways that information exchanged by the CALM protocol could influence traffic control will be an important input to such a security study.

24.6 Demand management techniques

A review of the potential impact of cooperative traffic control to support demand management was requested by the Department at the mid-point progress review. Ideas have been explored in this document, concluding that cooperative traffic signal control in isolation would not be very effective. However, a number of alternative approaches have been identified, largely based upon implementation of variable pricing of urban routes on a highly granular, dynamic basis. These ideas appear to go beyond the thinking in the recent DfT white paper of road user charging and deserve further investigation.

Some of the real benefits of road user charging would arise where this can be used to provide microscopic pricing in an urban area, in order to motivate drivers to avoid certain routes or sensitive areas at particular times of the day. This “soft” form of access control would only be possible if the driver has access to a trip planning tool that can take account of the variable charges that will be applied along the route. Current dynamic route guidance systems (DRG) do not provide this capability. There is a need for a feasibility study into this concept, looking into:

- Technical feasibility of implementing DRG that finds the most cost-effective route taking account of microscopic pricing in the urban area. What are the practical limits on granularity?
- Assessment of driver sensitivity to this kind of pricing. (The Durham Congestion Charging had more effect than was anticipated.) What level of pricing would be required to have the necessary impact?
- Assessment of the acceptability of this type of approach to pricing as an input to policy. It would be necessary to be specific about the reasons for making a surcharge. The level of surcharge would need to be determined first. A common thread might be to be proactive, to avoid likely congestion and other problems, rather than be reactive and divert traffic away from a problem, once it has happened. Examples might be
  - Protection of school children
  - Avoidance of environmentally sensitive areas
  - Avoidance of planned roadworks
  - Avoidance of accidents, and emergency situations (eg house fire)
  - Avoidance of area around a sports arena when traffic is set to arrive or depart.

24.7 Positioning technology

The long term vision for automated management of vehicles requires high performance positioning systems. There are many developments around the introduction of Galileo and its augmentation. Most of this work is of a generic nature, trying to achieve the “best” performance. However, this is not really focussed on meeting specific requirements. There would be sense in supporting research projects into the augmentation of Galileo so that it will meet the specific needs of road transport. It is noted that organisations such the Pinpoint Faraday Partnership are interested in coordinating this type of research.

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References

Anon. All purpose trunk roads MOVA system of traffic control of signals. Departmental Standard TD35/91, Department of Transport 1991.


Gillam, W.J. and R.A Withill. UTC and inclement weather conditions. In Road traffic monitoring and control IEE conference publication no. 335, April 1992


Information on MOTION is available in C. Bielefeldt, and F. Busch. MOTION, a new on-line traffic signal control system. Proceedings of Seventh international conference on road traffic monitoring and control, 26-28 April 1994. (IEE conference publication 391) Institution of Electrical Engineers (IEE), Savoy Place, London


Kennedy, J., A. Maxwell and M.R. Crabtree. The safety of MOVA traffic signal control at 'high-speed' junctions. Traffic Engineering and Control, Volume 46, No. 2. February 2005


Swain, J. The evaluation of amber arrow aspects at traffic signals with shared stoplines. BTEC continuing education diploma in Highway and Traffic Engineering, department of Civil and Structural Engineering, Nottingham Trent University, undated, believed to be 1997.

TAG Unit. *Values of time and operating costs TAG Unit 3.5.6*. Department for Transport, Transport Analysis Guidance (TAG). Available at [www.webtag.org.uk](http://www.webtag.org.uk) 2004

TRRL. *Report of the working group on the broadcasting of traffic information*. Department of the Environment, Department of Transport. TRRL Report SR506, Crowthorne, 1979


Van Aerde, M., B. Hellingu, L. Yu and H. Rakha. *Probes as sources of dynamic data* in Large urban systems, ed. Sam Yagar and Alberto Santiago. FHWA 1993