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Part IV

Conclusion
Chapter 10

Future Work

In this chapter I will discuss questions raised by my research and directions for future work to extend it. There is still a great deal of work required before the risk limit model could be implemented and used in the real world as there are many outstanding issues to address before an actual implementation. Furthermore, as described earlier, much work remains to accurately determine risk factors from experiments. In the following sections I will discuss each of these areas, along with some potential ways to address them.

10.1 Accident Risk Data

As discussed in Section 4.2.1, there is a scarcity of data on accident risk in an appropriate form to be used in the risk limit system. Since the model relies on differentiating between drivers’ and vehicles’ risk levels in order to leverage these differences for utility gains, the more risk factors that can be used in calculating the risk level, the higher the gains will be. In addition, improving the accuracy of the risk estimate allows the system to operate more efficiently while still remaining safe. To these ends, a useful direction for future work would be to gather and analyse more data on accident risk, particularly on the exposure for various risk factors in order to compare this to accident rates.

More — and more accurate — data on the effects of various risk factors may also lead to improvements in calculating the overall risk level based on the levels of the various factors present. Many risk factors are likely to interact and while we have
been able to test the system in a simulation environment where full information about the effects of each factor as well as combinations of factors is available, this is not so straightforward in the real world and requires further work as more and more factors are added to the system.

10.2 Vehicle Behaviours

A key way of expanding the risk limit system is to add more risk-mitigating and utility-increasing behaviours to it and it has been designed to allow for this kind of modular extension. Thus far I have addressed speed, headway, lane choice and link choice as possible behaviours for vehicles to take. However there are many more behaviours that can affect a vehicle’s risk and/or utility. These might include choosing to drive at a different time of day, when to overtake, and gap acceptance when changing lanes or negotiating intersections. One behaviour in particular, end-to-end route choice, will be discussed in more detail below.

10.2.1 End-to-End Risk-Aware Route Choice

Thus far, we have considered the choice of only a single link. However, vehicles are unlikely to face such choices in isolation — the situation where a vehicle must decide amongst links that are equally useful in getting to its destination does not occur very often. Instead, a link choice will typically be part of an entire route. We now consider two approaches to extending this work to deal with end-to-end route choice.

The first approach would be to use a similar process to that described in Section 4.4.1 but consider entire routes rather than single links. This would require calculating trip time over the entire route, taking into account the risk levels of each link along the route as well as current traffic conditions, and possibly incorporating social penalties as in Section 5.2.4.4. This essentially then becomes a shortest-path problem, where the edge weights are determined by not only travel time, but also risk and social cost.

However, using such a system, travel speeds along any given link are far more variable than in existing systems, as each vehicle adjusts its speed in accordance with its current risk level, although the use of social penalties mitigates this somewhat. A vehicle’s risk level also depends on the vehicles around it, and so traffic conditions on the link influence travel speeds not only by slowing them when there is congestion, but
also by varying the current risk level and thus the maximum speeds at which vehicles can travel. In addition, we have the usual variance in travel time due to traffic density changing with the time of day and other factors.

While the shortest-path problem itself is well-studied, standard algorithms such as Dijkstra’s [137] may produce suboptimal solutions in the case of dynamic and stochastic systems [138]. There is substantial previous work in this area, with a range of approaches that have been developed to deal with the time-varying and uncertain nature of traffic routing and travel time prediction [138–142]. Further work is required to determine the best approach under the conditions described above.

The second approach would be to include a measure of how useful each possible link at a given intersection is in reaching the destination and use this in calculating the score for that link, with links that cannot be used to reach the destination having a score of zero. This approach is more similar to the single link choice problem we have investigated and would be easier to adapt dynamically to changing conditions, however it could also result in the overall route being less optimal than an end-to-end approach.

10.3 Data Collection using VANETs

One means of providing the necessary data on both accident risk and vehicle behaviours required for expansion of the risk limit model lies in the future widespread deployment of vehicular ad-hoc networks. This will provide unprecedented opportunities for fine-grained and large-scale traffic data collection. This would be particularly beneficial for obtaining data on accident risk exposure, which is currently difficult to collect in an accurate, comprehensive and cost-effective way. Using VANETs, however, information on all road users, not just those involved in accidents, would become more available. Data collected from VANETs can thus provide a much more complete and accurate view of the risk associated with any given factor, or indeed combination of factors, than any existing methods for measuring exposure.

Additionally, widespread adoption of VANETs would give opportunities to improve modelling of risk factors and vehicle behaviours. It would be possible to directly observe how the presence of a given risk factor affects vehicle behaviour and what types of incidents are caused by this. Conversely, the effects of vehicle behaviour on both risk levels and road system utility can also be observed, allowing these behaviours to
be included in a traffic management model.

However collecting, storing and analysing this kind of traffic data is not without its own challenges. With full network penetration, VANETs will constantly produce a large volume of data including vehicle sensor readings, periodic beacons sent from each vehicle, and data from network applications. This is further complicated by the uncertainty of having a connection available to the wider Internet at any given time — vehicles may be exchanging data whilst far from any base station. This means that there will be a need for in-network data analysis and aggregation as it is unlikely all data can be stored or uploaded. There have been some proposals for data collection and aggregation methods for VANETs [143–147], however this is still an area that requires more research.

As well as the technical challenges involved in collecting traffic data from VANETs, there are also significant concerns surrounding privacy, ownership and usage of data. In order to obtain the most benefit from such data, it is desirable to have as complete a picture as possible of what happens in the network. However, this may lead to breaches of drivers’ privacy as their location over time and other personal data could potentially be extracted from these records. Moreover, there are questions surrounding who should have the right to collect such data — traffic authorities, corporations, private individuals? — and how it can be used. There is a large variety of possible uses of such data ranging from analysing traffic patterns in order to improve the road network to advertising to tracking of individuals. There is thus work required on these social and legal aspects before any such data collection system could be put in place.

10.4 Crash Severity

One aspect of accident risk that has not yet been addressed in any depth is crash severity; in this thesis I have focused on accident rates where each accident is viewed equally. However, crash severity is also an important consideration as not all accidents are equal in outcome. Currently, a minor accident at low speed resulting in property damage only is given the same weight as a high-speed accident resulting in severe injury or death. In future work, the potential outcome of a crash in terms of harm to vehicle occupants and other road users should be incorporated into the risk calculation to avoid this.

One means of doing this would be to adjust the risk level according to indicators
that an accident, should it occur, would result in severe injury or death. Since accident severity depends heavily on factors such as speed at impact, vehicle mass, and the presence of safety features designed to lessen the force on occupants at impact, it may be possible to determine the approximate severity of potential accidents based on the characteristics and state of the current vehicle and the vehicles surrounding it. The risk level could then be modified accordingly so that the risk limit can be achieved by affecting either accident probability, accident severity, or both.

### 10.5 Driver Interface

One major challenge in implementing the risk limit model into a real traffic management system lies in designing the interface for the driver. While self-driving vehicles will eventually make a driver interface unnecessary, the driver is likely to still be involved in vehicle control for some time to come and it is thus important to consider what information should be conveyed to the driver, how it would be best presented, and how the system should affect vehicle control.

One of the simplest forms of driver interface might be to just present the risk value to the driver, whether in numerical form, or in a form similar to current speedometers, or some other one-dimensional indicator. Evidence suggests that drivers’ awareness of their risk level plays a significant role in safety [12, 39] and so simply improving this may have benefits. However, further work would be needed to establish the effects of such a display on driver behaviour and this approach would limit the benefits obtainable from the risk limit system as it does not incorporate modification of vehicle behaviour in order to meet the risk limit.

In its current form, the risk limit system is able to adjust vehicles’ behaviour to compensate for risk levels and improve utility. While ideally an implementation of the system should allow drivers to also do this, the more information that needs to be communicated to the driver, the more complex the interface and the higher the driver’s cognitive load, potentially leading to driver distraction and decreased performance on the actual driving task. Thus it might be better for the system to present a limited set of behaviours for the driver to take to reduce risk or increase utility, rather than all the available information or the effects of all possible actions. With increasing levels of autonomous control of the vehicle, it may also be possible for the system to take some
manoeuvres on its own, thus jointly participating in the task of controlling the vehicle along with the driver. However, in such a situation, it would likely be important for the driver to be clearly informed of any such actions being taken, which still leaves the issue of an appropriate interface.

10.6 Driver Acceptance and Compliance

Closely linked to the problem of the driver interface are issues surrounding driver acceptance of and compliance with the system. In order to see the benefits of this system, particularly in the situation where the driver retains full control of the vehicle, it is imperative that drivers have confidence in the system and be willing to follow the behaviours indicated. This lies partly in drivers believing that the system is accurate in its determination of current risk levels and the effects of risk-mitigating and utility-increasing behaviours, and partly in drivers feeling that the system serves their own self-interest. Drivers are unlikely to comply fully, if at all, with a system that appears to be detrimental to their own goals, as can be evidenced by compliance (or lack thereof) with other traffic control measures such as speed limits, which require additional enforcement measures in order to be effective.

Work is thus needed to address a number of issues relating to driver acceptance and compliance. In the first place, before any implementation the system must be made sufficiently reliable and effective that drivers can indeed have confidence in it. This then needs to be communicated and demonstrated to drivers and the best means of doing so is an open question. Further to this, the level of compliance that can be expected and the effects on the system of non-compliance of some drivers need to be investigated.

In the likely event that driver compliance would be insufficient, then enforcement measures would also need to be designed and implemented, much as they are for existing road rules, and the social implications of these would also need to be studied. Too much control over and enforcement of driving behaviour may lead drivers to feel resentful and suspicious of any such system and thus make it difficult to introduce. Additionally, it would be important for drivers’ privacy to be protected and for information about their driving habits to be collected, stored, and used only in limited and acceptable ways.
10.7 Security

With any system for which a failure has the potential to cause injury or death, security is a major concern. However, it is not something I have addressed to this point. There is already a large amount of work being done in the area of security and privacy for vehicular ad-hoc networks (e.g. [148–152]) and so any additions to the risk limit system in order to make it secure should aim to be compatible with existing protocols.

In terms of security requirements for the system, since the algorithms used are primarily based on broadcast transmissions, confidentiality of information is not required. However, information integrity is very important as incorrect risk data disseminated into the system could result in either a loss of utility or unsafe vehicle behaviour. In addition, since risk estimates are in part based on driver and vehicle characteristics, privacy is a key concern and risk data should ideally be anonymised, although this may then present challenges in terms of assessing the value and relevance of received data. Availability is also an important requirement if such a system were to be relied on for traffic management and measures would need to be enacted to prevent or mitigate the effects of denial of service type attacks. Lastly, depending on local legislation, law enforcement authorities may require that the system provide non-repudiation in the form of tamper-proof logs or other records.

10.8 Integration with Existing Standards and Protocols

While I have aimed to take an agnostic approach to particular standards or protocols for vehicular ad-hoc networks in order for this work to be as general as possible, for any real-world implementation it would of course be necessary to integrate the risk limit system with existing standards. In Section 3.4.2 I have given an overview of the standards that are currently dominant in this area. While it should be possible to adapt the risk limit system to these standards with minimal difficulty, any such implementation should be carefully evaluated for its performance.

One aspect of current standards that could be particularly beneficial is the use of Cooperative Awareness Messages (CAMs) (for the ETSI standard) or Basic Safety Messages (BSMs) (for the IEEE 1609 standard). These messages are periodically broadcast by each vehicle and contain a variety of status information, some of which is redundant with information that is transmitted in beacons in our coupled risk estimation algorithm.
This means that by integrating with these standards, this information would already be available to vehicles, thus reducing the communications overhead of the risk limit system.

10.9 Variable Beaconing Rate Optimisation

Although the variable beaconing rate scheme developed in Section 8.2.3.5 for the coupled risk estimation algorithm resulted in significant improvements in terms of balancing the two goals of minimising error and minimising network resource usage, the values chosen were particular to this algorithm and as such do not readily apply to other distributed applications for VANETs. Here, we will examine how this problem might be generalised.

We now have an optimisation problem in determining the best beaconing rate(s) to use and how to change the beaconing rate to adapt to different circumstances. Essentially, we have a point in $N$-dimensional space which represents the desired values for the nodes — the “true” risk vector — and which moves constantly as the nodes move, the network topology changes, and the input values themselves change. Moreover, this target point does not move in a predictable or even continuous way and the rate of change of its position is highly variable, and in fact, because of discontinuities caused by sudden events or network topology changes, unbounded. The times when the target point moves the fastest, or jumps discontinuously, are also when it is most important that the actual output remains close to it, as these typically represent critical situations such as a new vehicle arriving or a hazard appearing suddenly.

We then want the vector of the actual node values to be as close as possible to the target point at all times, while also not wasting network resources unnecessarily. We can consider this problem in two ways: we can either optimise for minimal error given a constraint of available or desired network resource usage, or we can optimise for minimal resource usage given a constraint of allowable error. The best approach to take here will depend on the particular application. For a safety-critical application, it is likely to be necessary to put a hard limit on the error and then try to reduce resource usage as much as possible. However, for other applications, such as navigation, entertainment, traffic information services, etc. it may make more sense to limit resource usage as occasional breakdowns in the functioning of the application due to high errors
are likely to have less severe consequences than using too much bandwidth and thus causing contention or preventing other applications from functioning.

In both these cases, the question arises as to how to define the minimum error or resource usage that we are optimising for. In the previous sections, we have taken the Euclidean norm of the error vector as our measure of error, however, in some cases it may be better to instead minimise the maximum error across the nodes to ensure all are treated fairly and have reasonably accurate values. Similar arguments apply to resource usage, but here we are instead considering fairness in resource allocation to prevent high bandwidth usage in some parts of the network, even if the overall usage is minimised. The parameters used may be either the two beaconing rates as used above, i.e. a fast rate and a slow rate, along with the threshold for switching rates, or else a more complex scheme with more levels of beaconing rates could be used.

Given a method to solve this optimisation problem for a given set of constraints and utility function, it would then be possible to apply it to different traffic scenarios and applications as needed, or, for example, to use vehicle traces or traffic simulations to determine the best balance for a particular region, network architecture, etc.
Traffic safety and congestion both remain major problems today, with much active research aiming to reduce them but no full solution in sight as yet. Current methods of managing traffic are broad measures which do little to leverage the differences between individual vehicles and drivers, or between different locations, times and situations. New and emerging technologies will allow us to improve on this. Vehicular ad-hoc networks give us the potential to have up-to-date information about a given traffic situation at all times, including the risk factors present and the state of surrounding vehicles. Vehicles are also becoming increasingly capable of computation to process this information and make decisions based on it.

However, many applications of VANETs and advanced driver assistance systems are very specific, focusing on reducing risk or increasing efficiency in one particular situation or due to one particular factor, and often involving only a single vehicle or small group of vehicles. In this thesis, I have developed a general model for traffic management that balances risk and utility and applies across the road system as a whole, to each vehicle and driver using it.

This model assesses the current situation as each vehicle sees it, evaluating the risk factors that are present and determining each vehicle’s response based on its risk level and the behaviours available to it. It is modular in the sense that more risk factors and vehicle behaviours can be added, or the risk calculation itself can be modified, without changing the overall model. This means that further research can be conducted to collect data, and model and understand particular risk factors and vehicle behaviours. These are able to be incorporated into the model, increasing its accuracy and improving its performance as time goes on. The better our understanding of a given situation,
the more control — and the more confidence in that control — we are able to have
over the balance between accident risk and road system utility, meaning we can im-
prove efficiency and potentially also allow driving in situations or by drivers that would
previously have been considered too risky by modifying vehicle and driver behaviour
appropriately for the situation.

The risk limit model works by first determining the risk level based on the risk
factors that are currently present. This is then compared to the risk limit: a target risk
level that represents an acceptable level of accident risk which vehicles must stay below.
Vehicles then take behaviours which either reduce their risk — if their risk is currently
too high, i.e. above the risk limit — or maximise their utility — if their risk level is
currently below the risk limit, allowing some leeway for improved utility even where
this may increase risk.

In this thesis, I have demonstrated the feasibility of determining the risk level based
on current risk factors using real-world road accident data obtained from NSW Roads
and Maritime Services. I have shown how we can calculate the risk value for a given
vehicle, driver and situation’s constellation of risk factors given raw data. We can pre-
calculate risk values for combinations of factors to gain information about the inter-
actions between factors. This can require a substantial amount of computation time,
however it is only necessary to do once. The relevant data could then be stored on
an on-board computer in each vehicle, or could be accessed via the network (or some
combination of these). Combined with inter-vehicle communications, it is then possible
for each vehicle to have up-to-date information on its own risk level and those of the
vehicles around it.

I have then investigated vehicle behaviours to be used in the model and tested their
effectiveness in managing risk and utility. These behaviours include vehicle speed,
headway, lane choice and link choice. I have tested the overall effectiveness of the risk
limit system in managing traffic and shown that it is possible to achieve gains in utility
— as measured by average vehicle speed and traffic throughput — while maintaining
the accident rate at current levels. Given that a more complete risk model could be
reasonably expected to make possible even higher gains, it is clear that the methodology
of capitalising on dynamic risk levels is promising for future safe and highly effective
road networks.

I have developed an algorithm for risk-aware link choice which deals gracefully
with congestion, varied risk difference between links and any number of links to choose
from. I investigated strategies for incorporating the effect a vehicle’s link choice has on the following vehicles by including a social penalty as a factor in link choice. These strategies ranged from completely selfish to completely selfless. I found that an intermediate strategy is the best approach for maximising road system utility. However, including a social penalty causes greater variance in average speeds from vehicle to vehicle and so fairness is a concern that needs further attention. Since the experiments were carried out over a single link it is natural to extend the experiments to incorporate multiple link networks. It is not unlikely that several consecutive links will result in statistical averaging of the variance, hence increased fairness for the vehicles.

I have then proceeded to further examine the networking aspects of this model. I have developed a distributed algorithm for coupled risk estimation, in which vehicles determine their risk estimates not only based on the information they have immediately available to them, such as through stored information or on-board sensors, but also incorporate risk estimates received from their neighbours in the network. I have tested this algorithm and found that it provides more stability in managing accident risk in the presence of localised hazards such as ice patches or oil slicks and that it also improves the overall utility of the system. I have proved that this algorithm converges for all initial risk estimates. Moreover, I have conducted experiments to determine the feasibility and performance of this algorithm and have found that its bandwidth usage and convergence rate are feasible for implementation in an 802.11p vehicular ad-hoc network.

I have examined the convergence rate for the coupled risk estimation algorithm in more detail and measured how it is affected by node density and spacing. The update iteration count to convergence was stable under different conditions, resulting in longer convergence times for small and widely-spaced networks, given a constant beaconing rate. However, in all conditions tested, the convergence rate was sufficiently fast, relative to the reaction time of a human driver, for the risk estimation algorithm to be effective.

I also investigated how the beaconing rate affects the error in the algorithm’s output in a scenario with mobile nodes and a large change in input in the form of a new node with a high risk value. The results show that higher beaconing rates reduce error, particularly when the risk values change rapidly. However, higher beaconing rates also consume more network resources. To counteract this problem, I developed a variable beaconing rate scheme in which nodes test their change in risk value against a threshold to determine which of two different beaconing rates to use. I found that using this
scheme achieved good performance both in terms of error and resource usage. In the future, this work can be extended to a more general optimisation problem to determine how best to adapt the beaconing rate given a particular rate of change of the risk value.

This methodology can be applied to any distributed algorithm matching the same network and data model characteristics. Vehicular networks fit these characteristics and these kinds of applications are appearing more and more for them. Many applications in VANETs are safety-critical and thus require rapid and accurate responses to changing data, and data is often processed and used directly by vehicles in a distributed fashion without leaving the network. The process I have described can thus be followed to inform the parameters used for such applications in order to balance error levels with network resource usage.

There are a number of other areas in which my work could be extended and questions which it raises. Firstly, there is a need for more and better accident risk data, particularly in terms of better data on exposure rates in order to quantify the effects of particular factors on accident risk. One promising aspect in this regard is that with the advent of VANETs, a large amount of information will be continuously exchanged and collected between vehicles, possibly leading to the ability to obtain more plentiful traffic data, although the collection, storage and processing of such a large volume of data presents its own challenges. There is also a need to improve our understanding and modelling of risk factors so that they are more easily able to be incorporated into systems such as the one developed in this thesis. It is not enough to know that a particular factor increases accident rate: the risk factor must be possible to model, simulate and experiment with in order for its use in a traffic management system to be tested and implemented.

The model as presented in this thesis could also be extended and further developed. Crash severity is an important aspect of accident risk that we have not yet included in the system and the model could be expanded to include more vehicle behaviours, particularly end-to-end route choice. There are also many aspects related to how the system interacts with a driver that have not yet been addressed, such as the user interface for the driver, and issues surrounding driver acceptance and compliance. In order to implement this system, work would also need to be undertaken on how to secure the system from malicious parties and how to integrate it with existing inter-vehicle communications standards.

There is much previous work on understanding and mitigating accident risk, and on
inter-vehicle communications, autonomous vehicles and advanced driver assistance systems, but it would be beneficial if these fields worked more closely together. Accident risk should be a consideration in any system affecting road users and with advancing technology we have the capability to make this happen. We currently have a body of existing work — and research is continuing in this area — on assessing a vehicle’s environment and how to navigate through it and interact with other vehicles. However, these protocols and systems, while they generally aim for a high standard of safety, do not take a holistic or dynamic approach to accident risk. The focus is on the particular system rather than the overall situation the vehicle is in and how this should affect its behaviour.

Accident risk is not static; it is constantly changing as a vehicle and driver travel and interact with other vehicles and their surroundings. It is a complex phenomenon, however we are increasingly able to communicate, process and make decisions from large amounts of information very rapidly. As such, we no longer need to rely on blanket rules and instead can leverage a deeper understanding of accident risk and how our behaviour affects and is affected by it, allowing us to dynamically trade off accident risk with the desired utility of the road system as circumstances change moment to moment. The goal of any traffic management system is to balance accident risk and utility and this should be at the heart of such a system; it should be done explicitly and directly. Doing so will not only give us a better understanding of and a more direct relationship with accident risk but also allow us to improve the efficiency of our road system while keeping accidents to an acceptably low level.
Glossary

**802.11p** An amendment to the IEEE 802.11 (wireless local area network) standard to add vehicular wireless networks.

**ADAS** Advanced Driver Assistance System.

**Advanced Driver Assistance System** An electronic system to help the driver of a vehicle with the task of driving.

**Autonomous vehicle** A vehicle capable of driving itself, generally through the use of an array of sensors and actuators and an on-board computer.

**Basic Safety Message** A periodic message sent out by each vehicle in a vehicular network according to the IEEE 1609 standard, which contains current state information.

**Beacon** A broadcast message sent out periodically by a node in a wireless network.

**Beaconing** Sending out periodic messages containing current state information.

**BSM** Basic Safety Message.

**CAM** Co-operative Awareness Message.

**Co-operative Awareness Message** A periodic message sent out by each vehicle in a vehicular network according to the ETSI EN 302 665 standard, which contains current state information for that vehicle.

**Co-operative driving** Vehicles collaborating and communicating using a vehicular network to jointly determine manoeuvres.
Coupled risk estimation  Risk estimation in which vehicles use not only their own local information but also risk estimates received from neighbouring vehicles in order to determine their risk values.

Decentralized Environmental Notification Message  A periodic message sent out by each vehicle in a vehicular network according to the ETSI EN 302 665 standard, which contains current information about the environment.

Dedicated Short-Range Communications  General term for wireless communications channels, standards and protocols designed for vehicular networks.

DENM  Decentralized Environmental Notification Message.

DSRC  Dedicated Short-Range Communications.

ETSI  European Telecommunications Standards Institute.

Exposure  A measure of how much a given vehicle or driver is exposed to accident risk, e.g. time spent on the road or kilometres driven.

Goodput  Application-level throughput, i.e. the number of actual data bits (excluding protocol overhead) per unit time.

IEEE  Institute of Electrical and Electronic Engineers.

IVC  Inter-Vehicle Communications.

ns-3  A discrete-event network simulator.

OBU  On-Board Unit.

On-Board Unit  A radio unit in a vehicle to enable it to connect to a vehicular network.

Paramics  A road traffic simulator.

Risk limit  An acceptable or allowable level of accident risk which vehicles should not exceed.

Self-driving vehicle  See Autonomous vehicle.
**V2I** Vehicle-to-Infrastructure communications.

**V2V** Vehicle-to-Vehicle communications.

**VANET** Vehicular Ad-hoc Network.

**Vehicular Ad-hoc Network** A wireless network in which the nodes are vehicles and there is no centralised control or configuration.
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