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**EXPLORING ENABLING TECHNOLOGIES FOR ROAD TRAFFIC SAFETY**

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Abstract:

The paper explores the feasibility of five ADAS technologies (navigation, speed assistance, collision avoidance, intersection support and lane keeping) for enhancing road traffic safety. State-of-the-art technologies like positioning, radar, laser, vision and communication are analysed from a technical perspective. Technical obstacles and possible pitfalls for large-scale dedicated ADAS implementation for traffic safety are discussed.

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## INTRODUCTION

Traffic is the result of the interaction between humans, vehicles and road infrastructure. In this process the human is a key element, but also the weakest link. Nearly all traffic accidents are due to human error. Traffic safety measures in the Netherlands have concentrated in the past decade on infrastructure redesign in relation to the human factor. Basic idea is that infrastructure should be made such that accidents are less likely to happen, and that the consequences are less serious once they do actually happen. This concept, named *Duurzaam Veilige Infrastructuur* (DVI, Inherently Safe Infrastructure) (22), is summarised in three speed related principles, which were made operational in a set of road network design requirements for design of the road network (9), and an extensive program for infrastructure redesign, which covers several decades, and requires considerable investment.

ADAS applications are meant to improve the safety, efficiency, and comfort of driving, but also hold a promise for improvement of overall road traffic performance and safety. As some of these applications come closer to possible high volume introduction, it is important to investigate if certain ADAS functions can bring similar improvements in traffic safety as are expected from infrastructure redesign. A first step has been made in (26), which provides an analysis of the match between ADAS functions and DVI requirements. The preliminary conclusion is that navigation with some adaptations, speed assistance, collision avoidance, intersection support and lane keeping have the greatest potential for traffic safety, and are possible substitutes for, or additions to physical infrastructure measures. Also, their safety effects may actually be better than the safety effects of the planned road infrastructure redesign.

An important next step is to analyse how feasible each of the identified systems is, in terms of technology, development and implementation time frames and specific policy measures. In this paper the pro's and con's of these ADAS functions will be given from a technical and functional perspective, and technical issues concerning large-scale dedicated ADAS implementation for traffic safety will be discussed.

The DVI based infrastructure measures have a strong focus on speed control. Speed is the most important determinant of accident frequency and severity. Also it is a parameter that can be pragmatically controlled. Therefore we start the discussion with Speed Assistance.

## SPEED ASSISTANCE

Speeding of motor vehicles is a major cause of traffic accidents (6), and also aggravates the severity of such accidents. This is especially the case in the urban environment and on single carriageway rural roads. ADAS provides technologies to address the issue of speeding, and to promote better or even complete conformance with speed limits than other measures like police enforcement, education and physical infrastructure.

Although infrastructure based speed assistance is possible, it is generally accepted that future systems will be map-based. In an infrastructure based system the (rough) position of the car and the information regarding the speed limit may be obtained from (DSRC) beacons or transponder tags which may be installed at speed limit changes (in general at speed signs along the road). High infrastructure installation and maintenance costs seem to be prohibitive, while on the other hand the increase of ADAS components in the car favours the in-vehicle integration of a map-based system.

Map-based speed assistance uses (1) vehicle positioning (GPS, inertial sensors, map matching), (2) local speed limit determination (from map database information), (3) comparison of the actual vehicle speed with the local speed limit, and (4) information or warning (HMI), or vehicle control. Vehicle positioning and a digital map database will be common components in every car in the near future, and they are already today standard components of the navigation system, which rapidly gains popularity, even for the average driver, as it does not only provide route guidance, but also dynamic traffic information, best route alternative, and estimated time of arrival. Comparison with the actual vehicle speed is standard, as is information or warning through an HMI, or vehicle control (overrideable or non-overrideable).

### Flexible system design

Speed assistance systems may be designed in several different ways. An important element is the feedback model that is chosen. In general four different feedback levels are distinguished: information (visual or acoustic), warning (acoustic or haptic), overrideable control (haptic throttle) or full control (fuel supply control, gear change and/or braking). Another determinant is the mode of operation, which can be voluntary (on/off switch) or mandatory (autonomous, as soon as the engine is switched on). (27) In recent years many pilots have been carried out in different countries (Sweden, the UK, France, The Netherlands and Australia) (4,5,11,25,36), in which various system set-ups have been tested and demonstrated, and also user response and acceptance have been investigated. In these projects the technical feasibility of different speed assistance approaches has been amply demonstrated.

The intensive ongoing debate regarding the desirable or acceptable layout of the system (feedback level and mode of operation) hampers political decision making and the introduction of adequate speed assistance. As a sensible way to satisfy all the parties involved in the current animated discussion, (26) has suggested introducing a flexible system layout that differentiates according to road type and traffic safety requirements:

- mandatory full control on roads and crossings with mixed traffic
- mandatory overrideable control (haptic throttle) on roads with traffic separation
- voluntary warning on dual carriageway roads specifically designed for motor vehicles

### Requirements for the digital map database

Vehicle positioning as implemented in current navigation systems is very accurate. Only occasionally an error may occur, and for a very short period of time. In such cases the positioning unit generally knows that there is an uncertainty in the vehicle position, and a warning to the driver may be issued by the speed assistance system.

For a reliable operation of speed assistance systems, digital map databases need to contain up-to-date speed limit information. To enable this, two prerequisites need to be fulfilled. In the first place the responsible authorities need to organise the legal speed limit information for their roads in a timely and accessible way, and provide this information to digital map database suppliers on a continuous basis. This should enable the provision of certified speed limit data, as is proposed in (10). However, an enormous effort seems to be needed here, which should be organised at a European level, including standardisation of storage and exchange mechanisms. Issues involved will be studied in the French-German funded SAFEMAP project (37), and in the EU funded SPEEDALERT initiative (41). Secondly, incremental map data updates with respect to speed limits need to be supplied to the vehi-

cle in a timely manner, and integrated in the map database in the vehicle. This needs mechanisms for incremental updating, which are currently being investigated in the EU funded FP5 ActMAP project (3), and a suitable and watertight data versioning and transfer mechanism to get the right updates in every vehicle.

Introduction of speed assistance by statutory regulation (including the aforementioned differentiation) as an enforcement mechanism, while maintaining the legal liability to obey the posted speed traffic signs, may adequately address the liability issue, and allow speed assistance to be already used if speed limit data in digital maps is not yet complete and up-to-date.

### Further perspectives

Going one step beyond what is generally discussed, speed assistance could also be used to regulate speed at the approach of intersections, including a slow-down to the adequate speed, and a full stop at a stop sign or a red traffic light. In the latter case the traffic light system needs to be equipped with a beacon that transmits its state, and the system in the vehicle with a corresponding receiver, and processing capability.

Compared to physical infrastructure measures, speed assistance has some clear advantages. It has more extensive and homogeneous effects on speed and thereby on traffic safety. It also largely avoids negative effects in terms of land use, emissions and fuel consumption. Moreover, dynamisation of speed assistance provides a plausible perspective for mitigating the congestion problem.

It has been shown by simulation studies that dynamic speed limits could help to prevent, mitigate or eliminate traffic jams and shock waves, by adequate control of speed, density and flow (17). Congestion can be dissipated by raising the outflow (21), by limiting the inflow to a traffic jam or shock wave (7,24), or by homogenising the general traffic flow (1,40). All studies are based the use of variable speed limit signs and static speed assistance (42,39). However, the speed resolution of the variable speed limit signs is very coarse, and these signs are generally not very well obeyed. Dynamic speed assistance, also in the sense that it would temporarily change from warning to control mode in a motorway situation, could address this, and could also greatly improve the effect of speed assistance on the homogeneity of the traffic flow when needed. The models applied are quite complicated, and it would require fully automated floating vehicle data collection and processing, a position dependent dynamisation of the speed limit, and transmission of this information to the vehicle. The capacity of the RDS-TMC channel may be too limited for this, but other wideband channels like on DAB will be available in the near future. Extensive field operational testing of such system would be necessary, and could provide a platform for large-scale real world testing of traffic flow models. Obligatory lane keeping in dense traffic conditions could also contribute, but is difficult to implement with current technology.

## NAVIGATION SYSTEM

The navigation system is a state-of-the-art system, which comes in many different variants, and with user interfaces of different levels of sophistication. It uses vehicle positioning (inertial sensors, GPS and map matching), route calculation (map database) and route guidance as its main components. In (26) it was argued that five of the twelve DVI requirements could be addressed by the navigation system, with some adaptations. These

requirements are (1) minimise part of journey on relatively unsafe roads, (2) make journeys as short as possible, (3) let shortest and safest route coincide, (4) avoid search behaviour, and (5) make road categories recognisable.

By nature a navigation system implements requirement 4. Requirements 1, 2 and 3 are fairly related, and in a certain sense already implemented in a navigation system, to the extent that the outcome is still dependent on the route selection choice that the user has made. The available options for this generally include *fastest route*, *shortest distance*, *main roads* (as much as possible), and *avoid main roads* (as much as possible). A navigation system always creates the shortest route (requirement 2) in balance with the chosen route selection criterion. That means that actually the option *main roads* is likely to provide the best balance between the requirements 1, 2 and 3. The higher the level of the road, the better the separation of different kinds of traffic generally will be, and therefore the safer the route (requirements 1 and 3). These things work fine in principle. They depend on the choices that the map database provider has made with respect to the categorisation of roads, and on the choices that are made in the software of the navigation system, when calculating a route on the basis of the available map data. As an example, in a certain navigation system the setting shortest route does not always provide the real shortest route, but a smart shortest route, still taking into account some principle of preference of higher level roads and avoidance of residential areas. In view of improving safety, some harmonisation of road categorisation in map data, and of route selection criteria for navigation systems might be considered.

Requirement 5 is very much related to the concept of Self-explaining Roads (20). In summary the idea of this concept is that the visual layout of the road would inform the driver of the type of road he is driving on, and thus would induce the right driving behaviour, and in particular the right maximum speed. Of course a navigation system could in principle inform the driver about the type of road he/she is driving on. However, as this concept is very much speed related, it could in principle be considered redundant if a speed assistance system is present at the same time. The speed assistance system would in a much better and less intrusive way inform the driver of the expected driving behaviour (which is especially allowed speed, from which he/she can e.g. deduce if vulnerable road users (VRUs) may be present).

Integration of navigation with speed assistance, based on a platform with a central map server and vehicle positioning unit, could offer the potential for a mass market, and drop prices considerably. The technology is state-of-the-art, and would be short-term deployable. Fiscal measures and lower car insurance premiums may contribute to foster acceptance if authorities decide for voluntary introduction. However, authorities may also choose obligatory introduction, as a better tool for speed limit enforcement. Mentioned platform can also be used by other ADAS functions, among which is another contentious item, road pricing.

## ENABLING TECHNOLOGIES FOR COLLISION AVOIDANCE

Base technologies for collision avoidance are positioning and communication. Different options are available, and these can be combined in different ways to create autonomous systems and co-operative systems. For each of these we will first give a short review of currently available alternatives. Available does not necessarily mean off-the-shelf. It means that the concepts are existing. Some of these concepts are mature, but most of them still

need considerable improvement by further research and extensive implementation testing, because they as yet do not meet fundamental requirements. These prerequisites for the base technologies and for the systems that will be composed from them, are robustness, including reliability, permanent and fail-safe operation, and few or no false alarms. A further important issue is whether such systems are used in a warning or control mode, or a combination of both. And for the warning mode the choice of the driver interface (HMI) is a key factor. Yet another issue is sensor fusion, to improve robustness, reliability and operation permanence. It is also important to distinguish collision avoidance between two (or more) vehicles, and between a vehicle and (one or more) VRUs.

For positioning two different concepts may be distinguished. Relative positioning determines the position and velocity (speed and direction) of the vehicle relative to the road infrastructure and to other objects (stationary and moving), by using some kind of imaging sensor with suitable image processing. Suitable sensors for this include radar, lidar, and visible light and infrared imaging. Active sensors (radar, lidar) measure the reflections of signals that first were transmitted by the same sensor. Optical and infrared sensors are generally used (in automotive applications) in a passive sense, by measuring the radiation that is naturally transmitted by objects, although they may be used in an active mode by preceding illumination of objects. Another relative positioning method is the use of magnetic lane markers. Absolute positioning uses satellite positioning, preferably in combination with inertial sensors and map data, to provide an absolute position, as well as velocity. Relative positioning sensors are in the first place used in autonomous solutions, while absolute positioning requires bi-directional communication to issue the own position and velocity as well as to acquire position and velocity data of other nearby vehicles. Relative positioning may be used to avoid vehicle-vehicle encounters as well as vehicle-VRU encounters. Absolute positioning is not appropriate to avoid the latter type of collisions.

### Relative positioning sensors

Different types of radar are being used or investigated for automotive applications. ACC systems that are already on the market use frequency modulated continuous wave (FMCW) long range radar (LRR, range up to 150 m) in the 76 GHz millimetre-wave band. Ultra wide band (UWB) pulse operated short range radar (SRR, range up to 50 m) in the 24 GHz centimetre-wave band is proposed and tested for automotive applications (32). SRR is at current prices a factor 40 cheaper per unit than LRR (28), has smaller size and better penetrates bumper materials, which makes it easier to implement several (or an array) of such sensors in one car. However, in Europe there are still serious regulatory issues to be solved, and it is even debated if 24 GHz is the best solution. A large number of car manufacturers and system suppliers united in the SARA (Short range Automotive Radar frequency Allocation) Group is strongly promoting global harmonisation and regulation for this type of radar, especially for the use in applications to enhance road safety (38). Radar is insensitive to bad weather and environmental conditions, but it cannot “see” the (course of the) road.

Lidar (light detection and ranging) uses a highly directional beam of laser light. It needs to be used in a scanning mode to allow imaging, and is sensible for poor visibility and adverse ambient conditions.

Visible image processing for automotive applications is going on since 1987, with a boost since the Prometheus project in the early nineties (14). Although good progress has been made, prices of the necessary equipment have gone down, and stereo imaging makes dis-

tance determination possible, it seems to remain difficult to make the systems robust and sufficiently discriminatory with respect to different types of objects. Especially bad weather and adverse ambient conditions may drastically deteriorate the performance of these systems, while their operation during night-time may also be problematic. A clear advantage compared to radar is that vision systems in principle (dependent on clear road markings or other well visible road characteristics) are able to distinguish the road. Therefore it is obvious, for certain applications, to integrate radar and vision systems. Infrared sensors in principle can add night time vision capability, and better penetrate bad weather conditions.

### Absolute positioning

Current stand-alone, code based satellite positioning (GPS) allows a horizontal accuracy of about 10 m and in combination with inertial sensors and a digital map of about 5 m. Performance of GPS may be improved by differential corrections. A geostationary satellite based augmentation system like the European EGNOS (European Geostationary Navigation Overlay System) may be a solution for pan-European use of ITS applications, although accuracy will not be better than about 2 m. Also the signal of the geostationary satellite may sometimes be blocked, much like the signals of the GPS satellites themselves may be temporarily blocked by buildings (the urban canyon), foliage, mountains, or in tunnels. In a navigation system these satellite outages are sufficiently covered by the inertial sensors (relative positioning) and the digital map. More precise carrier-phase based positioning would be possible (to the cm level in combination with differential corrections), but the resolution of the initial cycle ambiguity parameters takes time, and each cycle slip (discontinuity in the carrier-phase measurements due to a temporarily blocked satellite signal) makes that this process has to start over again. (12) Galileo plans to provide a safety related service of 4 m or better horizontal accuracy (95%) based on dual-frequency measurements (15). As a conclusion it can therefore be said that sub-meter positioning using satellite technology in moving vehicles seems difficult to achieve. Use of a position with sub-meter accuracy would require a map database of similar or better accuracy, of which the economical feasibility yet has to be demonstrated. A proposed solution to cover satellite outages is the use of pseudolites (local augmentation) (12), but it is questionable if this is cost-effective and useful if sub-meter level positioning is not possible.

### Communication

Two different scenarios of medium distance communication are envisaged for road safety and traffic management applications: vehicle-to-vehicle (v2v) or inter-vehicle communication (IVC), using peer-to-peer mode, self-organising ad-hoc mobile radio networks (distributed, multi-hop), and vehicle-to-roadside (v2r) or road-vehicle communication (RVC), using master-slave mode, infrastructure centralised, one-hop mobile networks between vehicles and fixed roadside beacons. (19,30,34,43)

The proposed medium for this type of communication will use the IEEE 802.11a R/A (Roadside Applications) protocol, a variant of the Wireless LAN standard, in the 5.9 GHz band adjacent to the DSRC spectrum, and is developed as application M5 (Microwave 5 GHz) of the CALM architecture (Continuous Air interface for Long and Medium distance) in the framework of ISO TC204/WG 16 (2). The RVC links are intended to support a wide range of applications (including multimedia, entertainment and internet access), and therefore must support high data transfer rates. Stated data rates are 54 Mbps up to 80 m and 6

Mbps up to 1000 m (13). Various issues still need to be solved, and first-generation devices are expected by 2005, and full capability devices by 2010. An advantage of using the 5 GHz spectrum is that it can penetrate walls and propagate around corners. This development was initiated from the US, but has been adopted by the ITS community world-wide, although Europe has been remarkably slow in taking up this approach. (13) The eSafety final report (10) e.g. recommends identification, and where necessary development of new specifications for interfaces and communications protocols for vehicle-vehicle and vehicle-roadside communications, but does not reference CALM M5.

## COLLISION AVOIDANCE

Much research is ongoing on the development of autonomous sensing systems for the car with the aim of both avoiding collisions and mitigating the impact of collisions once they cannot be avoided. An ultimate configuration is a 360° car surround sensing system (providing a "virtual safety belt" around the car) with an approximate number of 10 SRR units per vehicle for luxury cars for all kinds of functions, including crash mitigation (28,38), and one LRR unit at the front side of the car, possibly combined with video image processing, for crash avoidance.

Clearly, from a perspective of replacing infrastructure measures that are meant to be all encompassing, such systems would only contribute sufficiently at high market penetration rates. Given the regulatory problems with the 24 GHz UWB systems, and proposals to limit market penetration of such systems to 10% to accommodate expected interference problems (28), it may be doubted if these systems will play an important role in traffic safety until 2010. For LRR and vision the implementation scenario is different, although here the cost of the system may be prohibitive to induce a large market penetration before 2010.

The EU funded FP5 project RadarNet focuses on the development and testing of a rear-end collision warning and urban collision avoidance up to vehicle speeds of 80 km/h. It uses one multi-beam narrow-angle 77 GHz radar for detection up to 150 m, and an array of four 77 GHz single-beam radar sensors for a range up to 25 m. Use of only 77 GHz technology is seen as an advantage, as it is basically the same as the one used for ACC. (18)

The EU funded FP5 project SAVE-U develops a near-by sensing system especially focusing on VRUs, for a maximum operative vehicle speed of 40 km/h, by implementing an imaging system consisting of passive infrared and visible spectrum sensors, and a radar network consisting of several 24 GHz sensors working in parallel. The chosen combination of sensors should make the system robust in all weather and lighting conditions. The work focuses also on improvement of the recognition of human obstacles, by employing a large database of VRU images. (29)

Following a conclusion of the ADASE joint research project (FP4) that for progress in ADAS technology a significant increase in the performance of driving environment monitoring systems is needed, the EU funded FP5 project CARSENSE develops, as a first step, a sensor system to provide sufficient information on the car environment to assist in low speed driving in complex (urban) situations. The system will combine information from laser, radar, image and the vehicle dynamics sensors. (23)

Of course these projects show only a fraction of all the research of such systems that is undoubtedly in progress at car manufacturers, in co-operation with system suppliers. Nevertheless one cannot escape the conclusion that these and similar projects are still very much in the experimental stage, and need follow-up projects in order to develop systems that are really robust and have an acceptable cost price.

Co-operative systems provide another approach, at least conceptually, for rear-end collision avoidance, by use of vehicle positioning and IVC. To make this work in a robust manner, the communication needs to be robust, and the positioning needs to be robust and of high accuracy. Although the standards work on the M5 application in the CALM framework is on its way, it still has some time to go, and its uptake in Europe may even take longer, as stated before. But it is to be expected that M5 based IVC can eventually be progressed to a state of maturity and robustness. For the vehicle positioning it is maybe a different matter. On a 3-lane road such system should provide lane discrimination: in which lane the vehicle is, and where in that lane. This would require a horizontal accuracy of about 0.3 m, which, as stated before is difficult to achieve. If this would be achievable, also a highly precise digital map would be required, of which the practical and economical feasibility yet needs to be demonstrated. Only a system using magnetic lane markers would be able to provide the stated precision.

The EU funded FP5 project CARTALK2000 investigates a co-operative longitudinal control system, using DGPS and INS based positioning and an ad-hoc mobile communication network based on UMTS terrestrial radio access network (UTRAN) technology (33). The limited set-up of the work, in view of the original plans, using only three vehicles, and concentrating on "the transparent front" vehicle, is another indication that it is still a long way before such systems will be mature and ready for large-scale implementation. Also for this type of applications follow-up projects may be necessary, and practical use is not to be expected before the end of this decade.

## INTERSECTION SUPPORT

In the US extensive research has been carried out on infrastructure based intersection collision avoidance systems (16,35). Both technological approaches described above (autonomous and co-operative) may also be used for non infrastructure based collision avoidance at intersections. The reliability of autonomous systems will, more than for longitudinal collision avoidance, be hampered by the fact that an unobstructed line of sight, a condition sine qua non, is sometimes not available. It seems to us that the co-operative approach may give better prospects. Performance may be enhanced, but also complexity and cost increased, by an integration of these solutions. Both approaches of course have also for intersection avoidance the prospect that large-scale market availability at affordable prices before the end of the decade may be doubted. For the longer term a co-operative system for intersection support could be envisaged that goes a step beyond mere collision (hazard) avoidance, and operates in an intersection negotiation mode.

## LANE KEEPING

Lane keeping in the framework of this paper especially relates to two-lane single carriage-way roads in the extra-urban environment. Much of the ongoing lane keeping research and development relates to lane keeping on motorways and to the prospect of future autonomous vehicle guidance on such roads. Certainly a reliable system for lane keeping for mo-

torways can have certain safety benefits, but in view of the aimed trade-off with proposed infrastructure adaptations, the issue is focused here on mentioned single carriageway roads. As these contribute significantly to traffic unsafety, it was originally proposed (in the DVI programme) to take a drastic infrastructure measure, i.e. physical lane separation, prohibiting overtaking and avoiding midline crossing due to inattention. As the cost of such adaptations are prohibitive, less drastic measures are actually implemented, like a double white line with some interspace. This measure may however prove to be less effective than needed.

Lane keeping based on precise positioning is hampered by the same issues as described above. Precise positioning for this type of application would require a horizontal accuracy of about 0.3 m, which, as stated before, seems difficult to achieve. Lane keeping based on video cameras and line recognition is available on the market, currently especially for trucks (MAN, DC). The system is not sufficiently reliable in adverse weather, lighting and ambient conditions.

Magnetic lane marker systems could provide a feasible and cost-effective alternative for lane keeping on certain relevant roads. Of course such systems require an additional infrastructure component, which brings additional cost. An advantage is however that their operation is independent of weather, lighting and ambient conditions. Also, the equipment in the car is relatively inexpensive. The best prospect gives a system that is based on the use of magnetic tape. This tape can be used in combination with the normal white lane markers, which nowadays are often also applied in the form of tape instead of the traditional painting. Painting in itself is cheaper, but the tape lasts longer, making it overall more attractive. (31)

## CONCLUSION

Of the various technologies that were discussed in this paper, navigation is mature and speed assistance options are in development, pointing the way to large-scale implementation. However, complete and up-to-date coverage of speed limits in digital maps needs to be organised, which may take at least another three to five years. In general, the introduction of integrated speed assistance and navigation may reduce the need for, and urgency of the various other systems that are being developed, as most safety effects will be achieved cost-effectively by these two integrated systems. Furthermore, they may establish a platform in the vehicle for future integration of other ADAS applications, as well as contribute to traffic flow improvement. Another technology that is mature and could be easily large-scale applied is lane keeping by use of magnetic line marking

The other discussed technologies (based on radar, laser, video imaging, communication and/or satellite positioning) are promising, and can also contribute to traffic safety, but need still considerable improvement in robustness, reliability and cost. It may be estimated that research and development on these systems at least need another five years, although certain sub-systems may be introduced to the market earlier. Important research in this field is going to take place in the EU funded FP6 Integrated Project Preventive Safety. The encountered difficulties do not only relate to the sensor technologies that are being employed, but also to other design parameters, like e.g. the algorithms for reliable VRU detection. IVC and vehicle positioning based systems seem conceptually to be the most promising, although they do not take into account VRUs.

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