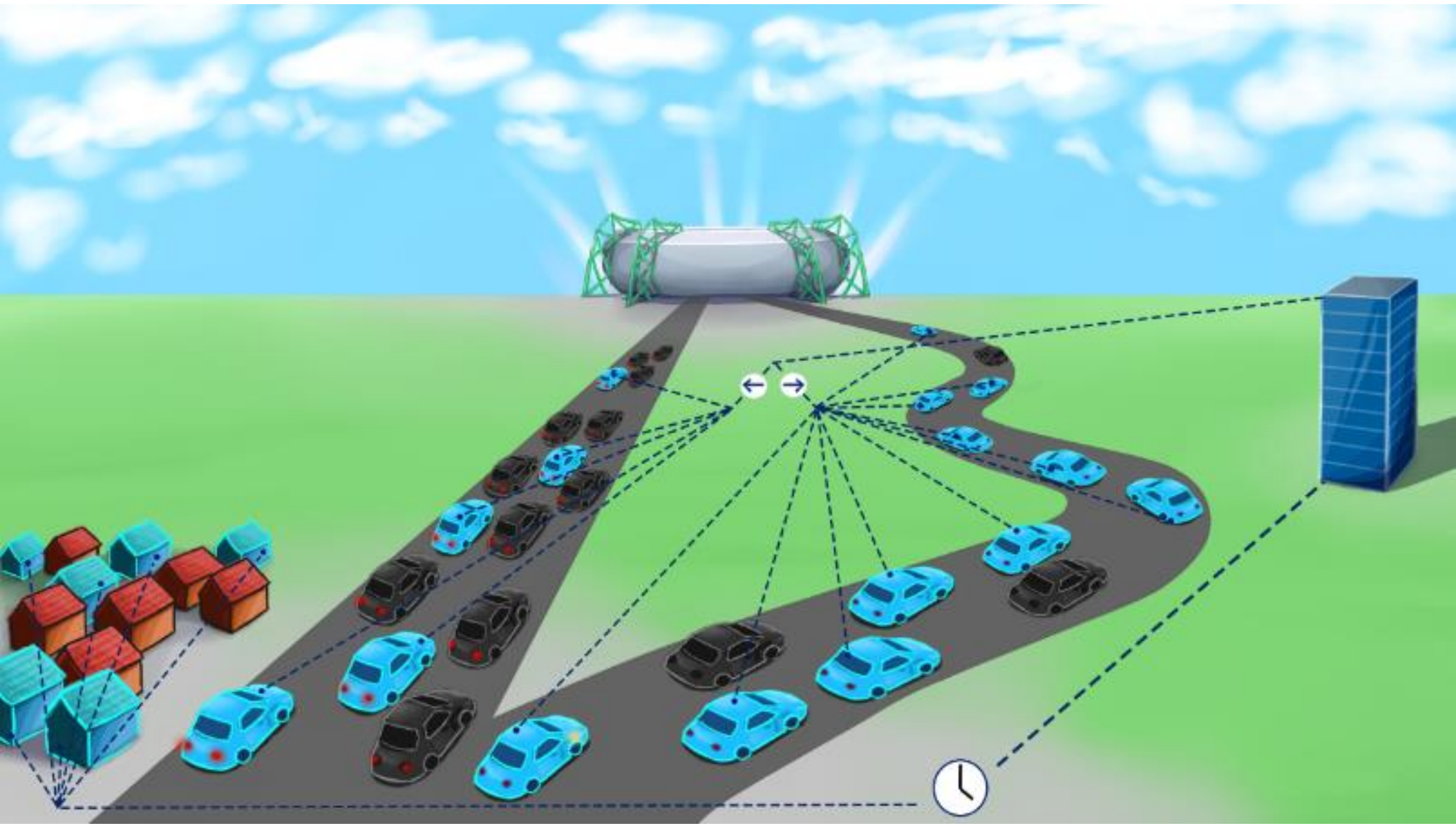
Traffic management at large-scale events

Design and evaluation of a controller providing route and departure time advice to individual visitors

Master Thesis Research: Final Report



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Preface

This report is the final result of my Master thesis work, executed at Antea Group. This thesis is conducted to obtain the degree of Master of Science in Civil Engineering (Transport & Planning) at the Delft University of Technology. In the past months, many people have contributed in some way to the creation of this Master thesis: in this preface, I take the opportunity to express my gratitude.

Firstly, I would like to thank the members of my graduation committee: Serge, Andreas, Matti and Tessa. Throughout the course of my graduation work, they have given vital feedback: both regarding the technical aspects of the research and the general process of the graduation work, their comments were very useful. Furthermore, they gave me the inspiration to approach my thesis work with renewed energy after every feedback meeting.

I would like to thank all my colleagues at Antea Group, who have made my time there so enjoyable: it was great having some distraction from the struggles of the graduation work. Specifically, I express thanks to Roel, Ronnie and Mark for their feedback on the proceedings of the research. Their observations have helped me to understand the possibilities for the practical application of my thesis work and the steps that still needed and need to be taken to achieve this implementation.

My parents, sister and brother have been an enormous support during my studies and this graduation work, through both the challenging and the happy times. I am very grateful to have the best parents, sister and brother one could wish for. Special thanks to my sister Samantha, for providing me with the nice front page figure.

Above all, I want to thank the Lord, who has given me the strength and support to finish my educational programme and who is with me every day.

Rutger Verschelling

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Summary

Introduction and problem definition

Large-scale events, like concerts, football matches and festivals, attract many visitors. Generally, a large portion of these visitors travels to the event venue by car. This large inflow of car traffic often exceeds the capacity of the available infrastructure in the direct surroundings of the large-scale event. Bottlenecks as parking facilities, traffic lights and off-ramps cause queues of event visitors: these queues can spill back to roads of a higher importance in the network (motorways). The motorways are not only used by event visitors, but also by through traffic that doesn't have the event venue as its destination. Therefore, any spillback of queues to higher level roads increases the hindrance caused by the event drastically. Not only event visitors will be delayed, the background traffic in the network also suffers unnecessarily from the event-bound traffic, as they will be caught by the congestion that is caused by the spillback from the event location. From scientific literature, it can be concluded that non-recurrent congestion conditions (like events) provide opportunities for traffic management: event visitors are mostly less familiar with the route alternatives to the event and the traffic dynamics in the network than commuter traffic. Therefore, the event visitors will make sub-optimal decisions regarding their departure time and route choice. Travel information and traffic management will help them to make better choices, possibly leading to a better distribution of traffic over the network.

Traffic management is evolving. In the current practice in the Netherlands, so-called *control scenarios* are made before a large-scale event, which describe the dynamic traffic management measures that may be taken using if-then-rules. However, the rise of smartphones with social media and all sorts of traffic (navigation) applications - as well as the implementation of automated vehicles in the longer term - requires traffic management to change. The first step in this process is to individualise traffic management, to use the possibilities of in-car traffic management more optimally. Individual traffic management (ITM) gives the opportunity to approach more travellers, and to distribute them very subtly over time and space with departure time advice and route guidance respectively. ITM is therefore an interesting solution direction for the spillback and congestion problems at large-scale events. The visitors can be approached using social media and navigation apps, to advise them about their departure time and route choices. Optimising the routes and departure times of the event visitors can reduce the inflow into the event bottleneck, which could lower the chance of spillback of queues to motorways and therefore also reduces the delay of background traffic in the network around the event venue.

Research setup

The goal of this Master thesis research is to design and evaluate a controller, which can be used to provide individual route guidance and possibly also departure time advice to visitors of a large-scale event (travelling by car), in order to reduce traffic hindrance at events. This thesis work consists of three main steps, which follow from the three main research questions.

1. *What theoretical control concepts can be used to improve the current methods of individual route guidance?*
   - Literature study into theoretical concepts that can be used in the design of a general ITM controller

2. *How can the theoretical concepts of individual traffic management be used in a controller design specifically aimed at car traffic at large-scale events?*
   - ➢ Design of an ITM controller for application at large-scale events, fulfilling requirements based on the problem definition and the literature study.
3. *What are the quantitative effects on traffic performance of individual traffic management at large-scale events?*
   - ➢ Evaluation of the (quantitative) effects of the ITM controller design in a simulation environment.

The three research steps lead to conclusions and recommendations regarding the opportunities of ITM at events. Furthermore, the practical application and implementation of the designed controller is discussed in this research.

Literature study

Firstly, scientific literature is studied to develop an overview of the possible design elements of an ITM controller. The controller design choices are broken down into three separate building blocks of the controller: 1) Controller structure and strategy; 2) Controller objective; 3) Integration of individual departure time advice in the controller's computations. The options within these building blocks are summarised in Figure S.1. Both within and between the building blocks, trade-offs must be made in the design process.

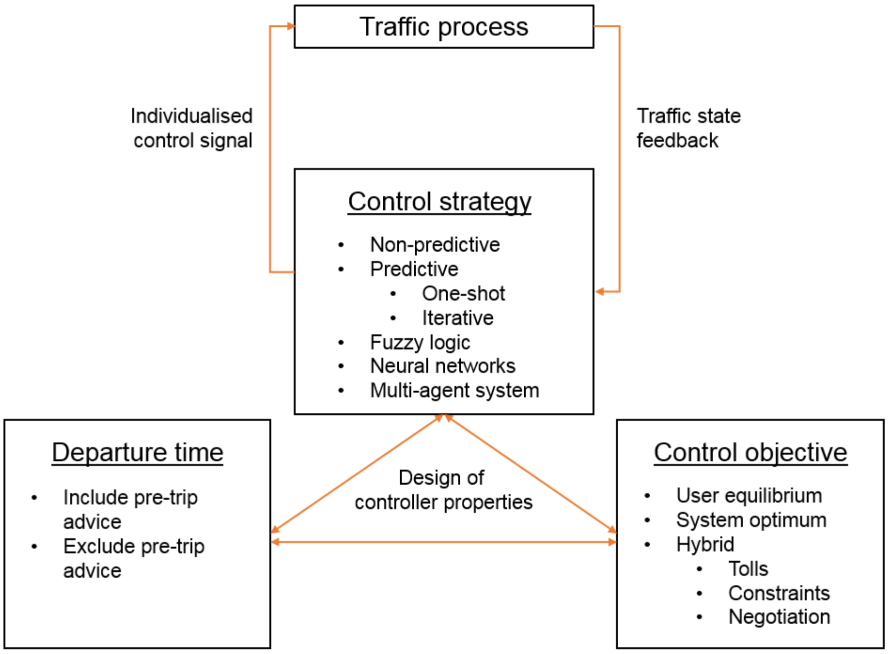


Figure S.1: Conceptual framework of ITM including the different building blocks and their elements

For the control strategy and structure, the main trade-off is between the accuracy and the complexity of the controller: complex control strategies (e.g. iterative predictive control) are very accurate, but require more computational time. This consideration is also important in the choice for control structure (centralised versus decentralised). Furthermore, the historical data requirements for strategies such as fuzzy logic and neural networks can be high: this is also a factor in the controller design choices. For the control objective, the trade-off between system optimal and user optimal advice must be made. While travellers will intuitively tend to the more 'fair' user equilibrium, the system optimum can lead to a lower *total* travel time in the network.

However, this minimised total travel time might require an unfair distribution of travellers over routes: the difference between the route travel times might become unacceptably large. A hybrid objective of the system and user optimal assignment is possible as well. For instance with an 'unfairness constraint', the travel time difference between routes (or departure time intervals) will not exceed a limit, while an absolute optimal assignment can still be approximated. These objectives are also applicable for departure time advice. Although the literature identifies strong effects on traffic conditions if departure times would be optimised, there is debate about the application of departure time *advice* on the shorter term. Possibly, controlling departure times on the short term is not effective as the advice might have no relevant effect anymore.

ITM controller design

These generic findings about ITM are applied to large-scale events in the controller design stage. Following the literature study, the problem statement, and the specific characteristics of events, a number of requirements for the design is formulated. These requirements indicate the choice for the following building blocks (and the options within these blocks):

- One-shot predictive control strategy, meaning that there is no iteration between the advice computation and the traffic state predictions;
- Constrained system optimal objective;
- Integration of individual route guidance and departure time advice in the ITM controller.

The conceptual design of the controller is depicted in Figure S.2.

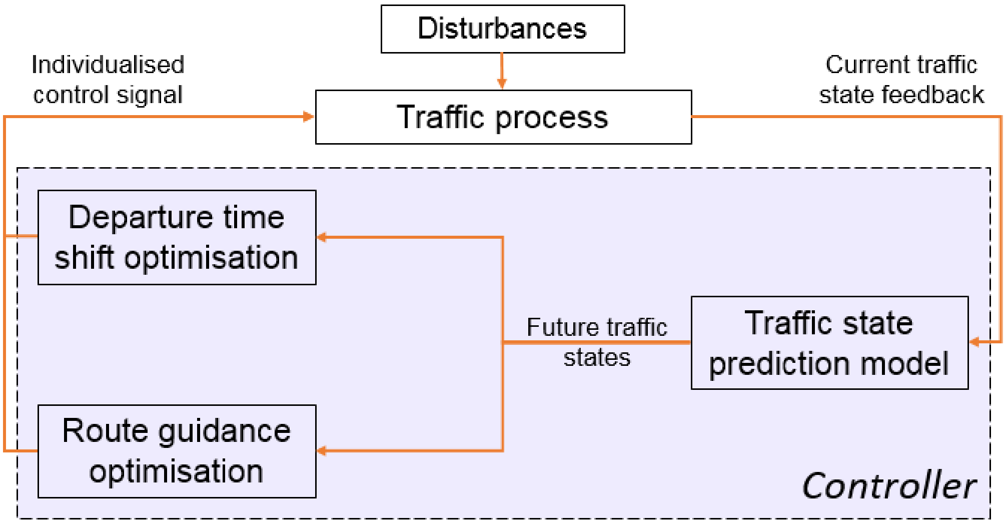


Figure S.2: Conceptual framework of the ITM controller for large-scale events

The Link Transmission Model (LTM) of Yperman (2007) is used as the basis of traffic state prediction model in the controller: this macroscopic model bases its predictions on the current traffic states, estimated demands and shockwave theory. The latter means that the LTM can model queue build-up and dissolving very accurately: this is important, regarding the problem statement of spillback from events. Furthermore, with some extensions of the LTM, it can keep track of the movements of both the event-bound traffic and background traffic in the network. The predictions of the LTM are input for the optimisation of the individual route and departure time advice.

The on-route route guidance optimisation component of the controller finds the optimal split fractions at nodes. In the objective function, the sum of the travel times of vehicles on all links is minimised. The route guidance optimisation is constrained by the sum of the split fractions at a node (equal to 1) and the maximum travel time difference between used alternative routes to the event location, which leads to a constrained system optimal assignment of event visitors.

The pre-trip departure time advice optimisation will determine if the preferred departure time of event visitors must be shifted towards an earlier or later departure time interval. The objective function contains the travel time sum of vehicles departing for a certain path to the event venue, as well as the total perceived shift time and some penalty for assigning traffic to departure time intervals that contain queues on the path from the origin to the event location. The departure time advice optimisation is constrained by the fulfilment of all advice requests, a maximum shift time of visitors, a maximum arrival time of visitors at the event, and a maximum unfairness between departure time alternatives.

Simulations

To evaluate the effectiveness of the ITM controller design, the controller's working is simulated in synthetic (fictive) networks and a case study network, which is a simplified representation of the network around the *Amsterdam Arena*. The simulations in the synthetic networks are meant to evaluate whether the controller (component) can solve the spillback issue and congestion in a simple network. These simulations show that the controller design is able to decrease total travel time delay in a network: both the individual route guidance and the departure time advice, separately and integrated, are able to prevent spillback – which occurred if no information was given to travellers –, reducing the delays (in terms of vehicle hours lost) for background traffic to practically zero. This indicates the potential of the controller to improve traffic performance in other situations as well.

In the Arena-network, two reference cases were compared to the full ITM controller design: no travel information and information provision through variable message signs (VMS). The effectiveness of the ITM controller was very clear: while the A2 motorway suffers from spillback from the western entrance of the Arena in the reference cases, the ITM controller is able to fully prevent this spillback, leading to a lower amount of vehicles hours lost during the simulation. The simulation with a representation of the working of VMS in the Arena-network already led to some improvement in traffic performance, but due to inaccuracies and myopic steering spillback could not be prevented, resulting in (still) large delays for the background traffic. The ITM controller distributes the event-bound traffic over the different entrances of the Arena, by guiding the majority of the guided traffic over different approach routes alternatingly (oscillatory behaviour of the solution). Deeper analysis shows that this is mostly due to the individual route guidance. In fact, the complexity of the network and the assumptions in the modelling lead to a slight degradation of the overall traffic performance in the network if the departure time advice is used. This suggests that the departure time advice optimisation (the current design) is only applicable at networks with a low number of approach routes to the event venue and a high penetration rate of the advice in the traffic system. A sensitivity analysis shows that the effects of the ITM controller design are also easily influenced by the event-bound traffic demand and the effective penetration rate (penetration rate and compliance) of the ITM controller. This leads to the conclusion that the ITM controller design has great potential to reduce the traffic hindrance (in terms of delays) at events, but the actual effects are dependent on the situation to which the controller is applied.

Practical application

These benefits of the controller in a simulation environment advocate the use of the controller in practice. Stakeholders such as road authorities and event organisations might find the ITM controller design interesting to reduce the hindrance at a certain event. With some additions, the controller design might also be applied at incidents or road works (the latter bringing contractors into play). For application in the current traffic system, two directions are possible. Firstly, the ITM controller could be applied in an offline (simulation) fashion, to qualitatively determine traffic management measures that should be applied in practice and what target groups should be approached to improve the traffic flows in the network. This requires a good match between the modelling in the ITM controller and the real traffic process. Next to some improvements to the controller, a calibration and validation process could be useful to improve the extent to which the model suits the reality. Secondly, the controller could be applied in real-time at an event. This would require the cooperation with a service provider, to have an interface between the controller's calculation and the actual advice provision to the end user. Barriers for the real-time implementation of the controller could be the computation time of the controller, the quality and accuracy of traffic state measurements, and the interaction with road-side guidance systems. Personalisation of the real-time ITM will increase the appreciation of users of the service, having effects on their compliance as well.

For a system with automated vehicles, the ITM controller design is suitable as well: the (constrained) system optimal goal, induced by managing individual vehicles by a centralised agent fits the concept of fleet management and sharing of automated vehicles.

Main conclusions of the research

- For the design of an ITM controller, there are many options for the control strategy, structure, objective and inclusion of departure time advice. For the specific application of ITM to large-scale events, trade-offs are needed regarding the complexity (computation time), accuracy and historical data needs in the choice for certain design elements.
- To apply ITM at a large-scale event to improve the traffic conditions there, a centralised one-shot predictive controller can be used. This controller induces a constrained system optimum on the road network by optimising the on-route route guidance and pre-trip departure time advice for individual event visitors.
- Simulation of this controller design has revealed that ITM at events has potential to solve traffic issues like spillback. In complex networks, the individual route guidance by the controller affects the traffic conditions the most, while in more simple networks (e.g. limited number of approach routes to the event venue) the departure time advice can be effective as well.
- A sensitivity analysis of the performance of the ITM controller shows that its effectiveness mainly depends on external factors such as demand, effective penetration rate and the network layout. Therefore, application of the ITM controller in a real-time manner should be done with care.
- To apply the ITM controller design in practice in the current traffic system, this research has proposed the development of an offline simulation tool, as well as a tool to apply the controller in real-time at an event.

Recommendations

Firstly, it is recommended to implement some minor improvements in the design of the ITM controller, to increase accuracy and applicability. Examples of improvements are: using an extended version of the LTM for more accurate representation of node flows and the dynamic assumptions in the departure time optimisation (this requires some interaction between the route guidance and departure time advice optimisations).

This controller can then be applied, both offline and in real-time. It is expected that this will have benefits for the traffic conditions at events (or similar non-recurrent situations). For both the offline and online application of the controller, it is recommended to develop a dedicated tool, which can execute the ITM controller’s calculations with input that is uploaded in a user interface. This simplifies the use of the controller and gives transparency regarding the inputs and the outputs of the controller’s calculations. The tool can be developed in a stepwise manner, to evaluate the different components of the designed controller in practice separately (e.g. first individual route guidance, then departure time advice at events). After the application of ITM in real-time at an event, a data-analysis is needed to evaluate its application and to find more improvements.

Next to this, future research efforts should focus on extending the controller’s application (e.g. mode choice, parking lot choice) and the use of the optimisations in a system of shared automated vehicles. Furthermore, other approaches to the calculation of the route guidance and departure time advice are possible as well. The components of the controller are relatively flexible. For instance, for the route guidance and departure time advice optimisation also other methodologies can be used (simple control rules finding optimum network state), to prevent high computational times of the controller’s optimisations in complex networks.

Samenvatting (Dutch)

Introductie en probleemstelling

Grootschalige evenementen, zoals concerten, voetbalwedstrijden en festivals, trekken veel bezoekers aan. Een groot deel van deze bezoekers reist per auto naar de evenementenlocatie. Deze grote instroom van autoverkeer leidt vaak tot de overschrijding van de capaciteit van de beschikbare infrastructuur in de directe omgeving van het evenement. Bottlenecks zoals parkeerfaciliteiten, verkeerslichten en afritten veroorzaken wachtrijen van bezoekers: deze wachtrijen kunnen terugslaan naar meer belangrijke wegen (snelwegen) in het wegennet. De snelwegen worden niet alleen door bezoekers gebruikt, maar ook door doorgaand verkeer dat niet het evenement als bestemming heeft. Daarom vergroot eventuele terugslag van wachtrijen de hinder die door een evenement veroorzaakt wordt. Niet alleen worden bezoekers vertraagd, ook doorgaand verkeer in het netwerk lijdt onnodig onder de instroom van evenementenverkeer, omdat zij worden gevangen in de terugslag van wachtrijen vanaf het evenement. In de literatuur wordt geconstateerd dat niet-terugkerende verkeerssituaties (bijv. evenementen) mogelijkheden bieden voor dynamisch verkeersmanagement (DVM): bezoekers zijn vaak minder bekend met de routealternatieven naar het evenement en de verkeersdynamiek in het netwerk dan forenzen. Daarom zullen bezoekers suboptimale beslissingen maken met betrekking tot hun routekeuze en vertrektijd. DVM kan hun helpen om betere keuzes te maken, wat kan leiden tot een betere verdeling van verkeer over het netwerk.

DVM maakt een groei door. In de huidige Nederlandse praktijk worden voorafgaand aan een evenement zogenoemde *regelscenario's* ontwikkeld, die met behulp van als-dan-regels beschrijven welke DVM-maatregelen getroffen moeten worden. De opkomst van smartphones met social media en allerlei verkeersapps (bijv. voor navigatie), evenals de toekomstige implementatie van autonome voertuigen, vraagt echter om een verandering in de huidige DVM-methoden. De eerste stap in dit proces is om DVM te individualiseren, om zo de mogelijkheden van *in-car* DVM optimaal te gebruiken. Met *individueel* verkeersmanagement (IVM) kunnen meer reizigers bereikt worden en kunnen zij op detailniveau over ruimte en tijd verdeeld worden, met behulp van respectievelijk route- en vertrektijdadvies. IVM is daarom een interessante oplossingsrichting voor het terugslag-probleem bij grootschalige evenementen: de bezoekers kunnen bereikt worden met onder meer social media, zodat zij advies kunnen krijgen op het gebied van hun route en vertrektijd. Het optimaliseren van de routes en vertrektijden van de bezoekers kan de instroom in de bottleneck bij het evenement reduceren, wat de kans op terugslag van wachtrijen naar snelwegen vermindert en zo ook de vertraging van doorgaand verkeer in het netwerk verkleint.

Onderzoeksopzet

Het doel van deze Master thesis is om een regelaar te ontwerpen en te evalueren: deze regelaar kan gebruikt worden om individueel routeadvies en mogelijk ook individueel vertrektijdadvies te geven aan evenementen-bezoekers (die per auto reizen), om zo verkeershinder bij evenementen te verminderen. Het onderzoek bestaat uit drie stappen, die gebaseerd zijn op de drie hoofdvragen van het onderzoek.

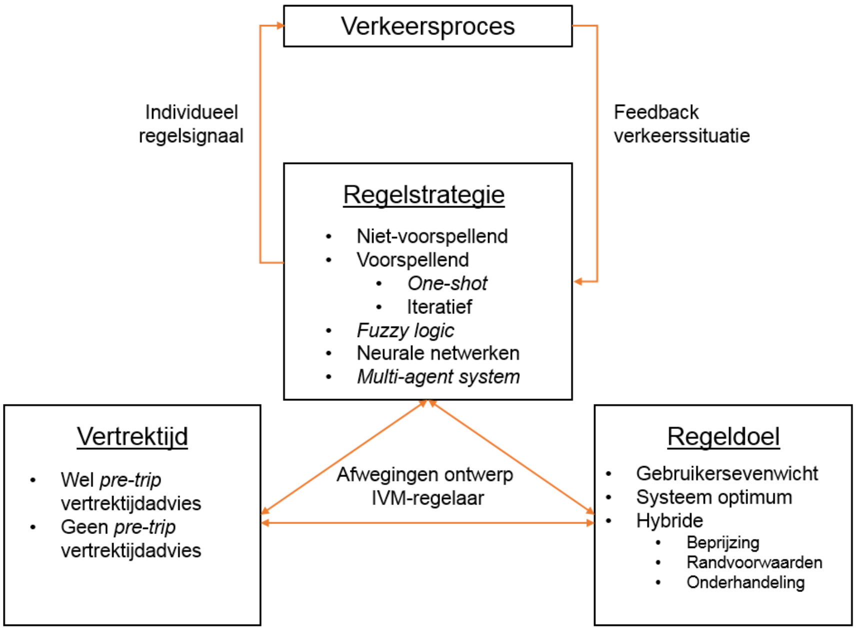
1. *Welke theoretische regelconcepten kunnen gebruikt worden om de huidige methoden van individueel verkeersmanagement te verbeteren?*
   - ➢ Literatuurstudie naar theoretische regelconcepten die gebruikt kunnen worden in het ontwerp van een regelaar voor individueel routeadvies.

2. *Hoe kunnen de theoretische concepten van individueel verkeersmanagement gebruikt worden in het ontwerp van een regelaar dat bedoeld is voor autoverkeer bij grootschalige evenementen?*
   - ➢ Ontwerp van een IVM-regelaar voor toepassing bij grootschalige evenementen, die de eisen vervult die gebaseerd zijn op de probleemdefinitie en de literatuuranalyse.
3. *Wat zijn de kwantitatieve effecten van individueel verkeersmanagement op de verkeerssituatie bij grootschalige evenementen?*
   - ➢ Evaluatie van de (kwantitatieve) effecten van de ontworpen IVM-regelaar in simulaties.

Deze drie stappen leiden tot conclusies en aanbevelingen aangaande de toepassing van IVM bij evenementen. Daarnaast wordt de praktische toepasbaarheid van de ontworpen regelaar besproken in dit onderzoek.

Literatuuranalyse

Eerst wordt de wetenschappelijke literatuur geanalyseerd om de mogelijke ontwerp-elementen van een IVM-regelaar te overzien. De ontwerpkeuzes voor de regelaar kunnen in drie bouwstenen onderscheiden worden: 1) Regelstrategie en -structuur; 2) Regeldoel; 3) Integratie van individueel vertrektijdadvies in de berekeningen van de regelaar. De opties binnen deze bouwstenen zijn samengevat in Figuur S.1. Zowel binnen de bouwstenen als daarbuiten moeten afwegingen gemaakt worden in het ontwerpproces.



Figuur S.1: Conceptueel kader voor IVM met de diverse bouwstenen en de bijbehorende ontwerpmogelijkheden

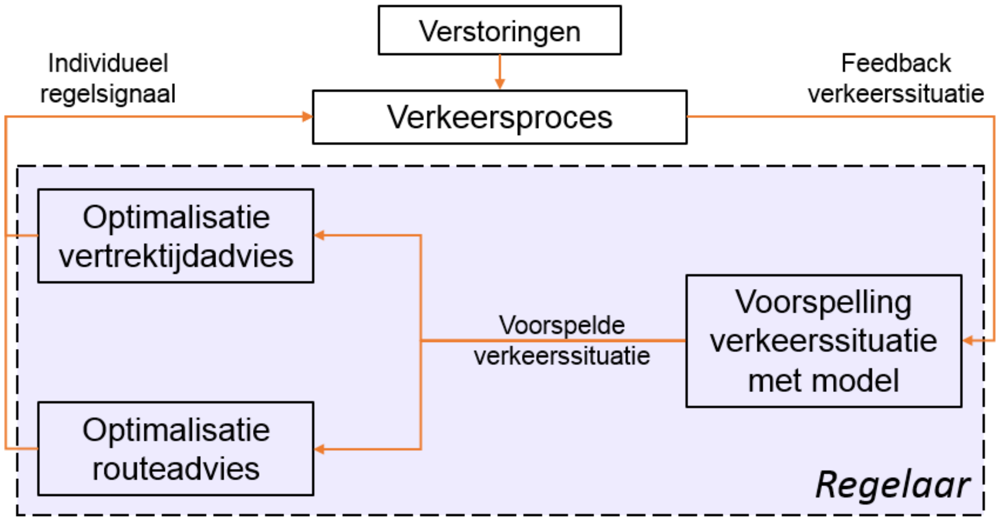
Complexe regelstrategieën (bijv. iteratief voorspellend) zijn zeer nauwkeurig, maar leiden tot meer rekentijd. Dit geeft ook de voornaamste afweging voor de keuze voor een regelstrategie en -structuur aan: het betreft de tegenstelling tussen de complexiteit en de nauwkeurigheid van de regelaar. De overweging van de rekentijd is ook belangrijk in de keuze voor regelstructuur (decentraal versus centraal). Verder is het gebruik van historische data een belangrijke factor in de ontwerpkeuzes: de data-benodigdheden voor strategieën als *fuzzy logic* en neurale netwerken kunnen vrij groot zijn. Voor het regeldoel is de afweging tussen het systeem optimum en het gebruikersevenwicht nodig. Van nature zullen reizigers geneigd zijn een gebruikersevenwicht te benaderen (dat is ‘eerlijker’), terwijl het systeem optimum leidt tot een lagere *totale* reistijd in het netwerk. De geminimaliseerde totale reistijd vereist echter een relatief oneerlijke verdeling van reizigers over routes. Het verschil tussen de reistijden op de routes kan onacceptabel groot worden. Een hybride variant van systeem- en gebruikersoptimum is ook mogelijk: dit kan bijvoorbeeld met een randvoorwaarde voor ‘oneerlijkheid’ bereikt worden, waarbij het reistijdverschil tussen routes (of vertrektijden) wordt beperkt, terwijl een optimale toewijzing benaderd kan worden. Deze regeldoelen zijn ook toepasbaar voor vertrektijdadvies. Hoewel vanuit de literatuur er aanwijzingen zijn dat het optimaliseren van vertrektijden sterke effecten heeft op de verkeerssituatie, kan het betwist worden of vertrektijd*advies* ook geschikt is voor korte-termijn-verkeersmanagement.

Ontwerp IVM-regelaar

Deze algemene bevindingen over IVM worden toegepast op evenementen in de ontwerpfase van de regelaar. De literatuuranalyse, de probleemdefinitie en de specifieke eigenschappen van evenementen leiden tot een aantal eisen voor het ontwerp. Deze eisen geven de keuze voor de volgende bouwstenen (en de opties daarbinnen) aan:

- Voorspellende regelstrategie (één voorspelling per regelinterval, geen iteratie tussen het geoptimaliseerde advies en de voorspellingsmodule);
- Systeem optimaal regeldoel met randvoorwaarden;
- Integratie van individueel routeadvies met vertrektijdadvies in de IVM-regelaar.

Het conceptuele ontwerp van de regelaar wordt afgebeeld in Figuur S.2.



Figuur S.2: Conceptueel kader voor de IVM-regelaar voor verkeer bij grootschalige evenementen

Het Link Transmissie Model (LTM) van Yperman (2007) wordt gebruikt als basis voor de module van verkeersvoorspelling: dit macroscopisch model baseert de voorspelling op de huidige verkeerssituatie, geschatte verkeersvraag en schokgolftheorie. Dat laatste betekent dat het LTM nauwkeurig de op- en afbouw van wachtrijen modelleert. Daarnaast - met enkele toevoegingen - houdt het LTM de bewegingen bij van zowel bezoekers als doorgaand verkeer in het netwerk. De voorspellingen van het LTM zijn input voor de optimalisaties van het individueel route- en vertrektijdadvies.

De optimalisatie van het on-route routeadvies van de regelaar berekent de optimale routefracties bij splitsingen. In de doelfunctie wordt de som van de reistijden van voertuigen op alle links geminimaliseerd. Randvoorwaarden bij deze optimalisatie zijn de som van de routefracties bij een splitsing (gelijk aan 1) en het maximale reistijdverschil tussen gebruikte alternatieve routes, hetgeen de ‘oneerlijkheid’ van het advies begrenst. Zo kan een systeem optimum benaderd worden.

De optimalisatie van het pre-trip vertrektijdadvies bepaalt of de voorkeursvertrektijd van bezoekers wordt verschoven naar een eerdere of latere vertrektijd. De doelfunctie bevat de som van de reistijd van voertuigen die via een bepaald pad naar de evenementenlocatie zullen reizen, evenals de totale waargenomen verschuivingstijd en straftijd voor het toewijzen van verkeer aan vertrektijden die wachtrijen bevatten op de route van herkomst naar de evenementenlocatie. Deze optimalisatie is onderworpen aan voorwaarden voor de voldoening van alle adviesaanvragen, een maximale verschuivingstijd, een maximale aankomsttijd bij het evenement en een maximale oneerlijkheid tussen vertrektijd-alternatieven.

Simulaties

Om de effectiviteit van het ontwerp te evalueren, wordt de werking van de IVM-regelaar gesimuleerd in synthetische (fictieve) netwerken en een *case study* netwerk. Dit laatstgenoemde netwerk is een vereenvoudigde weergave van het netwerk rond de Amsterdam Arena. De simulaties in de synthetische netwerken zijn bedoeld om te evalueren of (component van) de IVM-regelaar het terugslag-probleem kan oplossen in een eenvoudig netwerk, om zo de werking van het ontwerp te testen. Deze simulaties in de fictieve netwerken bevestigen dat de ontworpen regelaar de totale vertraging in een netwerk kan reduceren: zowel het individueel route- als vertrektijdadvies, apart en geïntegreerd, kunnen terugslag voorkomen. Deze terugslag kwam voor als reizigers geen informatie kregen: de regelaar was dus in staat om de vertraging voor doorgaand verkeer (voertuig verlies uren) naar bijna nul terug te brengen. Dit geeft de potentie van de ontworpen regelaar om de verkeerssituatie ook in andere situaties te verbeteren aan.

In het Arena-netwerk zijn twee referentiescenario’s – geen verkeersinformatie en verkeersinformatie via dynamische informatieborden langs de weg – vergeleken met het volledige ontwerp van de regelaar. De effecten van de IVM-regelaar waren zeer duidelijk. In de referentiescenario’s veroorzaakte terugslag vanaf de westelijke aanvoerroute van de Arena hevige congestie op de autosnelweg A2, terwijl de toepassing van de ontworpen regelaar dit volledig voorkomt (sterke reductie in voertuig verlies uren). De simulatie met een vereenvoudigde weergave van de werking van reizigersinformatie door wegkantsystemen leidde al tot wat verbetering in de verkeersafwikkeling, maar door onnauwkeurigheden en kortzichtige sturing kan terugslag niet voorkomen worden, wat nog steeds grote vertraging voor het doorgaand verkeer veroorzaakte. De IVM-regelaar verdeelt de bezoekers van het evenement over de verschillende aanvoerroutes van de Arena, door de meerderheid van het gestuurde verkeer om en om over de verschillende routes te sturen. Nadere analyses tonen aan dat dit vooral door het individueel routeadvies bewerkstelligd wordt. De complexiteit van het netwerk en de aannames in het modelleren van het vertrektijdadvies leiden tot een kleine verslechtering van de verkeersperformance als vertrektijdadvies wordt toegepast bij de Arena. Dit suggereert dat het huidige ontwerp van vertrektijdadvies-optimalisatie alleen toepasbaar is in netwerken met een klein aantal aanvoerroutes en een hoge penetratiegraad van het vertrektijdadvies in het verkeersproces. Een gevoeligheidsanalyse toont aan dat de verkeersvraag van bezoekers en de effectieve penetratiegraad (penetratiegraad en opvolggedrag) van IVM ook sterke invloed hebben op de effecten van de (volledige) ontworpen regelaar. Dit leidt tot de conclusie dat het ontwerp van de IVM-regelaar veel potentieel heeft om verkeershinder rond evenementen te verminderen, maar dat de daadwerkelijke effecten afhangen van de situatie waarin de regelaar toegepast wordt.

Praktische toepassing

De gevonden voordelen van de ontworpen regelaar in de simulaties pleiten voor het gebruik van de regelaar in de praktijk. Mogelijk vinden diverse stakeholders als wegbeheerders en evenementenorganisaties de IVM-regelaar interessant om verkeershinder bij een bepaald evenement te reduceren. Met enkele toevoegingen kan de regelaar ook toegepast worden bij incidenten of wegwerkzaamheden (bij de laatste zijn ook aannemers betrokken). Voor de toepassing in het huidige verkeerssysteem zijn er twee mogelijke denkrichtingen. Ten eerste kan de IVM-regelaar als een offline (simulatie) applicatie toegepast worden, om kwalitatief DVM- en IVM-maatregelen te bepalen die in het echt moeten worden toegepast en welke doelgroepen bereikt moeten worden om de verkeersdoorstroming te verbeteren. Dit vereist een goede overeenkomst tussen het modelleren in de IVM-regelaar en het verkeersproces in de werkelijkheid. Ten tweede kan de regelaar in *real-time* worden toegepast bij een evenement. Dit vergt een samenwerking met een serviceprovider, die dan dient als een interface tussen de berekeningen van de regelaar en het aanbieden van het advies bij de eindgebruiker. Mogelijke drempels voor de real-time toepassing van de regelaar zijn de rekentijd van de regelaar, de kwaliteit en nauwkeurigheid van de metingen van de verkeerssituatie, en de interactie met wegkantsystemen voor routeadvies. Door het personaliseren van IVM kan de dienst aantrekkelijker worden voor de eindgebruikers, wat effect zal hebben op hun opvolggedrag.

De ontworpen regelaar is ook geschikt voor een systeem met autonome voertuigen: het systeem optimale regeldoel (met randvoorwaarden), wat bereikt wordt door individuele voertuigen te sturen door een centrale entiteit, past goed bij het concept van *fleet management* en gedeelde autonome voertuigen.

Voornaamste conclusies van het onderzoek

- Voor het ontwerp van de IVM-regelaar zijn er veel opties voor de regelstrategie, -structuur, het regeldoel en de integratie met vertrektijdadvies. Voor de specifieke toepassing van IVM bij grootschalige evenementen zijn afwegingen nodig omtrent complexiteit (rekentijd), nauwkeurigheid en data benodigdheden om een keuze te maken voor bepaalde ontwerpelementen.
- Om IVM bij grootschalige evenementen toe te passen teneinde de verkeerssituatie daar te verbeteren, is een gecentraliseerde *one-shot* voorspellende regelaar nodig (een voorspelling per regelinterval). Deze regelaar bereikt een systeem optimum met randvoorwaarden op het wegennet door on-route routeadvies en pre-trip vertrektijdadvies voor individuele evenementenbezoekers te optimaliseren.
- Simulatie van de ontworpen regelaar toont aan dat IVM bij evenementen potentie heeft om verkeersproblemen aldaar (zoals terugslag) op te lossen. In complexe netwerken heeft het individueel routeadvies het meeste effect op de verkeerssituatie, terwijl in simpelere netwerken (slechts enkele aanvoerroutes naar het evenement) ook het vertrektijdadvies effectief kan zijn.
- Een gevoeligheidsanalyse van de performance van de IVM-regelaar toont aan dat de effectiviteit met name afhangt van externe invloeden als het verkeersaanbod, de effectieve penetratiegraad en de structuur van het netwerk. Daarom is bedachtzaamheid geboden bij het toepassen van de regelaar in de praktijk.

- Voor de toepassing van de ontworpen IVM-regelaar in de huidige praktijk, zijn er in dit onderzoek voorstellen gedaan voor de ontwikkeling van een offline simulatie (software) tool, evenals een tool voor het online gebruik van de IVM-regelaar.

Aanbevelingen

Ten eerste wordt het aangeraden om enkele kleine verbeteringen in het ontwerp van de IVM-regelaar te implementeren, om zo de nauwkeurigheid en toepasbaarheid te vergroten. Voorbeelden van verbeteringen zijn: het gebruiken van een uitgebreidere versie van het LTM voor een nauwkeurigere weergave van verkeersstromen op *nodes* en het toevoegen van dynamische aannames in de vertrektijdoptimalisatie. Dat laatste vereist enige interactie tussen de optimalisatie van routeadvies en van vertrektijdadvies in de regelaar.

Deze regelaar kan dan zowel offline als online toegepast worden: naar verwachting zal dit voordelen opleveren voor de verkeerssituatie bij evenementen (of vergelijkbare niet-terugkerende situaties). Voor zowel de offline en online toepassing van de regelaar wordt het aanbevolen om een applicatie te ontwikkelen, die de berekeningen van de IVM-regelaar kan uitvoeren met input die is ingevoerd in een *user interface*. Dit vereenvoudigt het gebruik van de regelaar en geeft inzicht in de in- en outputs van de berekeningen van de regelaar. De tool kan stapsgewijs ontwikkeld worden, om de verschillende componenten van de ontworpen regelaar afzonderlijk in de praktijk te evalueren (bijv. eerst individueel routeadvies, daarna vertrektijdadvies). Nadat IVM in real-time is toegepast bij een evenement, is het aan te raden om een data-analyse uit te voeren: hiermee kan de toepassing geëvalueerd worden en komen meer verbeteringen aan het licht.

Daarnaast zou toekomstig onderzoek zich moeten richten op het verbreden van de toepassing van de regelaar (bijv. keuze voor modaliteit, parkeerlocatie) en het gebruik van de ontworpen optimalisaties in een systeem van gedeelde autonome voertuigen. Verder zijn andere invullingen voor het berekenen van het route- en vertrektijdadvies ook mogelijk. De componenten van de ontworpen regelaar zijn relatief flexibel. Zo kan bijvoorbeeld voor de optimalisaties van het route- en vertrektijdadvies ook een andere aanpak gebruikt worden (eenvoudige regels die een optimale verkeersafwikkeling in een netwerk benaderen), om zo hoge rekentijden van de regelaar in complexe netwerken te voorkomen.

1 Introduction

In this chapter, the current developments in dynamic traffic management are described, as well as their (possible) application to large-scale events. The analysis of the traffic dynamics at a large-scale event leads to the problem definition, which will be used to define the research questions of this thesis.

1.1 Developments in dynamic traffic management

The route choice and departure time choice of travellers are important factors in the whole car traffic system. Wardrop (1952) described how road users will decide which route they take to their destination: instinctively, every traveller will choose his route in such a way, that he will minimise his travel time. Given that all road users will try to minimise their travel time, the traffic will distribute itself over the network in such a way that an equilibrium will arise between the travel times over the different route alternatives. Similarly, travellers decide on their departure time: they would like to maximise their benefit (or minimise their disbenefit) by choosing for a certain departure time. In a longer term, a traffic system can reach an equilibrium by the departure time choices of the individual travellers.

However, the assumption behind this concept is that travellers are fully informed about the traffic conditions on route and departure time alternatives and the traffic dynamics in the network. In reality, travellers will have a perception error regarding the travel times on the different routes over time. Providing travel time information to travellers might reduce this error and can enable travellers to make a route decision that is better for them and maybe also for the whole traffic system. Furthermore, the travel information could aid drivers to make a better choice regarding their departure time.

In modern practice, car traffic can receive travel information via several channels: road-side systems, in-vehicle navigation systems and pre-trip information providers. The route guidance providers base their advice on the actual and historical travel times on the road network. Variable message signs (VMS) exist since the 1980’s. A VMS is placed along the road to inform travellers about travel times on different routes to a downstream location in the network. A traveller might use this information to reconsider his route choice. The coverage of these information systems is of course very high, assuming that every traveller driving past these signs processes the information. The travel time information provided is however quite general: it informs about routes that some road users might not even take, or that are only a part of travellers’ routes.

Traffic information and route guidance aimed at individuals (in-car navigation, pre-trip route information) is more likely to achieve behavioural changes in route choice and departure time choice. Therefore, it has also more chance to benefit traffic performance in terms of travel time delay on individual or network level. In-car navigation systems also offer the possibility to change routes at any time, in contrary to fixed road-side information systems. The role of individual traffic management is growing: the evolution of automated driving will eventually enable full control of vehicle and traveller routings. The current possibilities of evolving individual traffic management are however limited to information provision for individuals using various sorts of channels like (navigation) apps and social media.

Guiding travellers in their route and departure time choice by informing them about traffic conditions is a dynamic traffic management (DTM) measure to improve the traffic performance in a road network. DTM aims to improve the traffic performance using four solution directions, which Hoogendoorn et al. (2012) identified:

1. *“Increase throughput*
2. *Effectively distribute traffic across the network*
3. *Regulate the inflow of traffic*
4. *Prevent spillbacks”*

Route guidance or departure time advice (for individuals) can be used to achieve a better distribution of traffic over the network and over time. It might also lead to the decision of travellers to enter or exit the network earlier or later. As any other traffic controller, a route guidance (and departure time advice) system bases its advice on the current state of the traffic system that is measured using sensors (e.g. loop detectors, floating car data). The controller computes an appropriate advice, which is fed back to the travellers using actuators (e.g. VMS, smartphone apps). The travellers might adapt their routes and departure times based on the information, changing the traffic states in the road network. This well-known control procedure is depicted in Figure 1.1.

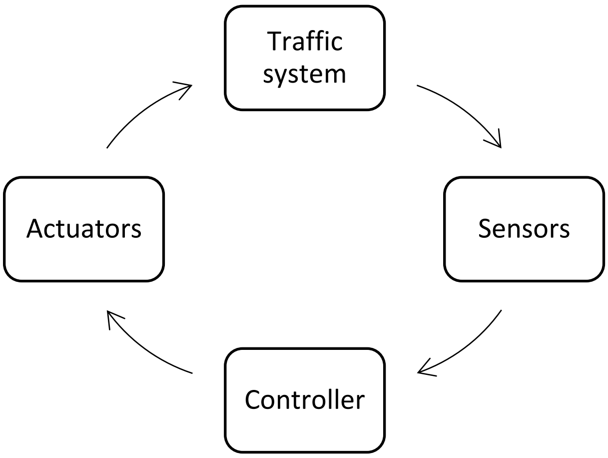


Figure 1.1: Working of a (route guidance) controller interacting with the traffic system

Next to route guidance and departure time advice, the travellers can also be guided regarding their mode choice, parking lot choice, and maybe even the choice to make a trip or not (demand management). Such methodologies of steering traffic have been tested and evaluated in the *Praktijkproef Amsterdam* (PPA). This research focuses however on individual route guidance and departure time advice (in this research described by the term *individual traffic management*) for car-traffic. Individual traffic management (ITM) – route guidance, possibly combined with departure time advice – has the potential to aid road authorities and operators to reduce congestion in different situations. The influence of the traffic management controller on the traffic system depends on its design and its properties. For each application of ITM, the properties of the controller can be different, in order to act on the specific characteristics of the problem that the ITM controller is encountering.

The focus of this Master thesis research is the application of ITM to large-scale events.

1.2 Large-scale events

Large-scale events like festivals, concerts and football matches often attract many visitors (10,000 – 250,000 per day), leading to a large amount of traffic in the surroundings of the event location. This large flow of visitors towards an event can cause quite some congestion, increasing travel time delays in the network significantly (Kwon et al. 2006). Obviously, event organisers would like to minimise the hindrance that their visitors encounter during their travel to the event. It is also in the interest of the (road) authorities to keep the accessibility of the surrounding area at a high level during an event. This way, both road users travelling to the event and travellers with other destinations can travel without encountering (too much) congestion. To achieve a better accessibility during an event, often a traffic management plan is developed: such a plan includes the design of so-called *scenarios*, which make the traffic management policies concrete using the available control systems. The downside of the current practice of traffic control scenarios is that the designed control mechanisms often have limited capability to react dynamically to the unique situation on the road and the individual behaviour of travellers.

The traffic attracted by large-scale events has different characteristics than common commuter traffic during peak hours, as identified by Muizelaar (2011). The congestion caused by an event is *non-recurrent*, while the congestion during peak hours is *recurrent*. This means that the event visitors encounter relatively rare traffic conditions. Moreover, they are relatively unfamiliar with the network as well (as compared to regular peak traffic). Therefore, managing the traffic towards the event requires a different control approach than commuting traffic.

Individual route guidance (IRG) can be used to dynamically inform and guide the event visitors, in order to distribute traffic in an effective way over the network. The effects of such information systems are expected to be the highest when travellers encounter unusual traffic situations, being unfamiliar with the layout of the road network (Ben-Elia et al. 2008; Muizelaar, 2011). This means that for large-scale events, the effects of IRG should be visible: without information provision, visitors are less known with the network structure - and therefore the routing possibilities - and the traffic situation on the network, leading to suboptimal usage of the road network. Moreover, the fact that travellers are less familiar with the network can lead to a higher compliance rate to the route guidance (Lappin & Bottom, 2001).

To some extent, large-scale events can be compared with evacuations: the massiveness, the sharp peak of departing or arriving travellers and few destinations are characteristics that evacuations and large-scale events have in common. Modelling evacuations has been identified to be significantly different than average traffic situations. Therefore, large-scale events should be treated differently by traffic management as well. Comparable to large-scale events, the effect of route guidance on route choice during evacuations has been evaluated in literature. Different approaches to individual traffic management have been simulated in studies regarding route choice behaviour during evacuations by Lämmel & Flötteröd (2009), Landman et al. (2012) and Huibregtse (2013). However, the quantitative effects of the dynamic IRG at evacuations in reality still remain unknown, as a real-life test of an emergency evacuation is impossible.

Until now, the focus of scientific contributions regarding large-scale events has mainly been on the analysis of pedestrian movements (e.g. Duives, 2016). For car traffic movements to large-scale events, IRG has been applied in the trial setting of PPA. The trials were described to be successful: however, the indicators that were used for the effects of the IRG were the coverage of the information and the satisfaction level of the informed travellers. These indicators do not necessarily give information about the effects in terms of traffic performance. This means that the quantitative effects of individual route information on the traffic performance in the network are not fully known yet. Furthermore, improvements can be made on the control aspect of the ITM.

1.3 Problem definition

Events may attract a large number of visitors. The road network should be able to process the event visitors by car, on top of the regular traffic in the road network in the surroundings of the event location. Often, there are bottlenecks at the event location (e.g. parking lots or intersections), but in the upstream road network there might be bottlenecks as well. These bottlenecks cause congestion as a consequence of the too high inflow of event-bound traffic. The traffic around large-scale events can be characterised as follows:

- Event visitors are unfamiliar with the road network and might not have knowledge of the available route alternatives from their origin to the event location.
- Both visitors of the event and through traffic (i.e. travellers not having the event as destination but driving in the surrounding network) encounter non-recurrent traffic conditions: there is congestion at a location and time where this doesn't occur very often.
- Lastly, a large portion of the traffic is directed to the large-scale event, which means that the event location dominates the origin-destination demand matrix (OD-matrix).

The bottlenecks close to the event (e.g. parking lots, traffic lights, off-ramps) cause queues, which might spill back onto the main road network. This spillback has consequences for the traffic that doesn't have a relation with the event (see Figure 1.2). These travellers will experience a significant travel time delay, because they were caught in the congestion caused by the event. This delay is undesired and unnecessary. Once the queue from the bottleneck has spilled back to the motorway, it is very difficult to resolve: the congested state has reached the motorway and affects all travellers over there. Depending on the amount of through traffic, the queue on the motorway might grow as well, maintaining the issues for the through traffic. This might continue, even when the demand for the event reduces over time. Moreover, once a congested state is present on the motorway, there might be a capacity drop that reduces the outflow and the throughput of this road (Cassidy & Bertini, 1999). This has significant disadvantages for travel time delays as well. For these reasons, the spillback from the bottlenecks onto the major roads must be prevented as much as possible, as this can cause heavy congestion, possibly heavier than rush hour congestion.

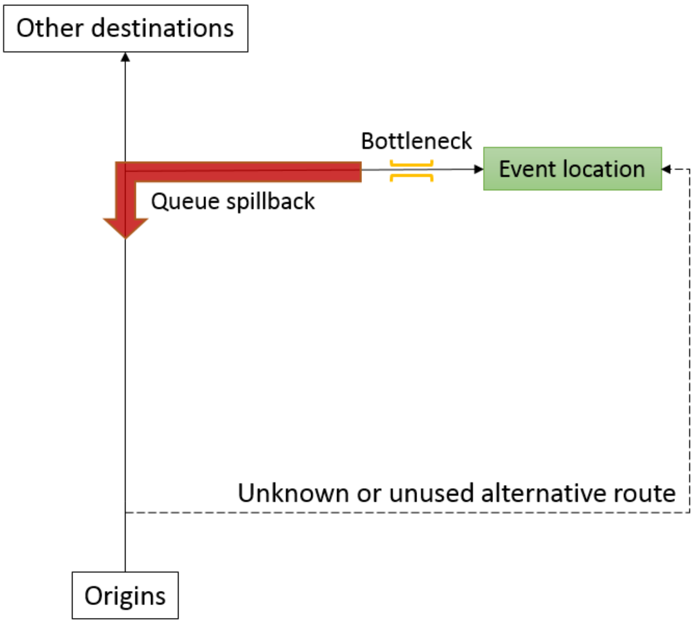


Figure 1.2: Spillback from bottleneck at the event location, causing undesired congestion for through traffic on the main roads

1.4 Potential of individual traffic management to reduce spillback at events

To prevent spillback, the inflow into the queue should be reduced. A method to do this, is to distribute the traffic over the network. The fact that event visitors are generally unaware of the detour alternatives and the traffic conditions downstream implies that the network capacity is not used to its full potential. A better distribution of traffic over the network can then be achieved with route guidance: the route guidance system will advise event visitors about alternative routes that they can take to the event location. By doing this, the event visitors will make less use of the already congested entry road of the event and the spillback might be reduced or even prevented. Of course, the alternative routes might also contain bottlenecks. This means that the route guidance system must consider multiple possibilities for spillback to the main road network and react accordingly. If the network is very highly congested, the route guidance will have less effect, since also the alternative routes are full. So the route guidance has the most influence when there is moderate congestion from the bottleneck at the event, causing spillback.

The current practice in traffic management at events is that road-side VMS are used to provide either descriptive or prescriptive information to the travellers. This information can be used by event visitors to deviate from their originally intended route. Guiding travellers *individually* gives the opportunity to give more fit-for-purpose advice to them. Individual route guidance is offered via in-car systems like mobile phones. This means that the route guidance can be requested and provided at any point in space, while VMS are fixed to a few locations in the road network. Another downside of VMS is that these can overreact if they have to give prescriptive route advice. They will deviate all event-bound traffic to the detour route, possibly causing congestion on the detour route. Individual route guidance is able to steer the traffic streams more subtly, by giving individuals from the same origin at the same time different route advices. A dense network with more route decision points also favours the use of IRG: VMS cannot be placed at all decision points in the network, while IRG can give guidance at any point in space. The chance of achieving an approximation of an optimal situation is therefore higher when IRG is used. Another advantage of individual route guidance is that the target group of the route advice (the event visitors) can be easily reached via all sorts of channels, like the event organisation and social media.

Although there are numerous providers of route information to individuals via in-vehicle navigation systems or applications (e.g. *TomTom*, *Waze*, *Flitsmeister*), the advice that these providers give is uniform along the population that they advise. The purpose of IRG is to give each individual that enters the network at the same time and location advice that might be unique, in order to distribute the traffic over the alternative routes in such a way that spillback and unnecessary delay can be reduced or even prevented. Therefore, a new method for controlling the traffic is needed.

Another method to reduce the inflow into the bottleneck (queue) is to spread the traffic demand of the event visitors over time. With individual departure time advice, flows on the network can be influenced, and the spillback might be prevented by a smart distribution of the traffic over various arrival times at the event. This can be integrated with the distribution of traffic over space with IRG.

In this Master thesis research, the potential to reduce the chance of spillback at large-scale events by providing departure time advice and route guidance to individual event visitors is studied in more detail.

1.5 Contributions of this Master thesis research

This research contributes from both a scientific and a practical perspective. From a scientific point of view, the design and evaluation of a controller for individual traffic management contain the main contributions of this research:

- A controller for ITM is designed, explicitly for the application at large-scale events. Events have specific traffic characteristics: this research identifies these characteristics and incorporates them in a conceptual design of an ITM controller and the mathematical definition of the controller's components, making trade-offs between different design options;
- The individual route and departure time advice is computed real-time in separate mathematical optimisations. The mathematical formulation of these optimisations is unique, as it is specifically designed for achieving a *constrained* system optimum at large-scale events. This way, the controller aims to improve the overall traffic conditions at an event;
- The optimisations take a prediction of the traffic conditions in the network into account. This prediction is performed by the Link Transmission Model (Yperman, 2007). In this research, the use of this specific prediction model is combined with the real-time optimisation of route and departure time advice;
- In this thesis, the design of the ITM controller is simulated for fictive networks and a network that represents the situation around a real event venue. The results of these simulations give insight into the (potential) effects of ITM at large-scale events.

The contributions of this Master thesis to practice, since the design and evaluation of the ITM controller also have implications for the practical application of ITM:

- The simulations, as executed in this study, indicate the possible use of the proposed ITM controller at an event in reality, as well as the limitations that must be solved if the controller is applied in practice;
- In this research, frameworks for the application of the controller design are proposed: for both an offline (simulation) application of the controller as well as the implementation of the controller's computations in real-time;
- Approaches for improving and extending the ITM controller design are proposed, to increase the potential benefits of ITM events.

2 Research setup

In this chapter, the research setup is explained. Firstly, the research questions are presented. Secondly, the objectives and scope of this thesis are defined. Furthermore, some important definitions of this research are described. Finally, the used research methodology of this thesis is shown.

2.1 Research questions

The problem description and the different aspects of individual traffic management are incorporated in the research questions for this Master thesis work.

1. *What theoretical control concepts can be used to improve the current methods of individual route guidance?*
    1.1. *What are the possible control strategies for individual route guidance and their corresponding advantages and disadvantages?*
    1.2. *What are the possible control objectives for individual route guidance and their corresponding advantages and disadvantages?*
    1.3. *What methods can be used to integrate departure time advice with route advice for individuals and what benefits do they have for car traffic in non-recurrent congestion?*
2. *How can the theoretical concepts of individual traffic management be used in a controller design specifically aimed at car traffic at large-scale events?*
    2.1. *What requirements does an individual traffic management controller for large-scale events have?*
    2.2. *What theoretical concepts and methodologies are the most suitable for an individual traffic management controller for large-scale events and how must these be implemented mathematically in the controller design?*
3. *What are the quantitative effects on traffic performance of individual traffic management at large-scale events?*
    3.1. *What is the performance of the theoretical design of the ITM controller in a simulation environment?*
    3.2. *How do the different components of the controller design affect the simulated traffic performance?*
    3.3. *What is the influence of the input variables on the performance of the designed controller in the simulations?*

2.2 Research objectives

The objectives of this Master thesis research follow from the formulated research questions. The main objective of the research is to *design and evaluate an individual traffic management controller that is able to improve the traffic conditions at large-scale events,*

Firstly, the research is aiming to give an overview of the different building blocks of individual route guidance controllers. The possible methodologies are identified for each of these building blocks and their advantages and disadvantages are studied. This study can be used to define control possibilities for IRG or ITM at events. The overview of the existing concepts from literature will lead to the answer of the first research question. This means that the answers are not necessarily new: the answers follow from literature and are needed for the next research steps.

Based on the overview from the literature study, a theoretical conceptual framework needs to be defined for a controller providing route guidance (and possibly departure time advice) for individuals travelling to a large-scale event. This conceptual framework must include all aspects of ITM, as defined in the theoretical study. Together with the problem definition, the framework can be used for a programme of requirements for ITM applied at large-scale events. Then, a design of the appropriate ITM controller can be made with the mathematical formulation of objectives, algorithms and constraints. The mathematical formulation of an ITM controller suitable for large-scale events is important for this research as an end product. The synthesis of the controller design will lead to the answer to the second research question.

In this research, another objective is to evaluate the theoretical design of an ITM controller using simulation. The simulations can be used to refine the theoretical and mathematical definition and to give insight into the expected practical effects of the designed controller. An aim of this research is also to investigate how the controller design reacts to any change in the input variables. This sensitivity should be evaluated in the simulations as well. The simulations will give indications about the use of the designed controller in practice. This thesis will also investigate the possibilities of this practical application of ITM.

2.3 Scope

The thesis research will focus on individual route guidance and departure time advice for *car traffic*. Including other modalities in the scope of the research will make the controller design too complex (at least for the time available). Individual traffic information at events is also applicable to public transport (PT). Shifting individuals over modes, routes and departure time might also reduce congestion and spillback issues on both the road and on PT lines. However, the definition of the PT network, access and egress combinations and loading mechanisms make the inclusion of other modes in the controller a too complex and extensive task for this thesis work.

Furthermore, the design of the ITM controller will only be applicable for visitors travelling *towards* an event: the spillback problem only occurs at the inflow of a large-scale event. Trips executed by the visitors from the event area back home will not be controlled, as these trips cause less or even no spillback on the major roads in the network. The controller influences the choices of individuals requesting route guidance and departure time advice and therefore, also the traffic performance in the whole network around the large-scale event. This is taken into account in the design of the ITM controller. The ITM is offered to the visitors using pre-trip or in-car systems. The reason for this is that road-side systems are simply not equipped to provide individual (or more individualised) route information, as was discussed in the problem statement. Non-visitors of the event (background traffic) are not informed by the ITM controller: it is assumed that they receive guidance via road side systems or other in-car service providers. The reason for this is that in practice, these non-visitors will be much more difficult to approach than the event visitors: the latter can be approached using social media and via the event organisation.

The theoretical design of the route guidance controller will not be implemented for practical analysis in this research, since it is a too extensive task: it would require the building of an application that would be used by visitors of a real event somewhere in the Netherlands. This is simply too much work for the scope of a Master thesis work and is left for future studies.

The analyses of this research will not focus on integrating of individual route information with other road-side DTM systems. Although integrating DTM measures is expected to be more effective than operating the controllers separately, integration requires quite some coordination between (commercial) individual route information providers and the road authorities or operators (Rijkswaterstaat, province, municipalities). Integration of DTM measures would also mean that it is more difficult to attribute the (possible) effects to the ITM. Lastly, the integration of road-side controllers with ITM would make the research very complex and extensive (regarding the time available).

2.4 Definitions

Traffic information is used by road authorities to help travellers with their route choice, simultaneously attempting to improve the traffic performance in the road network. Various types and delivery methods for travel information are possible, which will be defined in this paragraph.

- Descriptive versus prescriptive travel information
    - *Descriptive* travel information gives the travellers the travel times on different routes (or route sections), which can be used by the drivers to make a better route decision.
    - *Prescriptive* travel information is a more persuasive traffic management method, which is used to guide travellers in an optimal way over the road network to their destination.
- Pre-trip and on-route travel information
    - *Pre-trip* travel information offers information about more alternatives to travellers, but intrinsically has more difficulty in predicting the future traffic conditions for choice alternatives.
    - *On-route* information is more accurate, but there may be less alternatives available for travellers if they already have executed a part of their trip.
- In-car and road-side information systems
    - Route guidance with *in-car* navigation or information systems is more aimed at the individual, with many possible access points to the information.
    - *Road-side* traffic information (with VMS) is used for a more general steering of the traffic, at less information points.
- Individual versus personal traffic management
    - *Individual* traffic management means that advice is offered to individual travellers, possibly being different for individuals departing at the same time and location.
    - *Personal* traffic management is individual traffic management, but then the advice is fit to the personal preferences and properties of the individual traveller, so that the advice is given to the traveller that suits that advice the most.

Influencing the departure times of event visitors is also a subject of research in this study. Similar to route information, users can be informed about in a descriptive and prescriptive way to help them in their departure time choice behaviour. The individual aspect applies to departure time advice as well: drivers from the same origin requesting advice at the same time might get different advice to optimise the distribution of flows over time.

This Master thesis research will focus on the prescriptive individual in-car route guidance and pre-trip departure time advice.

2.5 Methodology

In this section, the research method is explained, which is used to achieve the research objectives that were formulated in section 2.2. This graduation work will follow the commonly used design steps of orientation, analysis, synthesis, simulation and evaluation to achieve the research goals and to answer the research questions. These research steps lead to conclusions and recommendations regarding the application and effects of individual route guidance and departure time advice at events, and how to fit these into a controller. An overview of the research steps can be seen in Figure 2.1.

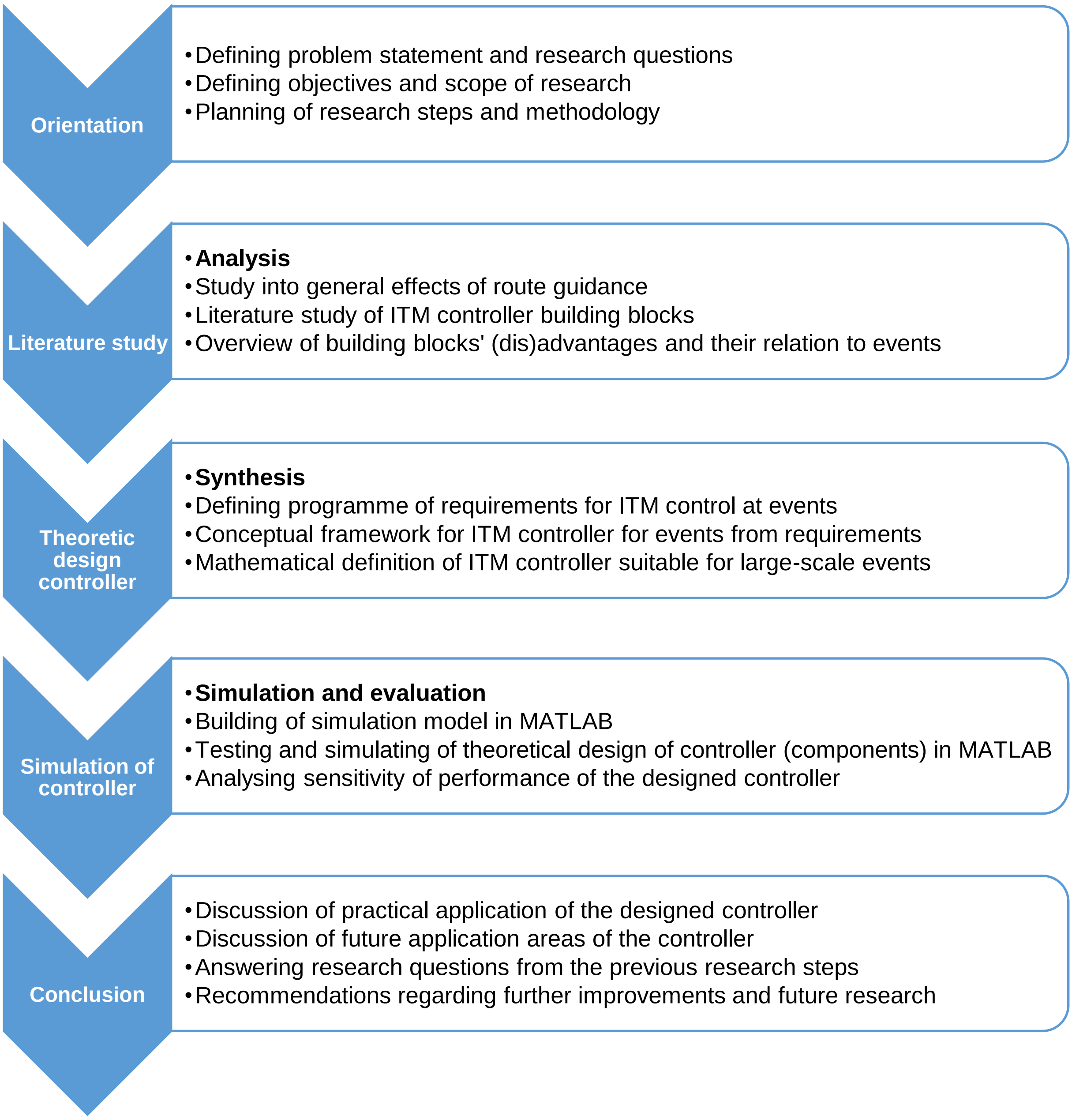


Figure 2.1: Overview of the Master thesis research steps

3 Analysis of scientific literature

In this chapter, different elements of ITM are researched using scientific literature. Firstly, an overview is given of route guidance in general and its (expected) effects on traveller behaviour and traffic performance. Afterwards, some building blocks of an ITM controller are discussed: the different options within these building blocks and how these relate to the application of an ITM controller to large-scale events. This leads to a conceptual framework of an ITM controller and the possible methodologies that can be used in the design of a controller for large-scale events.

3.1 Introduction

The focus of this literature study is mainly on the in-car (individual) prescriptive route guidance. The possible application area and traffic performance effects of an IRG controller depend on its specifications. Zuurbier (2010) identified that there are many different elements of route guidance and that the combinations of these elements (e.g. strategy or objective) vary among scientific contributions. In order to design a controller for ITM at large-scale events, the different design aspects must be researched, as well as their applicability to specific situations (such as large-scale events). The following building blocks of ITM will be researched in the literature study.

- Control strategy and structure
- Control objective
- Integration of individual route advice with departure time advice: evolution from IRG to ITM

There are more elements of route guidance that influence the working and effects of an ITM controller, but it is assumed that these three building blocks have the most potential to solve the problem of unnecessary delay at large-scale events, caused by spillback from bottlenecks. The different methodologies behind these building blocks will be investigated and discussed. The characteristics of these methods and their according advantages and disadvantages are identified as well.

Although the identified building blocks also might affect the compliance of travellers, the detailed modelling of user compliance and its effects will not be discussed elaborately in this literature study. Some general effects of (individual) route guidance are discussed in the next paragraph.

Next to the use of this literature study for the design of the ITM controller, the results of the literature study can also be used in the setup of the simulation of the controller design. The findings are useful to make scenarios for the simulations of the ITM controller, as well as the inputs that are needed for the simulations.

3.2 Potential effects of route guidance

The potential effects of (individual) route guidance have been evaluated frequently in literature. Field tests of different types of route guidance confirm that there are benefits for the traffic performance on individual and network level. Tsuji et al. (1985) used experimental data from in-vehicle route guidance in Tokyo to assess the benefits of this type of route guidance. They concluded that there is a significant reduction of travel time for individuals if the route guidance was used. Particularly for unexpected congestion – caused by for instance incidents or events – the performance gain due to the route guidance can be observed clearly. Mammar et al.

(1996) investigated the responses to and effects of route guidance with VMS in Aalborg, Denmark. The preliminary results of the field tests were positive, as the provision of information about incidents lead to more route diversion behaviour of drivers. Chatterjee & McDonald (2004) give an overview of several operational tests of VMS in Europe and the influence of these systems on traveller satisfaction, driver route choice and traffic performance. Again, an increase in the number of route diversions was found as a result of the VMS route guidance. Moreover, total travel times on congested routes and on a network scale were reduced.

Levinson (2003) simulated the influence of in-vehicle route guidance for different congestion levels and different penetration rates of the route guidance systems. The simulation results showed that both informed and uninformed road users can benefit from route advice provided to individuals. The benefits were most evident at a flow rate just below the capacity. The penetration rate is an important factor in the success of IRG. Informing relatively too many travellers can lead to degradation of the traffic conditions on alternative routes, leading to less benefits.

The effects of route guidance depend strongly on the number of informed drivers and their compliance to the individual route advice. The compliance behaviour of travellers is influenced by several factors such as: guidance information quality, information message type, driver familiarity with the network and travellers' previous experiences with (individual) route guidance. For non-recurrent congestion conditions - caused by for instance large-scale events - the familiarity of drivers with the road network and the usual traffic dynamics in the network is low. Several studies (Adler & McNally, 1994; Lappin & Bottom, 2001; Chorus et al. 2006; Ben-Elia et al. 2008) have identified that in these cases, the compliance of travellers will be higher than in common peak hour traffic. On the other hand, drivers tend to stick to their original route choice: despite the fact that some route alternatives might have a lower travel time, road users have some inertia towards their primary route. This means that some threshold value for travel time difference needs to be exceeded for travellers to deviate from their route. For evacuations, the influence of compliance on the effects of guidance was assessed by Huibregtse et al. (2009). The performance of the guidance reduced significantly when less people followed the optimised evacuation instructions.

It can be concluded from literature that route guidance is able to improve the traffic performance on an individual scale and on the network level. These effects are even enhanced when route guidance is applied at non-recurrent congestion situations, caused by incidents or events. The general quantitative effects of IRG on the performance is influenced by the following factors:

- Current traffic conditions;
- Traffic situation that the IRG is applied to: events, road works, incidents, rush hours;
- Compliance of users to the advice;
- Penetration rate of the route guidance in the traffic system.

3.3 Control strategy and structure

The structure and strategy of a route guidance controller determines how the controller processes the information that it receives from the sensors on the road and how the individual route and departure time advice is calculated. Therefore, the control strategy and structure are important components of the controller, since they determine the effects of the controller on an individual and network level. In this paragraph, an overview is given of some possibilities for

ITM controller strategy and structure. The properties of these elements and their (dis)advantages can be used in formulating the design of ITM control for large-scale events.

3.3.1 Non-predictive control

In many traffic management applications, a non-predictive control strategy is applied. In such a controller, the *current* traffic states are used to compute the control signal. The control signal is then a function of the current traffic state(s) in the network. This control signal is used to influence the behaviour of road users with the available actuators. The behavioural change of travellers – for route guidance this is route choice behaviour – and disturbances in the traffic process will lead to new traffic states (due to the traffic process), which can be fed back to the controller to update the control signal again. A schematic representation of this working of a reactive controller for IRG is shown in Figure 3.1.

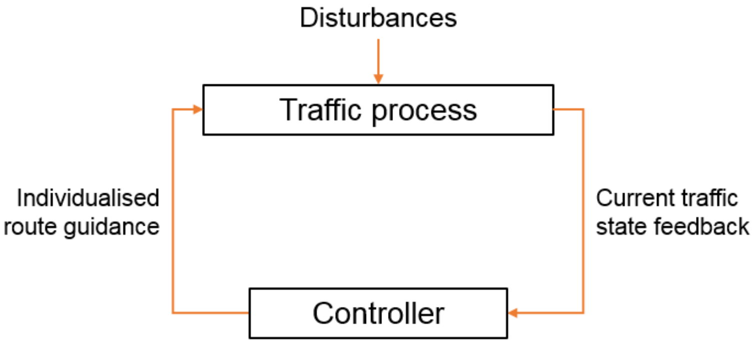


Figure 3.1: Non-predictive control strategy for IRG

Non-predictive (or reactive) feedback control for route guidance and dynamic traffic assignment has been researched by Papageorgiou & Messmer (1991). They concluded that a simple feedback structure that aims at the minimisation of travel time difference on alternative routes can lead to a stable traffic situation and is able to approach a user equilibrium assignment, but only under certain circumstances. They reported the following advantages of such a non-predictive control strategy: low computational effort of the control signal and low sensitivity to disturbances in the traffic system. Bottom (2000) identified opportunities for reactive route guidance control for trips with many alternative routes and many information provision moments. Because of the low computation time of the non-predictive controller, a large number of control signals can be evaluated without too much effort. Furthermore, a low amount of disturbances during the trip time can lead to effective control.

The disadvantage of reactive control is that for strong disturbances in compliance or demand, the convergence towards an equilibrium in the traffic conditions can take quite some time or will not even be reached (Papageorgiou & Messmer, 1991). The non-predictive nature of a controller also can lead to myopic provision of advice, since the controller is not able to foresee upcoming congestion in the network. This leads to oscillations in the control signal and the traffic states: the controller will overreact to the current traffic state and will try to correct this in the next control interval. If this correction is executed to strongly, the controller might overreact again. These (dis)advantages of reactive feedback control are also confirmed by Zuurbier (2010) in his literature study. Theoretically, non-predictive control is not that suitable to battle spillback of congestion onto other parts of the road network, since a reaction of the controller to imminent spillback would be too late. Due to the shockwave speed, the spillback might still reach the upstream links. This is a disadvantage for the application of reactive route guidance at events, as the route guidance should be able to prevent spillback as much as possible.

3.3.2 Predictive control

The problem of myopic steering by reactive controllers can be solved (to some extent) by making a prediction of the traffic states in the (near) future. Predictive controllers use a model to predict the traffic states: then, they determine the control signal based on these future traffic states. This control signal then influences the current traffic states. This control cycle for predictive feedback control is depicted in Figure 3.2.

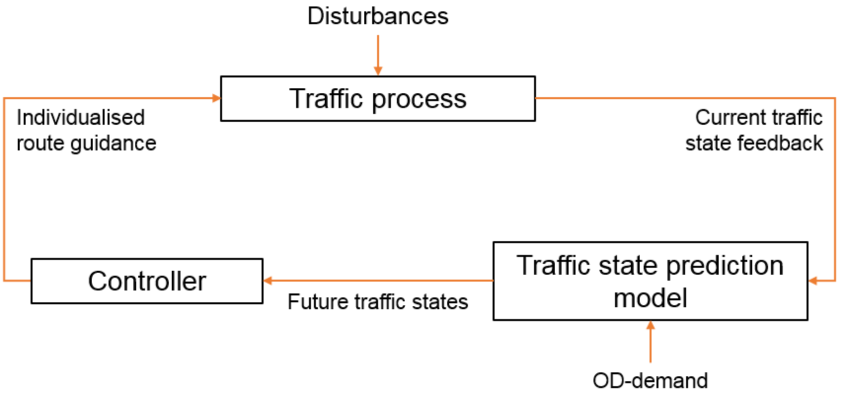


Figure 3.2: Predictive control strategy for IRG

Crucial for the working of predictive controllers is the traffic flow model: this model predicts the future traffic states and, if necessary, also the reaction of the road user to the route guidance. The type of model used in the controller depends on its purpose and application area. For (individual) route guidance, macro- or mesoscopic models seem to be the most logical choice. These models will have a lower computation time than microscopic models and will describe the routing dynamics in a better way. An overview and evaluation of traffic flow models – also for route guidance control purposes – can be found in the contribution of Boxill & Yu (2000). Choosing a traffic prediction model requires a trade-off between model complexity and computation time. Often, a traffic prediction model also uses historical data to enhance its predictive power with statistical analyses of traffic dynamics and traveller behaviour. However, for large-scale events the amount of suitable historical data will be scarce.

Messmer et al. (1998) evaluated the performance of an automatic (predictive) route guidance controller for VMS in Scotland. The traffic state predictions of this controller were directly used to determine the control signal. A similar predictive feedback strategy was proposed by Wang et al. (2003): the proposed controller executed prediction and control signal calculation – with a basic control rule to adapt the split fractions – in one shot. This means that computation time remains relatively low (no iterations are needed), but the performance of the controller is better than the performance of reactive route guidance.

Yang et al. (2000) used simulations to compare a non-predictive and predictive IRG control approach during recurrent congestion. For both control strategies, they report benefits for both informed and uninformed drivers. The advantage of the predictive control strategy is that there is less overreaction of the controller, since the signal is also based on future traffic states.

The disadvantage of predictive controllers is the accuracy of the prediction model, as identified by Hoogendoorn et al. (2012). They state that especially considering traffic management during non-recurrent traffic situations, the accuracy of prediction models is not very high. Having inaccurate predictions reduces the performance of the predictive controller. The accuracy of the prediction also depends on the prediction horizon. Looking too far ahead (accurately) is very difficult. Therefore, the prediction horizon should be chosen in such a way that it is not too long, but still can model the most important traffic dynamics, as for instance spillback.

3.3.3 Iterative route guidance control

Predictive controllers are already able to determine their control signal based on the predicted traffic states. However, the calculated control signal influences the future states as well. Bottom (2000) proposed anticipatory route guidance, which takes the effect of the computed control signal on the traffic forecast into account as well. This means that an iterative procedure is needed, where the control signal is used as input in the traffic state forecast and vice versa, until convergence is reached. This is a more extensive approach, which describes the interaction between the control signal, the traveller behaviour, and the future traffic states. In Model Predictive Control (MPC), this anticipation of the interaction between the control signal and the future traffic states is covered. Moreover, the *future* control signals can be optimised with such a method.

The optimization of the candidate control signal can be done for a certain objective function (e.g. minimizing total travel time). The influence of these controller objectives is discussed in paragraph 3.4. In short, MPC follows the process below (Rawlings, 2000; Hegyi, 2004).

1. Prediction
2. Performance evaluation
3. Optimisation
4. Control action

A representation of this process is depicted in Figure 3.3. Note that the candidate control signal is fed back to the traffic state prediction model until convergence is reached. Then, the optimal (future) control signal is used to determine the route advice for the individuals.

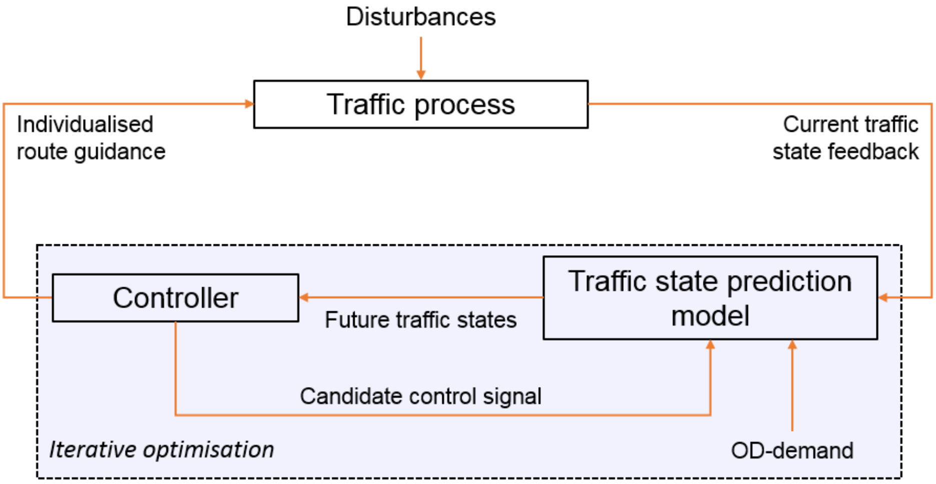


Figure 3.3: Iterative optimisation in an IRG controller

Le et al. (2013) describe the integration of optimising traffic lights and route guidance in urban networks using an MPC structure: the fact that the MPC structure takes its own effects into account in the optimisation improves the network performance significantly.

Next to the predictive power of MPC controllers and the resulting benefits on the control signal quality, Hegyi (2004) and Karimi et al. (2004) identify the advantage of the optimisation model used in MPC controllers: this optimization model offers great flexibility, as well as the possibility to add constraints and multivariable objectives easily. This results in a more sophisticated controller, which has more chance of achieving user equilibrium conditions on the road network than non-iterative control strategies (Papageorgiou et al. 2003). The downside of the iterations between prediction models and the control signal optimisation is mainly the computation time (Farver, 2005). It might be difficult to reach convergence to an optimal control signal. Especially for larger networks and more control signals to evaluate, the computation time becomes so large that it cannot keep up with the changing traffic states in reality.

3.3.4 Fuzzy logic control

Since prediction models might be inaccurate, it is interesting to study how the traveller behaviour and traffic dynamics can be modelled accurately by an ITM controller. One of the approaches that can be used for this is fuzzy logic.

Fuzzy logic is a method that can be used to describe characteristics of objects, phenomena, etc.: the characteristics or attributes can be true (1) or false (0), but by fuzzy reasoning also partially true (between 0 and 1). The reason why fuzzy logic is used in a traffic management context, is that it approximates the way travellers think about the attributes of their trip. For instance, the congestion can be 'heavy', 'medium', 'mild', and something in between. Travellers do not necessarily realise exactly how much delay there is on a route or how they can classify a certain amount of delay (Teodorović et al. 1998). They are likely to base their route choice on more abstract definitions as stated above. Fuzzy controllers are designed to anticipate on this kind of choice behaviour of travellers. These controllers attach certain values of for instance travel time to the abstract characterisations of the traffic state. The controller then uses these values between 0 and 1 (see Figure 3.4 for an example) to define the control signal with if-then rules.

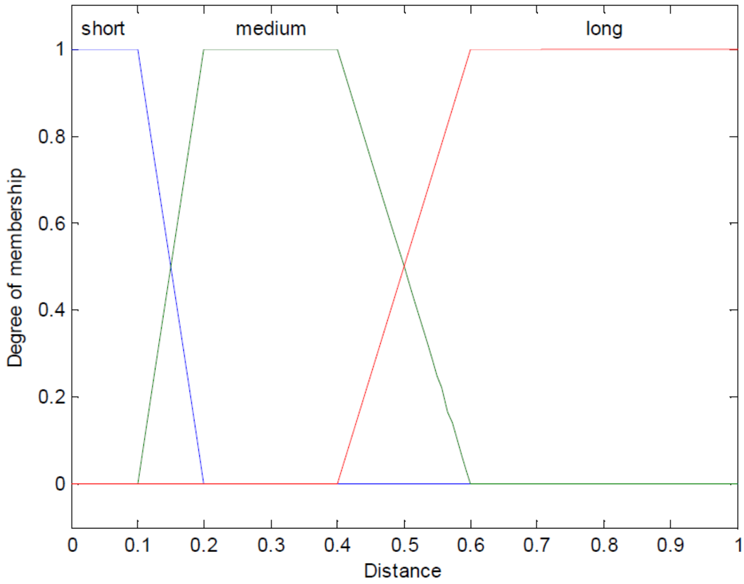


Figure 3.4: Example of a fuzzy definition of distance (Lin & Chou, 2008)

Modelling approaches to fuzzy route choice have been discussed by e.g. Teodorović et al. (1998), Henn (2000) and Pang et al. (1999). The latter use a hybrid approach of fuzzy logic and neural networks. These models can be used to predict the reactions of travellers to advanced traveller information systems. Possibly, these predictions can be used in an MPC strategy as well.

Fuzzy logic can therefore be applied in a prediction model, but it is also possible to formulate control rules for route guidance and departure time advice with fuzzy logic.

Kachroo & Özbay (1996) formulated a fuzzy logic controller that used a feedback structure to influence the split fractions on a simple network. Simulations indicated that inducing a dynamic user equilibrium is feasible with the implementation of such a controller. Lin & Chou (2008) also proposed a route guidance controller that takes these individual perceptions into account when defining the control signal. The benefit of such an approach is that the traveller behaviour is anticipated in an accurate way. Li et al. (2014) implemented a fuzzy approach in an IRG controller. Simulations showed that their design is very well capable of forecasting the traffic conditions on the road as a consequence of the dynamic route guidance. The disadvantage of fuzzy logic is that the fuzzy rules and the membership functions need to be calibrated, requiring quite some (historical) data about the route choice of travellers, which may be lacking in the case of large-scale events.

3.3.5 Neural networks

Another traffic control approach is using artificial neural networks to approximate road user behaviour. Neural networks learn from previous events on the road network and previous (route) decisions of travellers. After a while, these neural networks have very extensive statistical knowledge of the dynamics of the traffic system: the traffic dynamics are related in a statistical way to numerous parameters that can be evaluated. This knowledge is of interest for DTM control systems. For IRG (and ITM) as well, the application of neural networks is interesting. Specifically, the interaction between the control signal and the route choice of drivers can be analysed into detail. This means that the controller is able to predict the interaction between the control signal and the traveller behaviour more accurately, leading to a higher quality of the control signal (individual route guidance and maybe also departure time advice). Yang et al. (1993) proposed a methodology with neural networks to evaluate travellers' route choices while they are influenced by advanced traveller information systems. This method can be implemented in an ITM controller.

The downside of neural networks is that the reasoning behind the controller's actions is less transparent than for other control approaches (Baskar et al. 2011). There is a statistical relationship between the variables, not a relationship defined from a traffic engineering perspective. Additionally, neural networks might have difficulty controlling very rare or new traffic situations, as the controller did not learn how to act under such conditions: historical traffic data of these situations is not sufficiently available. This is also disadvantage for the application of neural networks for ITM at events, since events are relatively rare. Hence, it is questionable whether the neural networks controller would have access to enough historical data to control traffic optimally around large-scale events.

3.3.6 Multi-agent systems

A very distributed way of traffic management is self-organising traffic, or similarly: multi-agent systems or crowdsourcing. In these systems, every travelling vehicle or road user is considered as a separate agent, making its own decisions based on its own observations and those of other agents. These decisions and observations are communicated to other agents in the network, enabling them to update their own decisions again. No interference of a central entity such as a traffic control centre is needed for advising travellers about which route or departure time to take, as the travellers advise each other in some way. The fact that a multi-agent control strategy considers each traveller as an individual entity, means that it is a very interesting approach for ITM controllers.

The topic of multi-agent route guidance control systems has gained more and more interest in scientific literature, especially with the current developments in automated driving. Although inter-vehicular communication (IVC) is still not quite implemented in reality – due to communication limitations –, studies like Yang & Recker (2006) and Hawas et al. (2009) have investigated the potential benefits of such a system. Firstly, the computation time of such systems is relatively low, since the distributed controllers base their advice on local information. It was also concluded that IVC for routing of vehicles gives the opportunity to achieve better network performance. The quality of the advice that is communicated using the smart vehicles is high, and is used by the travellers to make better routing decisions.

In Weyns et al. (2007) and Claes et al. (2011), a delegate multi-agent system is proposed. This system is inspired by ants: when finding food, ants leave some pheromone trail behind, which can be smelled by other ants. This trail evaporates over time, so if the food supply has been exhausted, no ant will leave a trail behind and the smell will disappear. In the context of multi-agent route guidance, this method can be applied as well: delegate agents will communicate the traffic conditions (travel times, jams, incidents) on the road network to upstream travellers. Based on these bits of information, a traveller can make a route decision and will inform upstream drivers again about the situation on his chosen route. This process is shown in Figure 3.5.

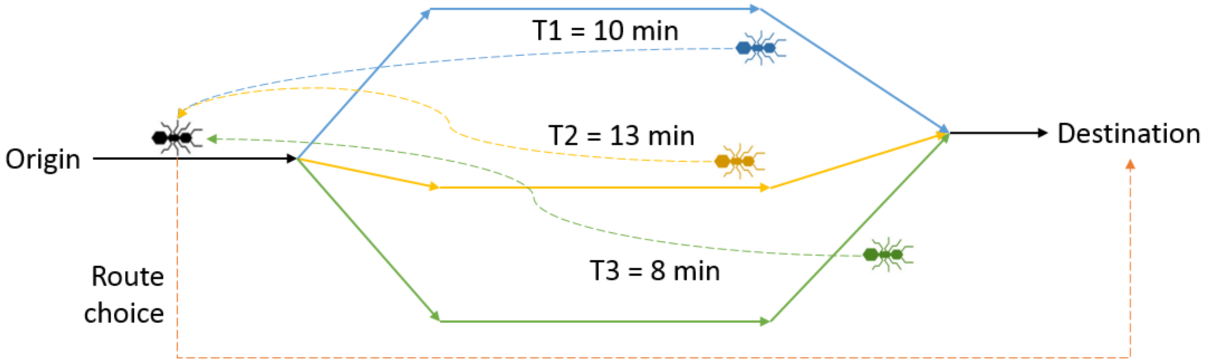


Figure 3.5: Working of an ant-like multi-agent system

In crowdsourcing, road users inform others about conditions on the road, enabling them to make better judgments on which route they must take. This concept is used in the Waze navigation app[1]. Crowdsourcing also offers possibilities for the enhancement of the quality of the route advice. The notifications that users of navigation apps (like Waze) send about traffic jams, incidents etc., can be used to make better estimations of the current and future traffic states. This is discussed in more detail in Ali et al. (2012) and Silva et al. (2013). The disadvantage of such a communicating-agents approach is that only *information* about the traffic conditions is communicated. There is no prescriptive nature of the messages, meaning that there is a lower likelihood that drivers make decisions that are better for the overall traffic system

A centralised agent is needed if any system optimal objective is desired. The strength of self-organising traffic in multi-agent systems, the very distributed way of controlling, is thus at the

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[1] www.waze.com

same time a disadvantage: the actions of the agents will most likely tend towards a user equilibrium, making it difficult for road authorities to induce another control objective (for instance system optimum).

Most of these researches consider a future situation with vehicles being fully aware of the traffic situation and fully objective in making a decision. The current situation on the road is however that the drivers still take the decisions: the choices of human beings are simply less predictable than those of automated vehicles. Therefore, the proposed multi-agent systems will have less influence in *current* practice than expected. A framework and model including a negotiation phase between a more centralised entity and the agents (travellers) in the system has been proposed by Adler et al. (2005).

Kammoun et al. (2014) combined different control strategies: they proposed a hierarchical multi-agent route guidance system, including ant-like behaviour of travellers with fuzzy logic. Simulations indicated the potential benefits of this method for the distribution of traffic over the road network.

It can be concluded that a multi-agent system is an interesting approach for the application of ITM. The distributed nature of the controller means that there is a low computation time. The enhancement of the advice quality leads to better routing decisions of road users. However, the distributed nature is also a disadvantage, as it might be more difficult to achieve objectives that have a centralised nature (e.g. finding optimal network performance). Another disadvantage is that the information about the routes' conditions is not prescriptive, meaning that multi-agent control has less power than prescriptive systems.

3.3.7 Control structure

The number of variables that a controller needs to control influences the computational performance of the ITM controller. Therefore, the distinction between centralised and decentralised controllers is made in literature. Centralised controllers have a better capability of improving overall network performance, since these controllers have an overview of the traffic states in the whole network. Decentralised controllers have less insight in the network dynamics, but can compute their control signal faster than centralised controllers; they take less traffic state measurements into account when determining their control action. Deflorio (2003) proposed a decentralised structure for in-vehicle route guidance. This controller influenced the splitting rate of traffic travelling towards a destination at each decision node, taking into account a fixed compliance rate to the route guidance. Another example of a feedback controller for dynamic route guidance is presented by Pavlis & Papageorgiou (1999). A very decentralised way of controlling traffic with route guidance is with multi-agent systems, as described in the previous section.

A hierarchical or hybrid structure – being a combination of a centralised controller and decentralised sub-controllers – can be used in order to keep the computation time low, while having insight into the traffic conditions in the whole network by the supervising controller. Farver (2005) researched the use of hybrid control structures elaborately, concluding that the quality of route guidance does improve when a combination of a centralised and decentralised control structure is used. A schematic overview of the different possibilities for the control structure is given in Figure 3.6.

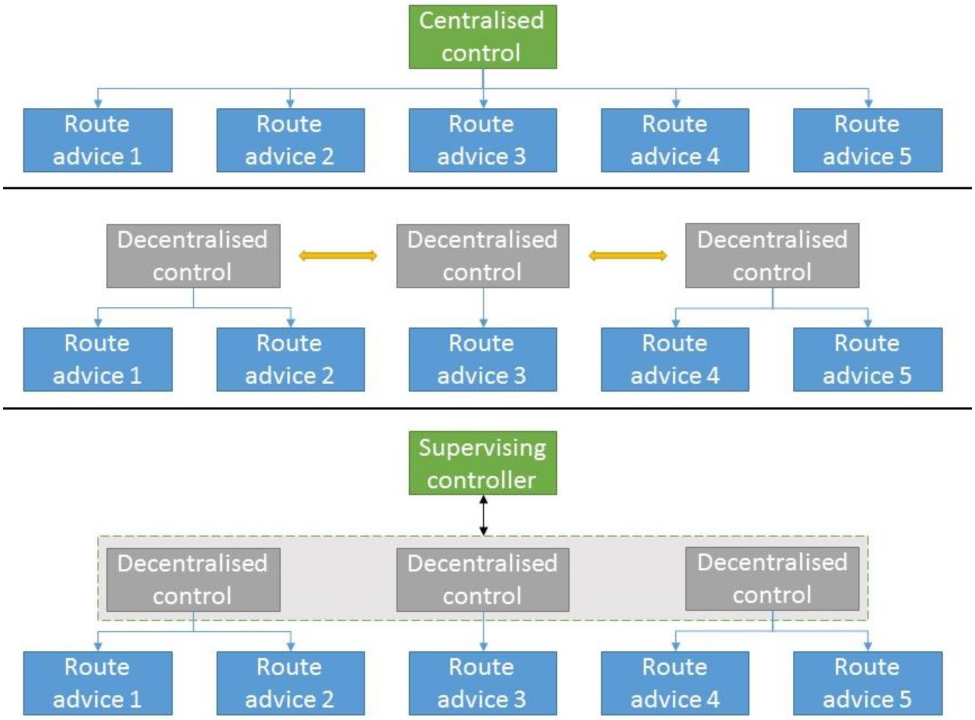

Figure 3.6: Different control structures, from top to bottom: centralised, decentralised, hybrid

3.3.8 Conclusion: comparison of control strategies for ITM

Different control strategies have been studied for an ITM controller in this paragraph. It was found that there is an important trade-off between the complexity of the controller and the accuracy of the route guidance and the effects thereof. Other properties of the controller, that depend on the strategy chosen, have been identified. A comparison between the advantages and disadvantages of the different control strategies is shown in Table 3.1. A clarification of the properties:

- Optimality: whether the strategy enables the traffic conditions to reach an optimal state;
- Accuracy: representing the traffic dynamics accurately in the controller's computations;
- Complexity: computational time that is needed for the computation of the control signal;
- Data needs: the amount of historical data that is needed for the controller's operations;
- Flexibility: the extent to which the controller can be applied to different situations.

The performance of the controller is also influenced by the control structure that is chosen. For this choice, again a trade-off between controller complexity (computation time) and accuracy is needed.

Table 3.1: Summary of control strategy (dis)advantages

Control strategy	**Controller properties**				
	Optimality	Accuracy	Complexity	Data needs	Flexibility
Non-predictive	-	-	+	+	+
Predictive	+	0	0	0	+
Iterative (predictive)	+	+	-	0	+
Fuzzy logic	0	+	0	-	0
Neural networks	+	+	-	-	-
Multi-agent systems	0	0	+	+	0

3.4 Route guidance control objectives

The objective of IRG (and also individual departure time advice) is crucial for the working and effects of the controller. An IRG controller can use an objective *value* or an objective *function* to achieve or approximate the control objective.

3.4.1 User and system optimal routing

Following from the formulations of Wardrop (1952), usually two possible control objectives for route guidance are considered.

- User optimum (or user equilibrium): natural traveller behaviour induces a travel time equilibrium on the road network, so that no traveller can improve his travel time by choosing another route. An example of the objective function for user equilibrium assignment is shown below (adapted from Peeta & Mahmassani, 1995), with the variables as presented in Table 3.2.

  Table 3.2: Variables used for the user equilibrium routing objective

Variable	***Description***
N	Set of indices of nodes in the network
P	Set of paths between a pair of nodes in the network
f_{ijp}	Vehicle flow between an origin i and destination j over path p
$T_{ijp}(f_{ijp})$	Travel time over path p between origin i and destination j, as function of the flows on that path p
τ_{ij}	Minimum travel time of the paths between origin i and j

  The flow between an origin and destination over a path is multiplied by the difference between the travel time on that path and the minimum travel time experienced between origin and destination. This is done for all origin-destination-pairs (OD-pairs) and the available paths between them. This travel time difference should be minimised, an equilibrium routing situation exists when the differences are zero:

$$\min_{f_{ijp}} f_{ijp} * \left(T_{ijp}(f_{ijp}) - \tau_{ij}\right), \quad \forall\, i, j \in N, p \in P \tag{3-1}$$

- System optimum: from the perspective of the network performance, this objective aims to minimise the total travel times in the traffic network, which leads to an optimal (average) travel time for the drivers. An example of the objective function of system optimal assignment is shown below, with the variables as presented in Table 3.3.

  Table 3.3: Variables used for the system optimal routing objective

Variable	***Description***
A	Set of indices of all arcs/links in the network
f_a	Vehicle flow over link a in the network
$T_a(f_a)$	Travel time over link a, as function of the flow on link a

  The total time spent in the system at is minimised by summing the travel times multiplied by the flows over all links in the network:

$$\min_{f_a} \sum_{a \in A} T_a(f_a) * f_a \tag{3-2}$$

Note that the objective function for both optimisation problems are non-linear, as the travel time over the link is dependent on the traffic flow there. The non-linearity of both problems mean that advanced optimisation techniques might be needed to come to a solution for an optimisation-based controller. With certain assumptions, the problems could also be linearized.

The definition of the user optimum assumes however perfect knowledge of travellers of the travel times in the network. Mahmassani & Jayakrishnan (1991) recognised the potential benefits of in-vehicle route guidance in creating a user equilibrium situation in a network. For the travelling population, a user optimum is more attractive than a system optimum, as every traveller has the same travel time (experience).

Hajiahmadi et al. (2013) evaluated the usage of a macroscopic fundamental diagram (MFD) to find a system optimum in the network for route guidance purposes. Using a hierarchical MPC structure, the aggregated traffic states in subnetworks were predicted every time step. The total delay in the whole network was optimised, together with the speed differences between different subnetworks to spread out congestion over the whole network. The results of the simulation of this approach and other reference approaches (reactive and static assignment approach) was that the usage of a MFD improved the performance on network level and was more able to spread out the congestion over the network.

Many comparisons have been made between user optimum and system optimum assignment. Van Vuren & Watling (1991) investigated the effect of different in-vehicle route guidance objectives for both the guided and unguided user classes. The results of their simulations were that system optimum routing reduced the total delays of travellers more than user equilibrium routing. This means that a system optimal assignment can reduce traffic flows over oversaturated roads as well, reducing the chance on spillback. However, system optimum route guidance tends to favour unguided travellers, while the guided drivers have a disadvantage because of their route guidance system.

Differences between user optimum and a system optimum assignment of traffic can only be observed in traffic conditions between free flow and heavy congestion (Peeta & Mahmassani, 1995). In Peeta & Mahmassani (1995), solution algorithms for the system optimum and user optimum dynamic traffic assignment are presented, including experimental results. They conclude that a system optimum assignment improves the total delay in the system, but only if there is some (but not too much) congestion in the network. Free flow conditions would mean that taking a different routing objective would not make a difference, since all vehicles would be able to travel using the fastest route. Too congested networks would not allow to reroute vehicles in a beneficial way, since the route alternatives are congested as well. Possibly, this offers opportunities for influencing the departure times of travellers to improve traffic conditions.

Murray-Tuite (2006) assessed user equilibrium and system optimum assignment of traffic for their effects on different aspects of network resilience: it was concluded that system optimum assignment mainly improves the mobility and recovery aspect of network resilience, while user equilibrium assignment gives better results on safety and adaptability aspects of resilience. For non-recurrent traffic conditions, this comparison is important because the sudden congestion caused by incidents or large-scale events requires a good network resilience to recover towards normal traffic conditions in an efficient way.

An evacuation is to some extent similar to a large-scale event. The massiveness, the sharp peak of departing or arriving travellers and few destinations are common characteristics of evacuations and large-scale events. Lämmel & Flötteröd (2009) compare the benefits of user optimum and system optimum in case of an evacuation of decision-agents from an area at risk. They conclude from case study simulation results that the system optimal routing allowed more people to be evacuated, although the benefits of the control objective differed per section of the evacuated network.

3.4.2 Hybrid user equilibrium and system optimum

Although system optimum assignment evidently has more benefits on the network level than a user optimum, travellers will not be attracted to a system optimum since some travellers will end up with a better (or worse) travel time than others. From the point of view of the road authorities this system optimum is more attractive, as the available infrastructure will be used more efficiently, leading to less overall delays. Various methods have been proposed in literature to enable an approach that is aimed at a system optimum, while still taking the natural user equilibrium behaviour of drivers into account. A few approaches to solve the unfairness issue are discussed below.

- **Tolls**: a very effective way to achieve a system optimum on the road network is to let drivers pay for routes with a lower travel time, or reward the ones taking a longer route. The travellers will then find an equilibrium of generalised costs on the network, instead of only an equilibrium in travel time. This new equilibrium will then be equal to a system optimum regarding the total travel times in the network. This approach was proposed by Bergendorff et al. (1997):

  “The tolls imposed should be such that the resulting tolled user equilibrium has at least one solution and every such solution is an untolled system optimal solution.”

  Yang (1999) found that tolls in the case of stochastic user equilibrium assignment can be helpful to approximate a system optimal distribution of traffic over the network, but only for certain demand levels and network structures. The effects also varied for the different generalised cost perception distributions of the driver population. Therefore, it can be concluded that in reality, tolls are not necessarily the solution to achieve a system optimum on the network. Another downside of tolls is the practical limitation, especially regarding in-vehicle IRG systems: it is difficult to collect tolls (in real-time) from travellers that receive route guidance with their in-vehicle systems. For events, tolls could be applied to the use of certain parking lots, also forcing a different route choice from the visitors.

- **Constraints and negotiation**: usually, travellers have a perception error regarding the travel times in the network. Therefore, they might perceive their chosen route to be better than others, while it isn’t. Furthermore, they might be indifferent to minor differences between the travel times (or generalised costs) of route alternatives. In scientific literature, some methods have been proposed to use this perception error and indifference to enable route guidance to steer more users towards a system optimum. This way, a balance between the user equilibrium and the system optimum can be found. In Jahn et al. (2005), the use of detour constraints is investigated: by defining a maximum detour that guided drivers may have with respect to the equilibrium travel times, the route set of the system optimum assignment is smaller. These detour constraints respect the limited willingness of travellers to take a longer route than others, while still offering a better network performance than user equilibrium assignment. Vreeswijk et al. (2012) used the indifference band of travellers to approach a system optimal assignment, while not interfering with the perceived travel times of road users. Their simulations revealed that accounting for the indifference band of travellers in the (individual) route guidance objective leads to a better overall network performance than a user equilibrium assignment. The perception and indifference of travellers can also be used in an interactive way between a centralised agent and the distributed agents (travellers). This is proposed in Adler et al. (2005): through negotiation between the control centre and the IRG users, travellers can be encouraged to take another (longer) route, which benefits the performance of the traffic system as a whole. The indifference band of the drivers is then used with their cooperation, leading to a higher compliance and to better network effects than for a user equilibrium objective.

3.4.3 Optimisation variables

The system optimum and user equilibrium (or a hybrid version of these objectives) minimise the travel time (difference) experienced by the drivers in the network. However, there are also other possible variables which can be optimised using the ITM controller objective function. A few examples:

- Costs of travelling (for e.g. parking or tolls);
- Distance if the route;
- Number of turning movements during the trip (indicator for the difficulty of the route);
- Encountered queue length during the trip;
- Queueing time during the trip;
- Emission, pollution and noise hindrance caused by taking a certain decision.

Some of these objectives are not dependent on the assignment of vehicles to routes, like distance and number of turning movements. These are therefore less suitable for the application to ITM. From the point of view of the problem statement, the minimisation of queueing time or queue lengths on the route might be interesting to use in an ITM controller at large-scale events. Making these dependent on the number of vehicles assigned to that route, would lead to an optimisation of the queues with IRG. Possibly, spillback could be prevented or reduced as well.

In Barth & Boriboonsomsin (2009), the application of an emission or pollution minimisation objective is discussed. The minimum emission paths were often the same as the minimum travel time paths, although during congested traffic conditions these advised paths differed. An environmental-friendly IRG system is able to reduce emissions to some extent. The question remains however how many travellers will comply with an environmental-friendly advice if there are additional travel time costs involved as well.

It is also possible to combine the different variables in the objective function, to find some optimal assignment for generalised costs. Weights are then applied to the variables (cost, distance, travel time, emissions): these weights represent the importance of each of these variables. The importance of the variables is of course subjective and debatable, but they can be used to represent the traveller route choice behaviour more accurately. Possibly, a sensitivity analysis could be executed to investigate the effects of different weighting in the objective function.

3.4.4 Conclusion

In conclusion, choosing an objective (function) for an ITM controller requires trade-offs between the network performance and the extent to which the natural traveller behaviour must be changed. User equilibrium is more logical from a driver perspective, while a system optimal assignment yields a better traffic performance on a network level. Furthermore, a system optimal objective requires a centralised control structure, as an overview of the states in the whole network is needed; a user equilibrium can also be approximated with more distributed control structures. Several options have been discussed to find a balance between the system and user optimum objective: making use of the indifference band or perception error of users in the route guidance objective has a good potential to approach the system optimal assignment in practice. These considerations (summarized in Table 3.4) will be taken into account in the design of the ITM controller for large-scale events.

Table 3.4: Summary of control objective (dis)advantages

Control objective	Advantage	Disadvantage
User equilibrium	Follows natural route choice behaviour of drivers	Suboptimal solution on the network scale
System optimum	Highest level of assignment optimality on network level	Unfairness of travel times among drivers, leading to lower compliance
Hybrid system-user optimum	Seeking balance between user equilibrium and system optimum	Knowledge about travellers' indifference bands needed

Lastly, the *input* into the optimisation of the individual route advice can be changed as well. Usually, the travel time (difference) is minimised, depending on the chosen optimal assignment. However, other variables like costs, queue lengths and emissions can be optimised as well. This can also lead to a user optimum or system optimum situation, but then for other control objectives.

3.5 Integrating route advice with departure time advice

The assignment of traffic to the network with route guidance controllers is often done using a fixed OD-demand over time. In reality, drivers might make their departure time and route choice in an integrated manner, as the perceived travel times on the route alternatives vary over time. Regarding the problem of spillback at large-scale events, it might be interesting to influence the departure or arrival times of travellers in order to counteract the spillback.

3.5.1 Potential effects of departure time advice

The departure time choice of travellers has a significant influence on the traffic conditions, especially at large-scale events where many visitors might want to arrive more or less at the same time. Trying to influence the departure time with a road pricing system has been proven to be quite effective (Arnott et al. 1990). The other way around, rewarding drivers to avoid the rush hours has also been researched and applied in practice. In the Netherlands, several projects of rewarding congestion avoidance have been finished, with considerable successes (see for instance Knockaert et al. 2012). It seems that pricing or rewarding drivers for using the road at certain times is primarily useful in battling recurrent congestion during the peak periods.

Travellers often have difficulties with estimating the (future) conditions on the road network, which vary over time: particularly when they are not familiar with the network topology and the traffic dynamics in it. Advanced Traveller Information Systems (ATIS) like ITM can help travellers to make better departure time decisions. These decisions are by definition made pre-trip. Many scientific contributions have focused on day-to-day learning behaviour of travellers with regard to their route and also departure time choice under the influence of ATIS. Mandir (2012) investigated the short-term changes in route and departure time choice behaviour due to ATIS. It was concluded that, above a certain travel time savings threshold, travellers are willing to change their departure time. This change also had a substantial potential effect on congestion levels during peak hours. For non-recurrent traffic conditions – for instance caused by large-scale events – long-term effects of ATIS are not relevant, since the road users encounter a quite rare traffic situation.

Next to *informing* the travellers about the existing traffic conditions, another (stronger) incentive for travellers to change their departure time is by the provision of departure time *advice*. In current practice, drivers can obtain integrated pre-trip route- and departure time advice using services like *Google Maps*. These advices are based on travel time predictions using a combination of current and historical traffic data. This approach to influencing departure times of road users might also have effect on the short term, therefore also influencing the traffic conditions in the road network during non-recurrent situations. For even shorter-term traffic management, only the *current* traffic states in the network can be used for predictions that enable service providers to offer travellers integrated route guidance and departure advice.

3.5.2 Departure time advice objective

Similar to route advice alone, integrated route and departure time advice can have two objectives: a user equilibrium and a system optimum. In the context of integrated departure time and route assignment, a user equilibrium means that no traveller can improve his travel time (including schedule delay costs) by changing his route or his departure time. Hence, there is a user equilibrium in both the time dimension and the space dimension. Mahmassani & Herman (1984) formulated the departure time choice behaviour and the route choices based on the traffic dynamics in the network. This joint choice model results in a user equilibrium on multiple routes from one origin to one destination. In Huang & Lam (2002), the simultaneous route and departure time user equilibrium problem is extended with the incorporation of network dynamics (flow-dependent travel costs). It is proven that a solution to this problem exists: such a solution can also be used for traffic management purposes in the form of integrated route guidance and departure time advice. In order to model the perception errors of the users as well, Lim & Heydecker (2005) developed an approach for the *stochastic* user equilibrium assignment for the space and time dimension.

A system optimum of integrated departure time and route assignment means that vehicles are departing and taking routes in such a way that the total travel time delay (including the schedule delay costs of the drivers) – summed for both the time and space dimension – is minimum. Chow (2009) investigated the dynamic system optimal assignment, integrating departure time and route choice. Iteratively, a solution for the assignment problem could be found. For evacuation purposes, system optimal assignment for both routes and departure times has been researched by Huibregtse et al. (2009). An ant colony optimization technique (as discussed earlier) was used to find the near-optimal solution for the choice of departure time, route and destination of the evacuees.

A hybrid variant of the system optimum and the user equilibrium (as discussed in section 3.4.2) can be used for individual departure time advice as well.

3.5.3 Relating arrival times to departure times

Note that both the user equilibrium and the system optimum formulation need to take the schedule deviation of drivers into account: this is the difference between the desired arrival time of the traveller and the expected arrival time corresponding to a certain departure time and a route alternative. If the difference exceeds a threshold, the driver will attribute a utility (or travel time) penalty to that alternative. The penalty of arriving late is usually higher than arriving early. This means that any IRG controller that also provides departure time advice should take the desired arrival time (or latest arrival time possible, the event start) of the visitor into account, as well as the time penalty that is attributed by individuals for arriving early or late at the destination. Mahmassani & Herman (1984) implemented this behaviour in the integrated departure time choice and route choice, with a user equilibrium objective. This concept also has implications for the ITM controller. While the desired arrival time of an individual can be requested when the advice is given, the perceived penalty of the schedule delay of the traveller is cumbersome to determine. Hence, some knowledge is needed about the departure time choice behaviour of the traveller population to ensure that the controller can give appropriate (departure time) advice.

3.5.4 Conclusion

Concluding, the departure time of travellers has a significant effect on the traffic dynamics and the resulting performance in the network. Travellers tend to make their departure time and pre-trip route choice simultaneously in practice. Therefore, it might also be interesting to influence this integrated decision with individualised traffic management. In this paragraph, methods have been discussed that can be used to model the integrated choice behaviour of travellers and to assign them to departure times and routes accordingly. Since the optimisation problem – both from user and system point of view – becomes more complex with the addition of the time dimension, computation times for a controller offering integrated advice will likely increase. It is also uncertain to what extent departure time advice will help in non-recurrent traffic conditions, because the current advice methods are based on historical data (which don’t capture non-recurrent events): how reliable is the advice on the shorter term if current and maybe predicted traffic states are used? This consideration must be taken into account in the choice for the departure time advice component in the ITM controller.

By definition, the departure time choice is made pre-trip, while the route choice also can be changed on-route. An ITM controller integrating departure time advice and route guidance should therefore be capable of both pre-trip and on-route guidance.

3.6 Conclusion of the literature study

This literature study has shown that there are various options for the design for an ITM controller. The trade-offs between the advantages and disadvantages of all these options within the studied building blocks have been discussed. An overview of the different building blocks and the corresponding possibilities for an ITM controller is shown in Figure 3.7. The theoretical control concepts are summarised in a conceptual framework of a ITM controller.

The control strategy and structure is the core building block of the controller. The decision for a certain control strategy will influence other design choices as well. Note that the control objective and the departure time advice are input to the structure and strategy of the ITM controller. The different building blocks interact with each other: some elements of the controller match better with each other than other elements. This means that in the design phase, trade-offs need to be made between different controller properties to find a suitable ITM controller for its specific purpose.

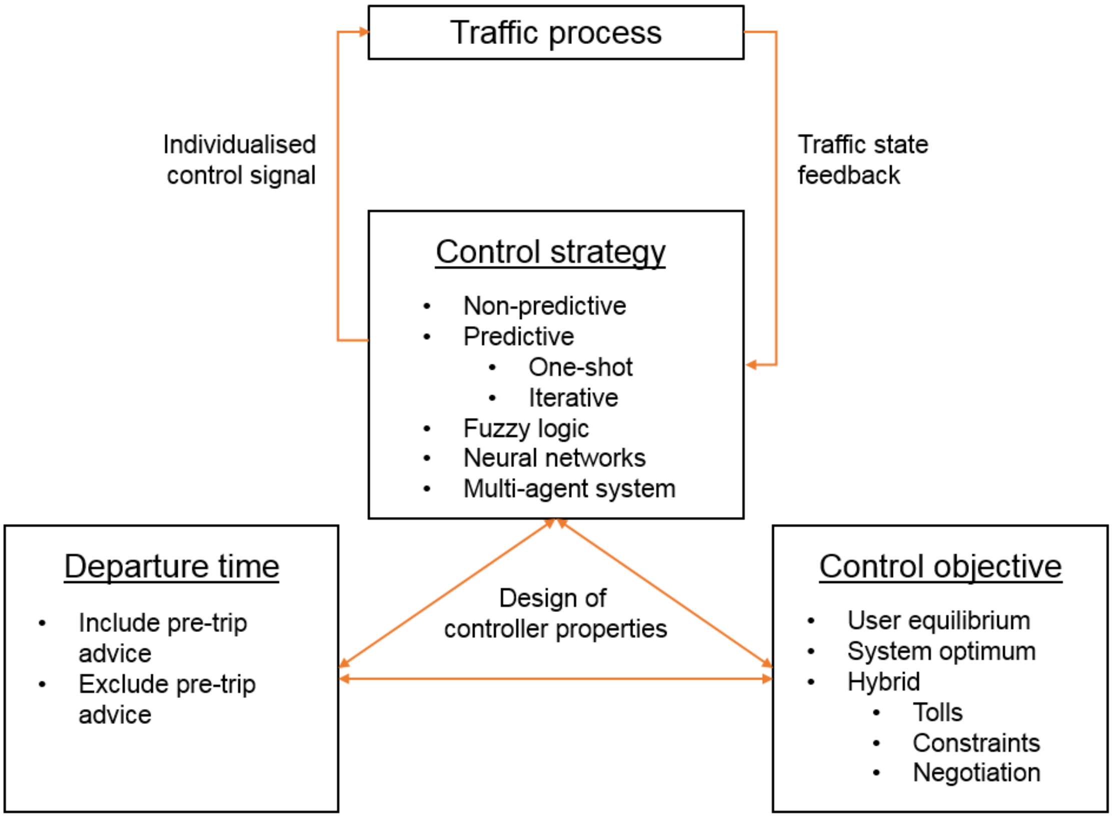

Figure 3.7: Conceptual framework of ITM including the different building blocks and their elements

The findings as presented in this chapter are not necessarily new, they follow from the analysis of existing contributions in scientific literature. The importance of these conclusions is that they will be used in the design phase of this Master thesis research. In this phase, the theoretical concepts of ITM will be applied to large-scale events specifically. For events, certain combinations of controller elements will be more suitable than others: this is because of the particular characteristics of traffic around a large-scale event.

In the next chapter, the design process is described: the requirements for event-specific controllers, the trade-offs between the building blocks and the reasoning behind the (mathematical) design of ITM control at events. This specific application of integrated individual route guidance and departure time advice at large-scale events has not yet been researched in literature, therefore the design can be valuable for the traffic conditions at events in practice.

4 Design of an ITM controller for large-scale events

In this chapter, the results of the design phase are presented. Firstly, requirements for an ITM controller for large-scale events are defined. These requirements follow from the problem statement, the properties of traffic around large-scale events and the literature study. Thereafter, a conceptual framework of the ITM controller for large-scale events is set up, as well as a specification of the controller's functionalities. Lastly, the functionalities of the controller are defined mathematically and the (dis)advantages of the design are discussed.

4.1 Introduction

Following the analysis of scientific literature, a conceptual framework for ITM controllers was defined. This conceptual framework generalises the different aspects of ITM controllers. If one would like to apply an ITM controller in practice, a choice needs to be made between the different elements in the building blocks. In the design phase, the specific purpose and application area of the ITM controller needs to be considered when making trade-offs between the design elements.

For this Master thesis research, an ITM controller will be designed for application at large-scale events. Large-scale events often cause quite some car traffic congestion in the surrounding areas. As described in the problem statement, the high demand towards the event location causes queues at the bottlenecks at the event. These queues spill back to the major roads in the network (highways), causing congestion and delays for through traffic. Obviously, the authorities and the event organisers would like to reduce these (unnecessary) congestion effects as much as possible. A possible method to resolve some of the traffic issues at events is to provide ITM to visitors, in order to achieve a better distribution of the traffic over the network.

Congestion caused by large-scale events can be characterised as *non-recurrent*. In literature, the potential of (individual) route guidance during non-recurrent traffic conditions has been acknowledged by e.g. Adler & McNally (1994), Chorus et al. (2006) and Muizelaar (2011). It is important to note that traffic around large-scale events has specific properties. In short, the traffic flows towards an event can be described as follows:

- There is a sharp peak in the amount of traffic on the road network, possibly at an unusual time and location;
- The traffic in the network is mainly directed to the event location (or parking areas in the surroundings), meaning that one destination is very dominant in the OD-matrix;
- The visitors of the event may have restrictions regarding their arrival time, for instance the start of a football match or a concert;
- The visitors of the large-scale event are generally less familiar with the road network than commuters.

The reasoning behind the potential of ITM at non-recurrent situations (and thus also events) is that the drivers are unfamiliar with both the network and the unexpected congestion on the road. This means that they are more willing to be informed about the travel times in the network or even be guided over preferable routes to their destination. This also implies that IITM at events requires another approach than IRG during common peak hour congestion.

In the following paragraphs, an event-specific ITM controller is designed. The requirements (to be defined in the next section) are used to make the trade-offs between the various controller elements as found in the literature study. The definitive choice for certain elements of the controller will lead to a mathematical formulation of the controller's objective, constraints and interaction with the traffic process.

4.2 Functional requirements for applying ITM to large-scale events

The first requirement of an ITM controller ensures that the controller is able to give individual advice to event visitors. This is a general requirement, that holds for every ITM controller.

1. *An ITM controller must be able to give different route (and possibly departure time) advice to travellers from the same origin that request guidance at the same time.*

The starting point for the line of reasoning behind the other requirements of an ITM controller for events is the problem statement and the specific traffic properties at large-scale events.

4.2.1 Counteracting spillback from bottlenecks at events

The purpose of the ITM controller at events is to improve the overall traffic conditions at an event by counteracting the spillback that occurs at the bottlenecks at the event venue. The inflow into the bottleneck is reduced through the individual guidance.

An important aspect of the ITM controller is whether it gives only pre-trip or also on-route route advice to event visitors. Here, a trade-off between complexity and accuracy must be made: pre-trip route guidance is much simpler, since the traffic demand at a certain control cycle is assigned at the start of the trip, not taking into account possible changes in the traffic conditions during the trip. On-route route guidance is more suitable regarding the actual route choice behaviour of travellers during non-recurrent traffic situations: the unexpected nature of these conditions can lead to sudden reconsideration of the route choice. Mathematically, on-route route guidance is more complex because of the (potentially) large number of decision points and the constant re-assigning of traffic flows. The following requirement is formulated for the design of the ITM controller for events:

2. *The ITM controller must be able to give pre-trip and on-route route advice to event visitors about their optimal route alternative.*

This means that the controller is able to cover the choice behaviour of travellers in an accurate way.

Another possible element of the ITM controller is the integration of pre-trip departure time advice with the route advice. Specifically for non-recurrent congestion situations, shifting departure times of event visitors slightly might enable a better distribution of traffic over time and consequently, less congestion (spillback) hindrance. However, including departure time advice in the controller leads to more complexity. With these considerations, the following requirement is defined:

3. *The ITM controller is able to give pre-trip departure time advice next to the route guidance to individuals travelling to an event.*

The purpose of the ITM controller – improving the overall traffic conditions at events by reducing spillback from bottlenecks towards the motorway – also has implications for the control strategy. There will be some lag between the control signal and the actual effect of the control signal on the traffic states. Especially further downstream in the network, the effects of rerouting traffic at a certain control interval might be noticed quite some time later. This means that the controller should not only react to the current traffic states: if spillback to higher level roads is threatening to occur, the effect of the control signal will be too late to prevent the spillback from actually occurring. Therefore, the individual route guidance should be predictive, to anticipate on occurring spillback in the future:

4. *The ITM controller for large-scale events has predictive capabilities in order to give the event visitors accurate and effective route guidance. With a traffic model, the current traffic states are used to compute future traffic conditions.*

The requirement that the controller must be predictive ensures that it will be capable of computing reasonably accurate pre-trip departure time advice and on-route route guidance from the current and future traffic states. The downside of this requirement is that the controller's computations will become more complex, as a traffic model is needed and the controller must control the traffic using more variables.

If any spillback occurs – or is prevented – the through traffic on the major roads in the network is affected. Thus, the actions of the ITM controller at events have effects on traffic that is not guided. Since these effects also determine the effectiveness and the accuracy of the controller, the through traffic must also be taken into account by the controller:

5. *The ITM controller accounts for unguided through traffic in the prediction of future traffic states and the evaluation of the calculated control signal.*

4.2.2 Event-specific traffic properties

The low familiarity of travellers with the (traffic) environment of the event means that they have relatively large indifference bands. Their perception errors regarding the travel times on alternative routes are large. This also increases their willingness to use route advice. These facts offer the opportunity for ITM to induce a system optimum or at least approach a system optimal assignment with some user-friendly constraints. This gives the next requirement of ITM at events:

6. *An ITM controller for large-scale events has the objective to achieve or approximate a system optimal assignment of travellers on the road network in the surroundings of the event.*

An ITM controller with an objective of user equilibrium assignment is therefore less suitable for events. Besides, such a controller would not be of that much added value: existing navigation providers advising the route with the shortest travel time to the individual event visitors, making the traffic in the network tend towards a user equilibrium. Furthermore, a system optimal objective is the most likely to reduce the inflow in the queues (threatening to spill back to higher level roads) as much as possible.

From the previous requirement, it also follows that the control structure enables the traffic to approach a system optimal assignment on the road network:

7. *The ITM controller needs a centralised agent to enable a system optimal route advice to the event visitors.*

Preferably, the ITM controller for events has a centralised or hierarchical structure. Fully decentralised or distributed structures cannot guarantee optimality of the route advice. If for instance a multi-agent system would be applied at large-scale events, still some centralised agent would be needed to coordinate the route choices of travellers.

A limitation of the fact that the ITM controller is applied at non-recurrent traffic conditions, is that there is a low amount of historical traffic data available. The traffic situation at events is too rare to have an extensive and statistically reliable database of the congestion dynamics and the traveller behaviour. Of course, the number of visitors towards the event can be estimated, as well as the background traffic. Data regarding other aspects of the traffic process is however not sufficient. This is why the following requirement is formulated:

8. *The ITM controller for large-scale events cannot rely on historical data for analysis of traffic dynamics or traveller behaviour.*

This means that an ITM controller using neural networks is not suitable for application at large-scale events, as such a controller fully relies on the learning from previous comparable traffic situations. Furthermore, the limited amount of data about traveller route choice behaviour at events implies that using fuzzy logic in an ITM controller is not preferred.

Note that there is a possible conflict between this requirement and the requirement that the controller must be predictive. Prediction models often make use of these historical datasets. The ITM controller design must be such that the state prediction model makes limited use of historical data:

9. *Each control interval, the ITM controller for large-scale events uses the time-dependent traffic states as feedback to determine the route advice for individuals at the current control interval.*

The route advice for the event visitors is therefore also time-dependent, as the traffic states are dynamic. It is assumed that the estimations of the current traffic conditions are correct and accurate: the methods behind the estimation of traffic states from different data sources are outside the scope of this research.

A specific characteristic of a large-scale event is that the guided travellers will have only one destination (area). Through traffic will have no detour options and will take a fixed route. Hence, the ITM controller should assume that all travellers that request advice will have the event as destination:

10. *The ITM controller guides travellers from multiple origins to only one destination, which is the event location.*

Another assumption behind the ITM controller is that the route alternatives between an origin and destination are known beforehand and that these are fixed. This is reflected in the following requirement:

11. *The ITM controller must determine the route advice for event visitors based on predefined and fixed route choice sets.*

Route choice sets could also be defined dynamically with a shortest path algorithm. However, the available route alternatives are fixed for this ITM controller design. The study into the shortest paths algorithms for control purposes is outside the scope of this research and is left for future research efforts.

From these requirements, a choice can be made between the different elements of ITM in general, in order to make a design of an ITM controller that is suitable for large-scale events. Furthermore, the requirements are used for the mathematical formulation of the controller design. Lastly, the requirements also help for the evaluation of the design in a simulation environment: the requirements already indicate some elements of the simulation setup.

4.3 Conceptual design for ITM at large-scale events

In this paragraph, the design of the ITM controller for large-scale events is presented, as well as the reasoning behind the design choices. The controller design consists of the building blocks and the elements of ITM that were found in the literature study. Furthermore, the interaction between the different elements in the controller and the interaction between the controller and the traffic process is described.

4.3.1 Controller objective, structure and strategy

The ITM controller for large-scale events is required to induce a system optimum (or an approximation thereof) on the road network. The unfamiliarity of the event visitors with the network offers space to do this. For the design of the ITM controller, a constrained system optimum is chosen as controller objective. Such a constrained system optimum approaches the optimal goal from the point of view of the road authorities and the event organisers, while also ensuring that the guided travellers experience a limited amount of unfairness in their advice. If they have a longer route (in time) than others, the controller will make sure that this detour is within a certain threshold, the indifference band. This means that the guided travellers are more likely to comply with the advice, as they will find the advice credible and do not perceive it to be unfair. The constrained system optimal assignment by the control signal can be found with an optimisation approach. This optimisation will have the objective to minimise the total travel time of all traffic, by computing the optimal flows of visitors from over different paths from a decision node (split node) in the network to the single destination, the event venue (see Figure 4.1). The on-route split fractions at the decision nodes influence the flows in the network, affecting the travel times again. The prediction model is able to incorporate these effects. The advice is based on the minimisation of total travel time in the network. Other performance measures – like queue length minimisation – could be suitable as well, as spillback from bottlenecks is one of the issues causing congestion hindrance at events. The gained on-route advice can be used to counteract the spillback that occurs at the event location bottlenecks. Obviously, the optimisation is constrained by a threshold for the travel time difference between the routes between an origin and the destination, making the assignment *constrained* system optimal. Note that the optimisation model will take the current and future traffic states on the road network into account in finding the optimal assignment of individual travellers, making it react to the traffic process. The calculations of the optimisations can be executed with optimisation tools: CPLEX is an example of such software, and will be used in the simulation stage of this thesis.

The (constrained) system optimal assignment objective requires the ITM controller to have a centralised structure. The traffic states are collected from all the links in the network and are used to define the departure time advice and the on-route route guidance for individuals in a centralised manner. This means that the controller will optimise the total travel time (delay) in the whole network. This will likely enable the ITM controller to resolve some traffic issues at events, as for instance spillback to main roads.

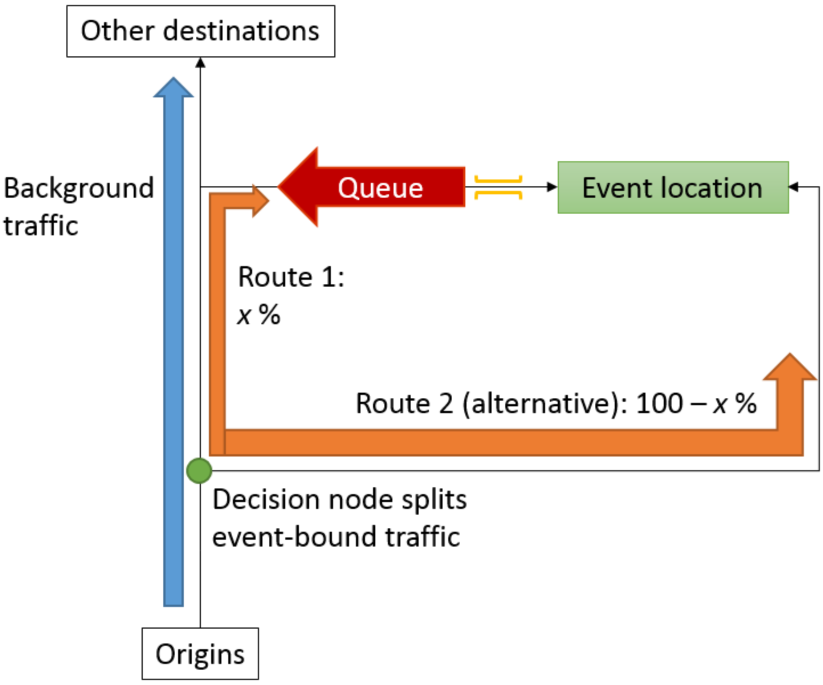

Figure 4.1: Using split fractions at decision nodes to minimise total travel time in the network. In this example, the result of the individual route guidance will be a lower inflow into the queue

The ITM controller is required to be predictive. This means that the current traffic state is fed back to the controller, where a prediction for the future state is made, leading to the optimisation of the control signal. Only one iteration of optimisation is performed, implying that the controller has a one-shot prediction strategy. The optimised control signal is not fed back to the prediction model, but within the optimisation the effects of the control signal on the travel times in the network are taken into account. The motivation for this choice is the computation time: since the controller is not iterative, the route advice for the individuals is less difficult to compute. There are also no issues with convergence (which might not be reached with an iterative strategy). Furthermore, the prediction model and the optimisation do not necessarily need to match perfectly: the outcomes of the prediction model are used in the optimisation, but not vice versa, so no translation is needed to initiate the prediction model.

The downside of this approach is that the prediction is less accurate, as no interaction between the control signal and the future traffic conditions is modelled. The computed advice will be sub-optimal as well. Moreover, the optimal solution will be found for the current control interval only. An MPC structure would enable optimality over time as well, also taking into account future control signals.

4.3.2 The role of departure time in the ITM controller design

Influencing the departure time of travellers has been proven to be effective in counteracting congestion. Therefore, the ITM controller for large-scale events will try to prevent spillback by advising event visitors about their departure time, next to the route guidance. The objective of this departure time advice is the same as the objective of the individual route guidance (constrained system optimum), to ensure consistency in the advice.

It is assumed that departure time advice requests of individuals are received every control interval, for the current control interval and the future ones (these are travellers that request advice some time in advance of their departure). Normally, the event visitor would depart at his preferred departure time interval: this is the time for which the departure time advice request is received. With departure time advice included in the controller, these requesting travellers may be shifted over time: shifts to both a later and an earlier departure time are possible (see Figure 4.2 for an example). The amount of time that a traveller may be shifted to the future is constrained, to make sure that the waiting (or shifting) time of a visitor is not disproportional to the travel time gains. Furthermore, the number of shifts to a certain interval is constrained by the capacity of the roads, so that the departure time shifts does not lead to new unnecessary congestion or the late arrival of guided event visitors. A final assumption is that a traveller will request departure time advice only once, which means that his departure time can be shifted only once.

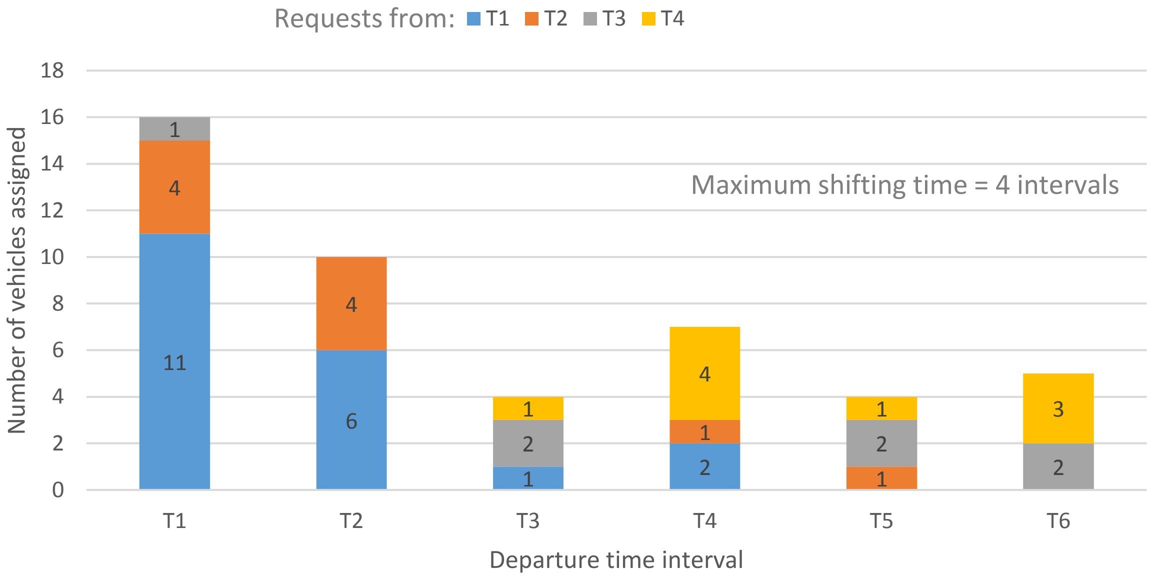

Figure 4.2: Example of shifting departure times of individual requests to optimise network performance

There is no interaction between the departure time advice and the on-route route guidance optimisations. The effects of the control signal of both components are incorporated in the next control interval again.

The choice for a one-shot control strategy is also positive regarding the inclusion of departure time advice in the controller. This additional module leads to extra computation time, so an iterative procedure would have made the ITM controller very complex and extensive.

4.3.3 Conclusion: conceptual framework ITM controller for large-scale events

Now the controller strategy and objective have been defined, a conceptual framework for this event-specific ITM controller can be set up. This conceptual framework is shown in Figure 4.3. The working of the conceptual controller design can be described by the following steps:

1. Start time step *t*;
2. Measure the current traffic state on all links in the network. The traffic states are the cumulative numbers of vehicles at the start and end of all links. In practice, these measurements can be made with several data-sources, like loop detectors or floating car data;

3. Predict the future traffic states on all links in the network with a traffic model. The current traffic states, the network properties, predicted demand and assumed split fractions (input from the optimisation) at decision nodes are input for this traffic model;
4. Use the current and future traffic states to find split fractions at bifurcation nodes, that lead to the system optimal assignment of the guided travellers, constraining the optimisation by e.g. the average indifference bands of the users.
5. Use the current and future traffic states to find the system optimal pre-trip departure time assignment of the guided travellers, constraining the optimisation by the average indifference bands of the users, capacities and maximum shifting times. The departure times are determined by evaluating possible shifts of the departure time of individual travellers to other control cycles;
6. Provide the individual advice to the event visitors. Proceed to time step *t+1* and repeat from step 2. Between these time steps, the traffic state will change again in the traffic process, influenced by disturbances as compliance, demand and unguided through traffic. The controller will stop its actions whenever the event has started and no requests for route or departure time advice are received anymore.

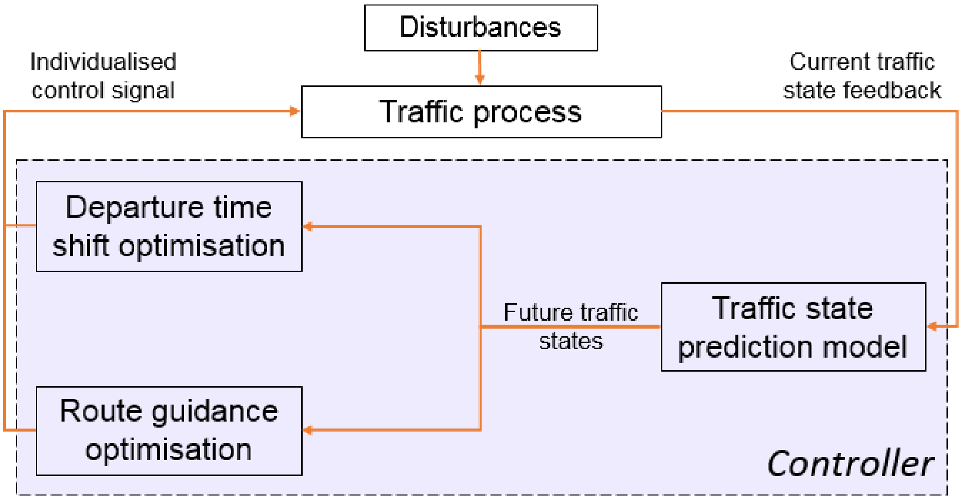

Figure 4.3: Conceptual framework of the ITM controller for large-scale events

Concluding this paragraph, the designed ITM controller for large-scale events has the following functionalities:

- The controller optimises the total travel time costs in the system. This way, the controller will try to approximate a system optimal assignment of traffic in reality, while also taking into account the spillback of queues to main roads in the network.
- The controller decides on destination-specific split fractions at bifurcation nodes, with regard to the minimum total cost objective.
- The split fractions are based on the predicted number of vehicles on the links in the network. This prediction is made with a macroscopic traffic flow model. This model uses a low amount of historical data (due to availability constraints).
- The controller is able to shift the departure time of individual event visitors through individual departure time advice, if the system will benefit (enough) from this.
- This departure time shift of individuals is constrained, to reduce the amount of inconvenience (waiting, departing earlier then preferred, late arrivals) experienced by the event visitors.

- The controller ensures that the assignment of individuals to route or departure time alternatives is not too unfair: this means that there is some threshold, which the travel time difference between two route or departure time alternatives may not exceed. This unfairness threshold is the result of the choice for a constrained system optimal control objective.

This functional description is the basis of the mathematical formulation of the ITM controller for car traffic travelling to large-scale events.

4.4 Mathematical formulation ITM controller for large-scale events

In this paragraph, the conceptual design of the ITM controller for large-scale events is translated to a mathematical design. Firstly, the choice of a traffic state prediction model is discussed. Thereafter, the methodology to determine the individual departure time and route advice is defined.

4.4.1 Traffic state prediction model

The traffic states in the current time step are used to define the future traffic states. The traffic condition on a link is described by the number of vehicles that passed certain locations in the network at a certain time. These are the cumulative numbers of vehicles, that are recorded throughout time. The propagation of traffic in the network depends on the number of vehicles on the upstream and downstream link(s). To describe the interaction between the traffic states on the different links over time, a traffic propagation model is needed.

This state prediction model can be microscopic, mesoscopic or macroscopic. As discussed in the literature study, mesoscopic or macroscopic traffic models are more accurate in modelling (individual) routing behaviour in networks, while microscopic models focus more on lane changing and car-following behaviour on links. An aggregate way of modelling traffic is with a macroscopic model. The computation time is relatively low for this kind of models.

The chosen prediction model should be able to model queueing, as queues and spillback are important characteristics of the problem definition. Queues can be represented vertically – they do not occupy space on the link – or horizontally, meaning that spillback from a bottleneck can also be modelled (see Figure 4.4). Hence, the latter representation is more suitable for route guidance at events (as spillback is an important element of the problem definition). It was also identified by Knoop et al. (2008) that spillback modelling enhances the quality of route guidance and improves the overall network performance.

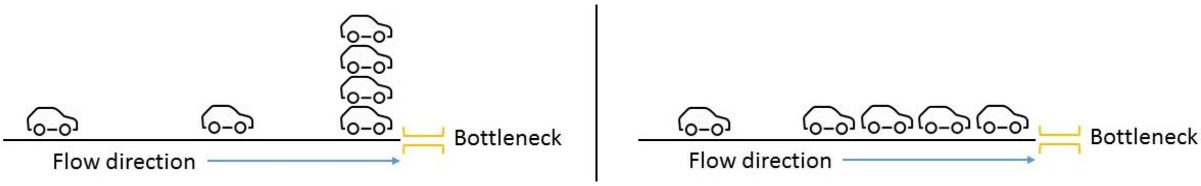

Figure 4.4: A vertical queue representation (left) and a horizontal queue (right) at a bottleneck

Another important characteristic of the queueing model is how the queue resolves in the model. In reality, queues resolve from the front: vehicles in the front of the queue will reach the outflow traffic state first. This traffic state propagates backward with a certain shockwave speed. This means that whenever a vehicle exits the queue at the front, it will take some time before the last vehicle in the queue can move forward as well. During this time, the queue tail propagates upstream because of the inflow in the queue. If the inflow into the queue is lower than the outflow of the queue (the capacity of the bottleneck) for a certain amount of time, the queue can resolve completely. Incorporating the shockwaves in the queue in the traffic state prediction model means a trade-off between model realism and complexity. Although shockwaves make the model more complex, it represents the queues over time more realistically.

To model the propagation of traffic, the Link Transmission Model (LTM) of Yperman (2007) is used. The LTM is able to macroscopically determine the sending and receiving flows of all links, taking into account shockwave (spillback) dynamics in the prediction model. Therefore, it is suitable for the purpose of ITM at large-scale events. Using this shockwave theory, the LTM models the flows of vehicles through nodes and over links over time. Cumulative curves are used for this: these cumulative vehicles numbers are equal to the total number of vehicles that has passed a location at a certain time. The predicted cumulative number of vehicles on the start and end of a link can be used to determine the traffic states over time, which is input into the optimisation of the individualised control signal.

The LTM of Yperman (2007) is explained in more (mathematical) detail. Table 4.1 shows the sets and the input variables that are used for the predictions of LTM.

Table 4.1: Sets and inputs for the application of the LTM of Yperman (2007) to ITM control

Sets	**Description**	**Unit**
V	Set of node indices, describing the nodes in the network	
A	Set of link indices, describing the links in the network	
I_n	Set of indices of incoming links of a node, I_n is a subset of A	
J_n	Set of indices of outgoing links of a node, J_n is a subset of A	
O	Set of all origin indices in the network. O is a subset of V	
T	Set of simulation time step indices. The maximum simulation time of the LTM can be fixed to a certain *prediction horizon*	
X	Set of space indices, describing space in the network	
Indices		
t	A certain time interval, $t \in T$	
n	A node in the network, $n \in V$	
r	An origin node in the network, $r \in O$	
a	A link in the network, $a \in A$	
i	Incoming link, $i \in I_n$	
j	Outgoing link, $j \in J_n$	
x	A point in space, $x \in X$	
x_a^0	Entrance point of link a	
x_a^L	Exit point of link a	
Model variables		
Δt	The amount of time between each time step of the controller's predictions	[s]/[min]/[h]
$v_{f,i}$	Free flow speed (forward shockwave speed) of link i	[km/h]
w_i	Backward shockwave speed (negative number) of link i	[km/h]
$q_{M,i}$	Link capacity of link i	[veh/h]
$k_{M,i}$	Critical density of link i	[veh/km]
$k_{jam,i}$	Jam density of link i	[veh/km]

L_i	Length of link i	[km]
N(x,t)	The cumulative number of vehicles that has passed location x at time t	[veh]
$N_r(t)$	The cumulative number of vehicles that has passed origin r at time t. This can be derived from the demand profile	[veh]
$S_{ij}(t)$	Sending flow from link i to j during a time interval	[veh]
$R_{ij}(t)$	Receiving flow of link j from i during a time interval	[veh]
$G_{ij}(t)$	Transition flow between i and j during a time interval	[veh]
β_{ij}	The split fraction at a node connecting link i and j. This split fraction is assumed to be fixed over the future time. It is retrieved from the optimisation of the individual route guidance	
Outputs		
ω_a^t	The predicted number of vehicles on link a at time interval t	[veh]
ψ_a^t	The predicted number of *queueing* vehicles on link a at time interval t	[veh]
T_a^t	The (predicted) travel time on link a	[s]
$\theta_x(N)$	The time at which N vehicles have passed location x	[s]
m_n^t	The predicted transition flow that arrives at decision node n at time interval t	[veh]

The LTM takes the following steps at each time step to compute the propagation of traffic over the links and the whole network. This methodology is defined by Yperman (2007).

1. Firstly, the LTM determines the potential sending and receiving flows of every link in the network. These flows are based on the cumulative number of vehicles at the entrance and exit of each link, taking into account the forward and backward shockwave speeds and the capacity.

   $$S_i(t) = min([N(x_i^0, t + \Delta t - \frac{L_i}{v_{f,i}}) - N(x_i^L, t)], q_{M,i} * \Delta t) \tag{4-1}$$

   Here, $S_i(t)$ is the sending flow of link i during time step t of the prediction. $N(x_i^0,t+\Delta t-L_i/v_{f,i})$ is the cumulative number of vehicles that passed the link start one free flow travel time unit of this link ago. $N(x_i^L,t)$ is the cumulative number of vehicles at the link end at the current time step. $q_{M,i}*\Delta t$ is the capacity of link i, expressed in a number of vehicles.

   $$R_j(t) = min([N(x_j^L, t + \Delta t + \frac{L_j}{w_j}) + k_{jam,j} * L_j - N(x_j^0, t)], q_{M,j} * \Delta t) \tag{4-2}$$

   In this function, $R_j(t)$ is the receiving flow of link j during time step t. $N(x_j^L,t+\Delta t+L_j/w_j)$ is the cumulative number of vehicles that passed the link start one backward shockwave time unit of this link ago. $N(x_j^0,t)$ is the cumulative number of vehicles at the link start of j at the current time step t. $q_{M,j}*\Delta t$ is the capacity of link j, again expressed in a number of vehicles.

   Note that the arguments in the sending and receiving flow make use of a certain shockwave propagation time: L/v_f for forward propagation, L/w for backward propagation of shockwaves. These input variables should be chosen with some care. The shockwave propagation time divided by Δt should be equal to an integer: otherwise, the LTM will not be able to find the cumulative vehicle numbers at a certain time. This is an important limitation of the application of the LTM in practice.

The shockwave speeds used in the LTM are constant; they are derived from the free flow speed of a link and the queue head propagation speed (backward shockwave). The constant shockwave speeds mean that, for this application of the LTM, a triangular fundamental diagram is chosen. This represents the real macroscopic traffic dynamics in a simplified way. In Figure 4.5, this fundamental diagram is shown, including variables used in the LTM component in the ITM controller.

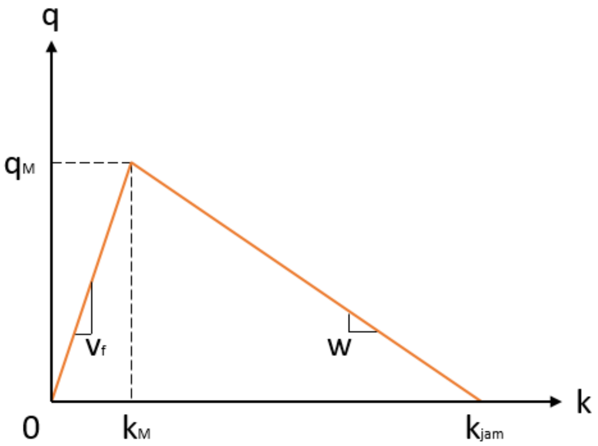

Figure 4.5: Triangular fundamental diagram variables, as used in the LTM for the ITM controller for large scale-events (Yperman, 2007)

2. For all nodes, the transition flows are determined. These are the flows from an incoming link to the outgoing link of the node. In the application of LTM for the ITM controller, a simplification is made: it is assumed that there are no complex nodes, with more than three in- and outgoing nodes in total. The incorporation of this kind of nodes (which are present at e.g. intersections) would lead to the use of more complex node models. The nodes that are present in the network and their transition flows are discussed below (and are depicted in Figure 4.6).

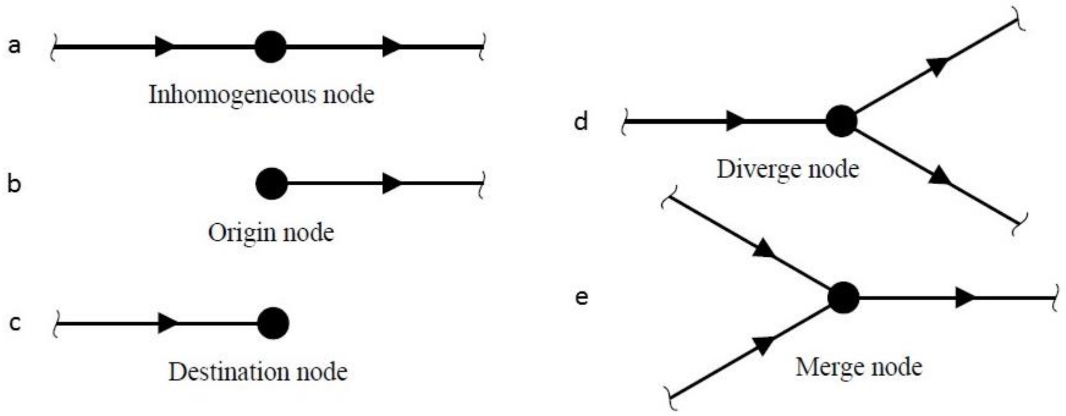

Figure 4.6: Used node types in the application of LTM to ITM at events (Yperman, 2007)

   a. Inhomogeneous nodes. These are nodes with one ingoing link and one outgoing link. These can be used to represent transitions in the infrastructure, for instance a lane drop. The transition flow is basically the minimum of the sending flow of the ingoing link and the receiving flow of the outgoing link:

$$G_{ij}(t) = min(S_i(t), R_j(t)) \qquad (4\text{-}3)$$

Here, $G_{ij}(t)$ is the transition flow at the node at the current time step. $S_i(t)$ is the current potential sending flow of incoming link i, while $R_j(t)$ is the potential receiving flow of outgoing link j.

b. Origin nodes. These nodes ensure that the demand is loaded to the network. They only have one outgoing link. The vehicle flow to this link is determined as follows:

$$G_j(t) = min([N_r(t+\Delta t) - N(x_j^0, t)], R_j(t)) \qquad (4\text{-}4)$$

This is the minimum of the demand at origin r ($N_r(t+\Delta t)-N(x_j^0,t)$) and the receiving flow of the first link from that origin node ($R_j(t)$). Note that the future demand profile at origin r is known by the controller (actually, an estimation is made), which enables the LTM to compute the transition flows here.

c. Destination nodes. These nodes enable vehicles to exit the network. They have no capacity restrictions, so the node flow is equal to the sending flow of the incoming link:

$$G_i(t) = S_i(t) \qquad (4\text{-}5)$$

$G_i(t)$ is the transition flow of link i at the current time step, while $S_i(t)$ is the link's sending flow.

d. Diverge nodes. At these nodes, there are two outgoing links and one incoming link. The sending flow from the incoming link must be split, before the transition flows can be computed. Here, the ITM application of the LTM plays a role: the ITM controller will determine the split fraction that is needed in the prediction model. Assumptions are needed for the future split fractions. A possible assumption could be that the split fractions stay constant during the whole prediction horizon, and are based on the output of the IRG optimisation.

$$S_{ij}(t) = S_i(t) * \beta_{ij},\ \forall\ i \in I_n; j \in J_n \qquad (4\text{-}6)$$

The sending flow from incoming link i to outgoing link j at time step t is $S_{ij}(t)$. It is the total sending flow of link i ($S_i(t)$) times the split fraction of traffic from i to j (β_{ij}).

With the sending flows from the incoming link to the outgoing links specified, the transition flows can be determined:

$$G_{ij}(t) = \min_{j' \in J_n}\left(\frac{R_{j'}(t) * S_{ij}(t)}{S_{ij'}(t)}, S_{ij}(t)\right),\ \forall\ j \in J_n \qquad (4\text{-}7)$$

Here, $G_{ij}(t)$ is the transition flow between i and j, $R_j(t)$ the receiving flow of an outgoing link, and $S_{ij}(t)$ the potential sending flow from link i to j at the current node.

Hence, the sending flows are constrained by any outgoing capacity restrictions. If any sending flow cannot fully be assigned to the outgoing link, the transition flow for *both* outgoing links will be reduced, proportionally to the ratio between the (too high) sending flow and the restricting capacity. The assumption behind this is that congestion due to an outflow restriction will affect both the directions at the node equally. This represents the effects of spillback, where traffic that is not travelling through the bottleneck is delayed as well.

e. Merge nodes. At these nodes, there are two incoming links and one outgoing link. The transition flows are restricted by the receiving flow of the outgoing link. If the sum of the sending flows of the incoming links exceeds this, the transition flow will hold back some of the sending flow of the incoming links. The relative penalty for both of the incoming links is equal. Mathematically, this is formulated as follows:

$$G_{ij}(t) = min(\frac{R_j(t)*S_{ij}(t)}{\sum_{i'\in I_n} S_{i'j}(t)}, S_{ij}(t)), \ \forall\, i \in I_n \tag{4-8}$$

Here, $G_{ij}(t)$ is the transition flow between i and j, $R_j(t)$ the receiving flow of the outgoing link, and $S_{ij}(t)$ the potential sending flow from an incoming link i to j at the current node.

The assumption behind the equal restriction of both incoming links is that there is no priority of an incoming link over the other. Vehicles from the incoming links will enter the outgoing link one after another alternately. In reality, other priorities can be present, for instance at an intersection with priority rules or traffic lights. For simplicity, this is not taken into account in the LTM for ITM applications. Still, this can be a limitation when real networks must be represented.

3. After the calculation of all transition flows, the cumulative number of vehicles on each link can be updated by adding the number of passing vehicles (at the link start and end) to the number that had already passed until now.

$$N\left(x_i^L, t+\Delta t\right) = N\left(x_i^L, t\right) + \sum_{j\in J_n} G_{ij}(t), \ \forall\, i \in I_n \tag{4-9}$$

$N(x_i^L,t+\Delta t)$ is the cumulative count at the link end at the *next* time interval, $N(x_i^L,t)$ is the count at the link end at the *current* interval. This is added up to the sum of all transition flows $G_{ij}(t)$ to the outgoing links j of link i.

$$N\left(x_j^0, t+\Delta t\right) = N\left(x_j^0, t\right) + \sum_{i\in I_n} G_{ij}(t), \ \forall\, j \in J_n \tag{4-10}$$

$N(x_i^0,t+\Delta t)$ is the cumulative count at the link start at the *next* time interval, $N(x_i^0,t)$ is the count at the link start at the *current* interval. This is added up to the sum of all transition flows $G_{ij}(t)$ from the incoming links i to j.

These new cumulative vehicle counts can be used in the next time step of the LTM. From the (predicted) cumulative curves of all links over time, the travel times and the number of vehicles on a link can be determined. The number of vehicles on a link can be computed as follows:

$$\omega_a^t = N(x_a^0, t) - N(x_a^L, t), \quad \forall\, a \in A; t \in T \tag{4-11}$$

ω_a^t is the number of vehicles on link a at time interval t. This is the cumulative count at the link start ($N(x_a^0,t)$), minus the cumulative number of vehicles that have passed the link end ($N(x_a^L,t)$).

The number of *queueing* vehicles is also of importance for ITM at events. Since spillback must be prevented or reduced by the controller, it is important to have insight in the (predicted) queue lengths on the links. These are computed by shifting the cumulative curve of the link end to the left, by the free flow travel time of the link:

$$\psi_a^t = N(x_a^0, t) - N\left(x_a^L, t + \frac{L_a}{v_{f,a}}\right), \quad \forall\, a \in A; t \in T \tag{4-12}$$

The number of queueing vehicles (ψ_a^t) on link a at time t is the cumulative count at the link start ($N(x_a^0,t)$), minus the cumulative count at the link end at t plus the free flow travel time of the link($N(x_a^L,t+L_a/v_{f,a})$). This value of ψ_a^t will be calculated after the whole prediction model run.

The predicted link travel times can be derived from the cumulative curves. It is the time at which a certain cumulative number of vehicles has passed the link end minus the time at which that same number had passed the link start.

$$T_a^t = \theta_{x_a^L}(N(x_a^0, t)) - \theta_{x_a^0}(N(x_a^0, t)), \ \forall\, a \in A; t \in T \tag{4-13}$$

The instantaneous travel time T_a^t of link a at time t, is the time at which a cumulative number of vehicles at the link start ($N(x_a^0,t)$) has passed the link end (θ_{xa}^L), minus the time at which this number has passed the link start (θ_{xa}^0).

Figure 4.7 shows graphically how the outputs of the LTM (as discussed above) can be derived from the predicted cumulative curves of each link.

For the ITM optimisation, it is also necessary to store the predicted transition flows of each time step. These transition flows are input into the route guidance optimisation. The individual route guidance at bifurcation nodes will affect the route choice of the event visitors.

$$m_n^t = \sum_{j \in J_n} G_{ij}(t), \ \forall\, i \in I_n;\ n \in V; t \in T \tag{4-14}$$

The flows through node n that might require route guidance at time t (m_n^t) is equal to the sum of all transition flows $G_{ij}(t)$ through that diverge node n at time t.

The symbols of these outputs of the LTM will also be used in the mathematical formulation of the optimisation of the pre-trip departure time advice and the on-route route guidance.

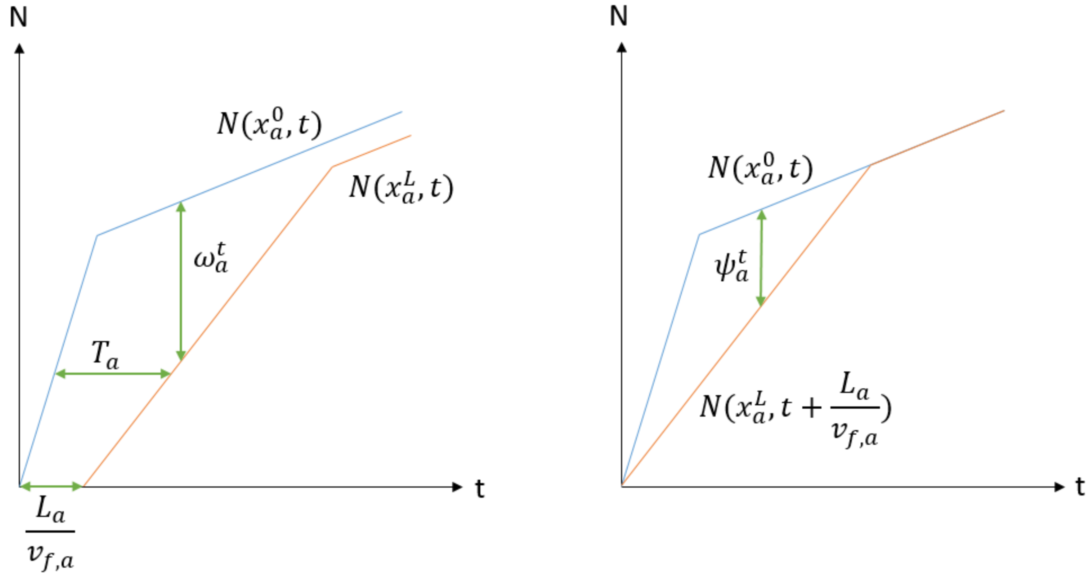

Figure 4.7: Derivation of outputs from the predicted cumulative curves in the LTM. On the right, the outflow curve is shifted by the free flow travel time of the link

For the purpose of ITM, it is important to make a distinction between guided and unguided traffic in the LTM. For both the guided traffic towards the event and the unguided (background) traffic, the transition flows are calculated, as well as the cumulative curves. This means that the LTM needs input for these different commodities, namely the demand at the origins and assumed split fractions. The effects of any congestion is distributed among the commodities in such a way, that the delay (or holding back of traffic at bottlenecks) is attributed to the commodities according to the ratio between their flows. The transition flows of guided traffic at diverge nodes can be used to optimise split fractions. The incorporation of the distinction between event-bound traffic and background traffic in the LTM is explained in *Appendix A.*

The resulting predicted outputs of the LTM will be used in the optimisation of the individual departure time advice and on-route route guidance. For the time steps of the LTM and the optimisations, the following holds:

$$\Delta t_{LTM} \leq \Delta t_{RG} \leq \Delta t_{DEP} \tag{4-15}$$

The time step of the route guidance (Δt_{RG}) determines the size of the control interval. Every control interval, the LTM will compute the future traffic states, with time step Δt_{LTM}. This step size depends on the minimum link size in the network (Yperman, 2007). Likely, the time step of the LTM will be smaller than the control interval (route guidance optimisation time step): the duration of a control interval can be roughly one minute. The departure time advice will have a larger time step (Δt_{DEP}), since this is more convenient for the guided travellers requesting departure time advice.

4.4.2 On-route route guidance optimisation

After the traffic states have been predicted by the model, the controller will handle the requests for departure time advice and the individual route guidance. Before the mathematical definitions are presented, the optimisations are firstly explained in more detail.

At the core of the controller is the optimisation of the IRG towards the event location. The current and future traffic states are input in this optimisation. The optimisation will determine the split fraction of guided event-bound traffic at all decision nodes in the network for the current control interval.

The optimal split fractions are found by minimising the total travel time of all traffic in the network. This travel time is (linearly) dependent on the number of vehicles on a link, which is influenced by the controller's decision regarding the split fractions. The total travel time is then equal to the link travel times multiplied by the number of vehicles on a link. This makes the objective function quadratic. This means that the solution of the optimisation is not trivial: fixed travel times (not depending on vehicles on a link) would lead to an all-or-nothing assignment in the time dimension.

The optimisation of the split fractions is constrained by the following:

- Firstly, the relationship between the split fractions and the number of vehicles on a link at a certain time is defined. The number of vehicles on a link is the number of *guided* vehicles assigned to that link, plus the number of *unguided* event visitors choosing a route containing that link, plus vehicles that were already on that link in the previous time interval;
- Secondly, a constraint is added to ensure that the total of the split fractions at a decision node is equal to 1. This way, all the guided traffic is assigned to a path;

- Furthermore, an unfairness constraint is defined. This unfairness constraint limits the difference between the travel times of alternative paths originating at a decision node, to constrain the system optimal assignment.

The output of this optimisation is the split fraction at each decision node in the network and the number of vehicles induced by these split fractions on each link over time. These aggregated split fractions can be used to give individual travellers advice for their route choice at a decision point. If the split fraction at a certain node is e.g. 60% / 40%, then 60% of the guided individuals will receive advice to take the first route and 40% the advice to take the second route. Such a split fraction would be more difficult to achieve with the use of road-side advice systems, as the advice cannot be given individually.

The mathematical definition of the objective function and the constraints is introduced in this section. The used sets and variables for this optimisation are shown in Table 4.2.

Table 4.2: Overview of the sets and variables used in the optimisation of on-route route guidance

Sets	**Description**	**Unit**
V	Set of node indices, describing the nodes in the network	
A	Set of link indices, describing the links in the network	
P	Set of indices of all origins in the network. O is a subset of V	
P_n	Set of indices of all paths in the network from a certain decision node to the event location. P_n is a subset of P	
T	Set of simulation time step indices	
T_f	Set of all future time interval indices (including the current interval) that are considered by the controller. T_f is a subset of T, and is determined by the prediction horizon of the controller	
Indices		
t	A certain time interval	
n	A decision node in the network	
a	A link in the network	
p	A path between a node and the destination	
r	A certain path between a node and the destination, other than p	
Decision variable		
β_{np}	The dynamic fraction of guided vehicles that follows path p to the destination at decision node n at the current control interval. This value determines the individual advice that is given to the event visitors at the decision points in the network	
Other variables		
Δt	The amount of time between each time step of the controller and the IRG computations	[s]
x_a^t	The total number of vehicles on link a at time interval t. This is not the flow rate, but the link vehicle count (derived from the LTM)	[veh]
ψ_a^t	The predicted number of queueing vehicles on link a at time interval t. This is derived from the results of the LTM (as discussed before)	[veh]

ω_a^t	The predicted number of vehicles (from the LTM) on link a at time interval t. This includes the transition flows of that time interval. Again, this is expressed in a vehicle count, not in a flow rate.	[veh]
$T_a^t(x_a^t)$	The travel time on link a at time interval t, as a function of the number of vehicles on that link on that time	[s]
$\tau_{f,a}$	Free flow travel time on link a	[s]
α	Linear factor in the travel time function. Determines how heavily the travel time increases if a link is congested	
$q_{M,a}$	Maximum flow (capacity[2]) of link a	[veh/h]
L_a	Length of link a	[km]
$v_{f,a}$	Free flow speed of link a	[km/h]
c_a	Capacity of link a (in number of vehicles, not vehicle flows: k_{jam}*L from the LTM). This is assumed to be fixed over time.	[veh]
m_n	The predicted number of vehicles that reach decision node n in the current control interval. These are the transition flows at the diverge nodes from the LTM	[veh]
ε	The share of vehicles arriving at a decision node that requires guidance and complies to it. This value is between 0 and 1 and represents the penetration rate multiplied by the compliance rate (effective penetration rate). This variable ensures the distinction between guided and unguided traffic and reflects the compliance behaviour of guided drivers	
z_{npa}^t	Binary indicator. It indicates whether vehicles from decision node n that follow path p will be present on link a at (future) control interval t. This variable can be obtained from the LTM prediction model	
γ_{np}	The fixed split fraction of unguided and non-complying guided individuals, that follow path p from decision node n to the destination at the current control interval	
z'^{t}_{npa}	Binary indicator. It indicates whether the vehicles from decision node n will enter link a at control interval t. This value is also obtained from the predictions of the LTM	
H_n	Maximum travel time difference between two paths to the destination for guided travellers passing node n	[s]
u_{np}	Binary variable, indicating whether a compared path p is (un)used by traffic from node n. This softens the unfairness constraint	[s]

Objective function for IRG optimisation

The objective of the controller is to induce a (constrained) system optimum in the network by influencing the route choice of the event visitors. The objective function optimises the total travel time of all travellers in the network: this is the travel time of each link times the predicted number of vehicles on that link.

$$\min_{\beta_{np}} \sum_{t\in T_f} \sum_{a\in A} T_a^t(x_a^t) * x_a^t \tag{4-16}$$

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[2] Extended applications could also use a dynamic capacity, e.g. a simulation of an incident at a large-scale event

The total travel time, defined as the sum of the predicted link travel times on links a T_a^t, is multiplied by the predicted number of vehicles on that link at time t, x_a^t. The link travel time T_a^t is a function of x_a^t. This function resembles the working of the LTM as much as possible, to make sure that the optimisation and the predictions from the LTM are in line. For both the route guidance optimisation and the departure time optimisation, the travel time function is set up conditionally: if there are no queueing vehicles on a link (or path), the travel time of that link will be the free flow travel time. If there are queues, the travel time will increase, depending on the number of vehicles that are on the link. This is reflected in the function below.

$$if\ \psi_a^t = 0:\ T_a^t(x_a^t) = \tau_{f,a},\ \forall\, a \in A; t \in T_f \qquad (4\text{-}17)$$

$$else: \qquad T_a^t(x_a^t) = \tau_{f,a} * \left(1 + \alpha * \frac{x_a^t}{q_{m,a} * (L_a/v_{f,a})}\right),\ \forall\, a \in A; t \in T_f \qquad (4\text{-}18)$$

If the queues on link a at time t (ψ_a^t) are zero, then the travel time on that link will be the free flow time of that link ($T_{f,a}$). If there are queues, this travel time is increased with a linear factor (α) times the number of vehicles on the link (x_a^t) divided by the link capacity $q_{M,a}$ times the free flow time ($L_a/v_{f,a}$). Hence, two states are defined (free flow and congested), in which the travel time is defined differently.

Constraints for route guidance

The mathematical definition of the constraints is as follows.

1. Definition of relationship between split fractions and number of vehicles on a link. This relation is dependent on time. The number of vehicles on link a, at any time t in the future, is defined as the number of guided vehicles from decision node n present at that link at time t, plus the number of unguided vehicles from node n present at time t on link a. This is summed with the predicted number of vehicles that were already present on that link in the time interval before t. This is defined in the following expression:

   $$x_a^t = \sum_{n \in V} \sum_{p \in P_n} \left[\varepsilon * m_n * \beta_{np} * z_{npa}^t + (1-\varepsilon) * m_n * \gamma_{np} * z_{npa}^t\right] + \omega_a^{t-1},\ \forall\, a \in A;\ t \in T_f \qquad (4\text{-}19)$$

   The (future) number of vehicles on a link (x_a^t) is defined as the total number of *guided* vehicles that is assigned to it, namely the split fraction at node n for path p (β_{np}) times the transition flow at node n (m_n) times the penetration rate of the advice (ε) times the indicator z_{npa}^t, which describes at what time t the guided vehicles from node n using path p will be present on link a. This is added to the number of *unguided vehicles*, $(1 - \varepsilon) * m_n$, using that link in their chosen path (defined by fixed split fraction γ_{np}) at time t, which is indicated by z_{npa}^t again. This number is added to the predicted number of vehicles that is already on link a in the time interval before these vehicles arrive (ω_a^{t-1}). This value of ω follows from equation 4-11.

   The z-indicator is defined using the travel time outputs of the LTM. z_{npa}^t is equal to 1, if:

   - Path p crosses decision node n;
   - Link a is part of that particular path p between n and the destination;
   - Traffic passing decision node n at the current time interval will be present on link a at future time interval t;
     - This can be derived from the predicted instantaneous travel times that were found in the predictions of the LTM (see equation 4-13). It can be determined

how many time intervals it will take for the travellers to drive from the decision node n to link a via path p.

z'^{t}_{npa} is very similar to z^{t}_{npa}. The latter indicates the time steps at which vehicles will be *present* on a link. z'^{t}_{npa} will indicate when (at what t) vehicles from a decision node n will *enter* link a when they follow path p. Hence, z'^{t}_{npa} is only equal to 1 at one instance of t for a certain link. z^{t}_{npa} could be equal to 1 at more time instances for a certain link, depending on the link travel time. In Figure 4.8, an example of how the z-indicators may differ is shown.

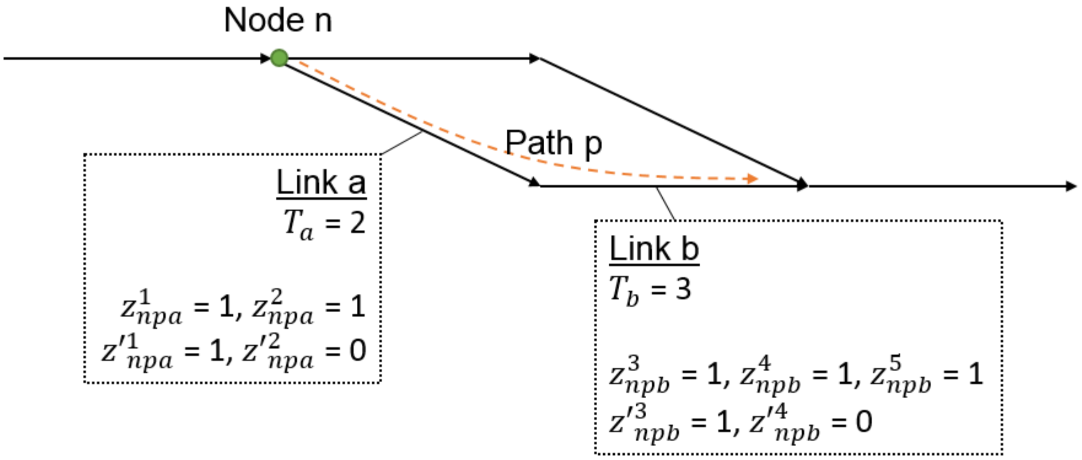

Figure 4.8: Example of the definition of z-indicators. z indicates the time that a vehicle is present on a link in the future, while z' indicates when a vehicle will enter a link in the future

Note that in reality, the z-indicator is dependent on the travel times of the different links: such a dependency would make this constraint non-linear, which is undesired. The LTM is also capable of estimating the value of this binary indicator (as discussed before). This leads however to less accurate and optimal guidance, as the value of the z-indicator might change (in reality) if a certain split fraction would be realised.

2. All vehicles at the decision node should be assigned to a path p, by constraining the sum of all split fractions β_{np} at a node n to be equal to 1.

$$\sum_{p \in P_n} \beta_{np} = 1, \ \forall\, n \in V \qquad (4\text{-}20)$$

3. Constraint to limit unfairness between route advice for individuals. The unfairness between two alternative paths originating at a decision node is defined as the travel time difference between these two routes. For all combinations of alternative routes at all decision nodes, the unfairness must be below a certain threshold to satisfy this constraint:

$$\left| \sum_{t \in T_f} \sum_{a \in A} T^t_a(x^t_a) * z'^t_{npa} - \sum_{t \in T_f} \sum_{a \in A} T^t_a(x^t_a) * z'^t_{nra} \right| \leq H_n + (1 - u_{np}) * 10000 + (1 - u_{nr}) * 10000, \ \forall\, n \in V;\ p, r \in P_n\ (p \neq r) \qquad (4\text{-}21)$$

$$if\ \beta_{np} = 0: \quad u_{np} = 0, \ \forall\, n \in V;\ p \in P_n \qquad (4\text{-}22)$$

$$else: \quad u_{np} = 1, \ \forall\, n \in V;\ p \in P_n \qquad (4\text{-}23)$$

The unfairness between two alternative routes p and r from decision node n is computed as the absolute difference between the sum of the instantaneous travel times T_a^t on all arcs on the route (p or r) at time t, which is indicated by z'^{t}_{nra}. This travel time is a function of the number of vehicles on the link (x_a^t). This travel time difference between the routes may not exceed the threshold H_n. This unfairness threshold may differ per decision node, depending on the distance between the decision node and the destination. A larger distance (or free flow travel time) would allow for a larger threshold value, as travellers will accept large travel time differences between routes then.

The dummy variables u_{np} and u_{nr} are responsible for maintaining the optimisation feasible: if any route would be unused by guided traffic from a split fraction, the unfairness constraint is relaxed. If the controller doesn't use a certain route to the event location from a certain decision node (split fraction for that path is equal to zero), the u-variable will be zero as well. The comparison of travel times will then always fulfil the relaxed constraint.

4. Lastly, constraints are needed to define the decision variables. The number of vehicles on a link a at time t (x_a^t) must always be non-negative, while the split fractions β_{np} should be a number between 0 and 1.

$$x_a^t \geq 0, \ \forall\, a \in A;\ t \in T \tag{4-24}$$

$$\beta_{np} \in [0{,}1], \ \forall\, n \in V; p \in P \tag{4-25}$$

4.4.3 Departure time advice optimisation

In this section, the optimisation of departure time advice is discussed. Similarly to the route guidance, the reasoning behind the objective function and the constraints is discussed, after which the mathematical formulation is presented.

At some control intervals (at which departure time advice is given), the ITM controller will collect departure time advice requests from individuals. These individuals will communicate their *preferred* departure time to the centralised controller. They might want to depart during the current control interval, but it is also possible that they prefer to depart in a future control interval (e.g. in half an hour). The goal of the controller is to optimise the total travel time of the traffic in the network (system optimum). This goal can be achieved by giving individuals advice about their departure time: the controller can give the advice to event visitors to *shift* their departure time from their preferred interval to another interval, in order to optimise the travel times. The departure time of individuals can be shifted to a future interval and, if possible, to an earlier interval than the preferred departure time interval. This is only possible if the preferred departure time interval is later than the current time interval.

The total travel time of travellers includes the shift time that individuals experience: this is the time difference between their preferred departure time interval and their advised departure time interval. This difference causes some discomfort for the shifted travellers, as they will have to adapt their plans by waiting until they may depart or by departing earlier than they were expecting initially.

The objective function will therefore firstly consist of a non-linear part, where the *path* travel times (as a function of the number of vehicles on a *path*) will be multiplied by the number of vehicles departing on that path. Secondly, the linear part of the travel time function will describe the shift time of the guided travellers.

The departure time optimisation is constrained by the following:

- Firstly, a definition is needed that describes the relationship between the number of vehicles assigned to a departure time interval and the actual number of departures in that time interval. The actual number of departures on a path at a certain time interval is the number of uninfluenced departures of event visitors, plus the sum of all the individuals that have been assigned from their preferred departure interval to the departure time interval in question;
- Secondly, a constraint is needed to ensure that all the departure time requests of individuals are served, whether they are shifted from their preferred departure time interval to another interval or not;
- Next, a constraint must assure that shifted individuals will not arrive too late at the event. The departure time plus the travel time of the advised individuals may not be later than the event start time. It is assumed that all requests are received on time, so that visitors will not be late because they departed too late anyway;
- Furthermore, the shift time should be restricted as well. The departure time of individuals may not deviate too much from their preferred departure time, as a too large shifting discomfort could cause a reduction in compliance to the advice;
- To achieve a *constrained* system optimum, a constraint is added to limit the unfairness between two departure time alternatives. This unfairness is defined as the difference between the travel times, plus the shift time that is the result of choosing for a certain departure time interval. All the *used* departure time intervals are compared, checking if the difference between these intervals is not too high.

Using optimisation software (CPLEX), the optimal value for the decision variables – the departure time assignment – is calculated. The shifted departure times of individuals is processed into the actual departure time profile: this is the base departure time profile, plus some adaptations caused by the shifting of the preferred departure time advice of some individuals.

Now, the mathematical definition of the objective function and the constraints will follow.

Table 4.3 shows what variables and sets will be used for the optimisation of departure time advice.

Table 4.3: Overview of the sets and variables used in the optimisation of departure time shifts

Sets	Description	Unit
V	Set of node indices, describing the nodes in the network	
A	Set of link indices, describing the links in the network	
O	Set of indices of all origins in the network. O is a subset of V	
P	Set of indices of all paths from the origins to the event location in the network	
P_i	Set of indices of all paths from origin i to the event location. P_i is a subset of P	
T	Set of simulation time step indices	

T_f	Set of all future time interval indices (including the current interval) that are considered by the controller. T_f is a subset of T, and is determined by the prediction horizon of the controller	
Indices		
τ	The time interval from which the departure time advice requests are shifted (this is the preferred departure time interval of a request)	
t, θ	A certain time interval to which individuals' departure times are shifted. This can be the same value as the preferred departure time interval, meaning that individuals receive the advice to depart at their preferred departure time	
k_{dep}	Control interval, in which departure time advice is given to individuals	
i	An origin node in the network	
p	A path from an origin to the event location in the network	
Decision variable		
$q_p^{\tau t}$	The number of vehicles using path p, with preferred departure time interval τ, that are assigned to departure time interval t	[veh]
Other variables		
$T_p^t(x_p^t)$	The instantaneous travel time on path p to the destination at departure time t, as a function of the number of vehicles assigned to depart at that time interval	[s]
x_p^t	The number of vehicles using path p from the origin to the destination departing at time interval t	[veh]
$\tau_{f,p}$	Free flow travel time on path p to the destination. This is the sum of the free flow travel time of all links on the path p	[s]
c_p	Maximum occupancy of path p to the destination, expressed in the maximum number of vehicles on a path (jam density * length). For all the links on a path, the minimum value is chosen as an aggregate value for the whole path	[veh]
ψ_p^t	The predicted *total* number of queueing vehicles on path p, at time interval t. This is derived from the LTM (as discussed before): the queues on all links on path p at time t are summed to obtain this value	[veh]
δ_p	Penalty factor of assigning vehicles to path p, which has queues on it. The penalty is then related to the travel time: the value of δ_p can depend on the link free flow travel time, for instance. This value is the sum of al link δ's on path p	[s]
Δt	The amount of time between each departure time interval. *Important: the time step for the departure time optimisation is larger than the time step of the LTM and the route guidance optimisation*	[s]
R_p^τ	The number of departure time advice requests that are received for preferred departure time interval τ and path p. At an origin, the requests are received and distributed over the paths p using fixed split fractions	[veh]
M	The maximum arrival time interval of the event visitors. The event starts at this time, advised visitors are not allowed to arrive later due to the actions of the departure time advice optimisation	

$a^{\tau t}$	Dummy variable for the maximum shifting time constraint	[veh]
φ	Weight factor for the shifting time. This factor reflects the discomfort of the shifting time for the event visitors (relative to in-vehicle travel time)	
B	Maximum shifting time for the guided travellers	[s]
H_p	Maximum travel time difference between two departure times for travellers using path p. For paths from the same origin, this threshold is equal	[s]
u_p^t	Binary variable, indicating whether a departure time slot is (un)used by traffic on path p. This softens the unfairness constraint (further defined in constraints)	[s]
$D_i^t(k_{dep})$	The fixed number of departures from origin i at a time interval t, as defined in all control intervals until k_{dep} (describing the current departure time control interval). This value is the result of the optimised departure time shifts of the previous control intervals and is input into the traffic process	[veh]

Objective function for departure time shift optimisation

The objective of the departure time optimisation is to minimise the total travel costs (travel time plus weighted shifting time) of the event visitors that request advice.

$$\min_{q_p^{\tau t}} \sum_{t \in T_f} \sum_{p \in P} \left\{ \left[T_p^t\left(x_p^t\right) + \delta_p * \frac{\psi_p^t}{c_p} \right] * x_p^t + \sum_{\tau \in T_f} \varphi * |t - \tau| * \Delta t * q_p^{\tau t} \right\} \quad (4\text{-}26)$$

The path travel time T_p^t at time t is multiplied by the total number of departures x_p^t, as well as the time penalty δ_p that is given for the relative fullness of the link (ψ_p^t/c_p). The predicted value of the queues on a path on a certain departure time (ψ_p^t) is derived directly from the predictions of the LTM (equation 4-12).

The travel time function of a path ($T_p^t(x_p^t)$) is linear. It is the same as the travel time function for route guidance optimisation (equation 4-16), but the link properties are aggregated into path-based values. This aggregated, path-based travel time function also explains why the penalty for assigning traffic to time intervals with queues is necessary: the step of aggregating the (dynamic) link properties into path-based properties can lead to some inaccuracy. Therefore, in the objective function an expression is added to penalise the shift of individuals to time intervals in which the queues in the network are threatening to spill back to main roads. This ensures that the inaccuracies caused by the aggregation of link values does not lead to counteractive actions of the controller. A downside of this penalty expression is that the controller could tend to optimise the queues in the network by the departure times, and not the travel times. Hence, a balance must be sought in the objective function. Furthermore, the route guidance can correct slight errors in the departure time advice by optimising the total travel time as well.

The shift time between the preferred departure time τ and assigned departure time t, $|t - \tau| * \Delta t$ is summed for all assignments $q_p^{\tau t}$. The weight factor φ determines the relative discomfort experienced by travellers that have to shift their departure time. The value of φ will be equal for shifts to earlier or future control intervals than the request interval: this assumption can be debated. Especially when visitors would arrive *too* late at the event, they are likely to perceive shifts to future time intervals as very undesired. A constraint will be formulated to prevent these late arrivals of guided individuals.

Constraints for departure times

The mathematical definition of the constraints is as follows.

1. The number of departures for a path at a certain time interval are expressed in a definition. Firstly, this is the sum of all departure time shifts from the preferred departure intervals to the certain time interval that is being evaluated. Secondly, this number of departures contains the departures that *cannot* be influenced by the controller. These are unguided travellers or travellers that have already received their departure time shift advice in an earlier control interval.

   $$x_p^t = \sum\nolimits_{\tau \in T_f} q_p^{\tau t} + D_p^t(k_{dep}),\ \forall\, p \in P; t \in T_f \qquad (4\text{-}27)$$

   In this function, x_p^t is the actual number of departures (in vehicles) for path p at time interval t. For all preferred departure time intervals τ, the assignments from the preferred intervals to interval t are summed (for path p). These assignments – by shifting departure times – are defined in the variable $q_p^{\tau t}$. This is added up to the fixed number of departures at time t for path p (D_p^t). These fixed departures cannot be influenced in the current control interval (anymore). Firstly, D_p^t contains all event-bound traffic that does not use individual guidance by the controller. However, these still influence the travel times on the routes and should be taken into account by the optimisation. Secondly, D_p^t contains all previous requests from previous control intervals until the current one (k_{dep}), that were shifted to departure time interval t.

2. The following constraint means that all requests from the preferred departure time intervals are assigned to a departure time, whether it is the preferred time interval or another departure time.

   $$\sum\nolimits_{t \in T_f} q_p^{\tau t} = R_p^\tau,\ \forall\, p \in P;\ \tau \in T_f \qquad (4\text{-}28)$$

   The sum of the requests $q_p^{\tau t}$ for the preferred interval τ being assigned to any departure time interval t (including the current one) must be equal to the requests R_p^τ for preferred departure time τ for a certain path p.

   It is important to note that the individuals requesting departure time advice are unique. Once they have been advised (assigned to a certain departure time interval), they will not receive renewed advice, being shifted again. The advices that were given in previous control intervals are collected in the variable D_p^t.

3. To ensure that guided travellers will arrive on time, a constraint is added to the optimisation. A maximum arrival time interval is defined: a departure time (interval) plus the travel time for that departure time interval should be lower than or equal to the maximum arrival time at the destination (the event venue). This constraint only is necessary if a path and a departure time interval is used by *guided* individuals. Unguided individuals cannot be influenced (whether they will arrive on time or not). The constraint does not need to be satisfied for these unguided travellers.

$$\frac{T_p^t(x_p^t)}{\Delta t} + t \leq M + \left(1 - u_p^t\right) * 10000, \ \forall \, p \in P; t \in T \tag{4-29}$$

$$if \sum\nolimits_{\tau \in T_f} q_p^{\tau t} = 0{:} \ u_p^t = 0, \ \forall \, p \in P; \ t \in T \tag{4-30}$$

$$else{:} \qquad\qquad u_p^t = 1, \ \forall \, p \in P; \ t \in T \tag{4-31}$$

The instantaneous travel time T_p^t over path p - at time t - divided by the time step Δt. is equal to the number of intervals that it takes to get from origin to destination. This is added up to the departure time interval index t. These together should not exceed the maximum arrival time index M, to ensure that all travellers arrive on time. This constraint is relaxed if the used-indicator u_p^t is zero, meaning that the path and/or time interval is not used by assigned traffic.

4. The shift time of guided individuals is constrained to a maximum. If the shift time exceeds a fixed maximum shift time, the constraint will allow no shifts from the preferred departure time interval to the time interval in question.

$$q_p^{\tau t} \leq a^{\tau t}, \ \forall \, p \in P; \ \tau, t \in T \tag{4-32}$$

$$if{:} \ -B \leq (t - \tau) * \Delta t \ \leq B, \ a^{\tau t} = \infty, \ \forall \, \tau, t \in T \tag{4-33}$$

$$else{:} \qquad\qquad a^{\tau t} = 0, \ \forall \, \tau, t \in T \tag{4-34}$$

To define dummy variable $a^{\tau t}$, the shift time (t – τ)*Δt is compared to the maximum shift time B. If the shift time exceeds B, $a^{\tau t}$ becomes zero and the assignments $q_p^{\tau t}$ from τ to t are prohibited by the constraint.

5. Constraint for maximum unfairness between departure time assignment alternatives t and θ. For both alternatives, the costs are defined as the instantaneous travel time at the departure time interval plus the shift time of that assignment interval. The (absolute) difference between the costs of both alternatives must not exceed an *unfairness threshold*. If any of the departure time interval alternatives are not used, the constraint must be relaxed to make sure that the optimisation is still feasible.

$$\left|\left[T_p^t\left(x_p^t\right) + \varphi * |t - \tau| * \Delta t\right] - \left[T_p^\theta\left(x_p^\theta\right) + \varphi * |\theta - \tau| * \Delta t\right]\right| \leq H_p + \left(1 - u_p^t\right) * 10000 + \left(1 - u_p^\theta\right) * 10000, \ \forall \, p \in P_i; \ i \in O; \tau, t, \theta \in T_f \ (t \neq \theta) \tag{4-35}$$

The instantaneous travel times of both alternatives (T_p^t or T_p^θ) are a function of the number of departing vehicles at the specific time interval. The (experienced) shift time of departure time interval is defined as φ*(t-τ)*Δt (or φ*(θ-τ)*Δt). H_p is the threshold for the unfairness between the alternatives, which may not be exceeded. Note that the unfairness threshold differs per origin. The threshold is larger for longer trips, and smaller for shorter trips.

If any of the departure time interval alternatives are not used, u_p^t and/or u_p^θ will relax this constraint to avoid infeasibility of the optimisation.

6. Non-negativity constraint for the decision variables. Negative assignments of flows to departure times is not possible. Departures, for all times and paths, are non-negative as well.

$$q_p^{\tau t} \geq 0, \ \forall \, p \in P; \ \tau, t \in T \tag{4-36}$$

$$x_p^t \geq 0, \ \forall\, p \in P;\ t \in T \qquad (4\text{-}37)$$

Update of departure time profile

The resulting departure time shifts lead to changes in the departure profile of the event-bound travellers. The number of departures for each origin is updated every control time step, in which the departure time advice is given (k_{dep}). This is done after the individual departure time shift advice has been computed. The actual number of departures for all future departure time intervals t is then equal to the number of departures that has been found in this current control interval (x_p^t). The next control interval at which departure time advice is given (k_{dep}+1), these departures cannot be influenced again and they will be incorporated in the value of D_p^t. This value is input into constraint 1 (see equation 4-27).

$$D_i^t\left(k_{dep} + 1\right) = \sum\nolimits_{p \in P_i} x_p^t\,, \ \forall\, i \in O;\ t \in T \qquad (4\text{-}38)$$

The assumptions and simplifications behind this optimisation model are discussed in more detail in the next section.

4.5 Discussion

In this section, the designed controller is reviewed critically. The advantages and disadvantages of the overall controller design are identified. For both the route and departure time optimisation components, the assumptions, limitations and simplifications are discussed in more detail.

General remarks

The expected benefits of the designed ITM controller with respect to other route guidance systems are as follows:

- In contrary to current navigation service providers, the ITM control signal is operated from the point of view of the road authorities. This enables a shift of the controller objective from inducing a user equilibrium towards a (time-dependent) constrained system optimum. This means that overall, the travellers in the network will benefit from the designed control approach in terms of travel time delay, while not experiencing an unfair distribution of travel times on the individual level. This way, the queues that are threatening to spill back to main roads are being counteracted as much as possible in the optimisations.
- The ITM controller is able to steer drivers individually: drivers from the same decision node departing at the same time can receive different route advice, in order to enhance the traffic performance on the network level. In comparison, the aggregate approach of road-side systems gives limited flexibility in guiding traffic on a detailed level.
- The designed ITM controller has predictive capabilities, meaning that the advice given to the event visitors is more accurate than advice based on instantaneous travel times (current traffic states only). This enhancement in guidance accuracy will likely lead to better traffic performance on the network level, since the spillback of queues at the event to the motorways can be anticipated and counteracted appropriately.
- An important feature of the controller design is the ability to give pre-trip departure time advice. Shifting the departure times of users is expected to have a significant positive effect on the traffic conditions (queues and spillback) in the network.
- The controller design is flexible: the optimisations can be applied to any event network and can even be adapted slightly to fit specific situations.

Of course, the design has disadvantages as well. The disadvantages and possible limitations of the ITM controller design are as follows:

- Although the controller has some predictive capabilities, the interaction between the optimised control signal and the future traffic states is not modelled: no iterative procedure is followed. The departure time advice and the route guidance also has no interactive procedure to account for the interdependencies between these aspects of the controller. Therefore, the advice will not be fully accurate: there are however many other disturbances that will have a significant effect on the controller performance as well. For instance, the current state feedback is assumed to be accurate, while the data sources for this state feedback might not be that accurate in practice.

  Note that this also means that the route guidance and departure time advice given by the controller might not always be synchronised. For instance, a certain path might have received departure time shift advices, while in the route guidance the traffic is deviated from that path to another path. Therefore, the actions of the controller might have minor contradictory effects, or a double effect is achieved because an individual might be shifted in both the time and route dimension.

- The controller will assign the event visitors to a pre-determined route choice set, according to the benefits of a certain route in a choice set. Pre-determining the route choice set has the great advantage that no shortest path algorithms are required for the ITM controller. However, the given choice set might leave out route alternatives that might be used (or desired) by the travellers. The choice set must be defined carefully in practice, as not all routes might be available at the time of the event (e.g. due to road works) or are not even allowed by local authorities (e.g. due to safety or policy reasons).
- Furthermore, the control design assumes that the route guidance and departure time advice requests from the event visitors are received at the discrete control intervals. In reality, these requests will come at any random time and not strictly every minute or every five minutes. An assumption has also been made on the interaction between the users and the ITM controller: the controller’s success depends strongly on the willingness of users to share their preferred departure time and whether they will check for route advice updates during their trips.
- The controller does not take the actions of other DTM measures into account in the optimisation of the control signal. These other measures influence the traffic states as well. This lack of integration might also be a reason why the controller will not have the optimal solution in reality.

Note that there might be also other solutions possible to achieve constrained system optimal advice. In the ITM controller design, both the optimal route guidance and departure time advice is computed through a mathematical optimisation. However, other solution directions might be possible as well to compute the optimal route guidance and departure time advice. This might reduce the complexity of the controller and computation time of the optimisations in (very) large networks. The contribution of Wang et al. (2003) is an example of how another solution direction (predictive feedback controller) could be used to determine the route advice. Possibly, this can also be done for departure time advice.

LTM use in the controller design

The LTM is powerful in the modelling of the traffic propagation in the network and the dynamics of queues, which is important for the working of the ITM controller design at large-scale events. However, the use of the LTM – as proposed in this chapter – has some limitations with regard to the application of the controller in practice. This is mainly because of the simplified representation of the network that the chosen version of the LTM uses: the number of possible link lengths and node layouts are limited to keep the prediction model simple and fast. A solution could be to extend the node model, so that more complex intersection dynamics can be represented in the model as well.

Route guidance optimisation

The following simplifications were applied in the route guidance optimisation:

- The path-link incidence indicators z and z' are assumed to be fixed during a control interval, in order to maintain the linearity of the constraints. In reality, this indicator is dependent on the travel times and thus, also on the on-route assignment via the IRG. The dependency between these variables can be established, but then the controller would need to make more complex calculations, inherently taking more time to do so.
- It is assumed that unguided vehicles and the individuals that do not comply to the given advice follow a fixed route fraction through the network from their origin to the destination. This split fraction is assumed to be the same for these groups. In reality, the non-complying individuals might follow a different split fraction than the guided vehicles, as they do receive traffic information and would possibly follow the advised route *partially*. These split fractions can also vary over time, but in the optimisation they are assumed to be fixed.
- The optimisation of the route guidance doesn’t contain a capacity constraint. The reason for this is to prevent infeasibility of the optimisation problem: especially for this specific problem statement, where the inflow into a bottleneck exceeds the capacity (causing congestion spillback), a capacity constraint is not suitable because capacity excess is part of the defined problem.

Further extensions of this optimisation would entail the definition of additional dependencies between different variables, making the constraints non-linear. The relation between the assigned vehicles, travel times and queues could also be represented in a more sophisticated manner, to improve the accuracy of this optimisation.

Departure time advice optimisation

The presented departure time optimisation method can be used to shift the departure time of individuals requesting (route and departure time) advice. There are a number of assumptions and simplifications behind this optimisation, that influence its accuracy and efficiency.

- The model allows for only one departure time shift per individual. Once an individual is shifted, it is added to the demand of the time interval it is shifted to. Individuals cannot be re-shifted, although this might be beneficial for the traffic performance in the network. However, it is less likely that travellers will comply to the departure time advice if it would be constantly changing: the control signal will lose credibility.
- Furthermore, the travel times that are used for the optimal assignment are calculated per path. The choice of travellers for the different routes is not taken into account, as a fixed assumed split fraction at the origins is used. This simplification is made because the route

fractions of the travellers are not known yet. It is expected that subtle control actions for both route guidance and departure time advice can eventually lead to an equilibrium in the network. The fact that the optimisation is path-based, means that some link-based properties must be aggregated into path-based properties (e.g. in the travel time function). This can however lead to a slightly inaccurate representation of the real traffic dynamics in the optimisation model.

- Another property of this optimisation is that there is no capacity constraint for the assignments of individuals to departure time intervals. Similar to the route guidance, the reason for this is the chance that infeasibility occurs: the capacity constraint will constrain the optimisation too much, possibly leading to a situation where no solution can be found. In the travel time function and the penalty for assigning individuals to departure time intervals with queues, a penalty for exceeding the capacity is already incorporated in the optimisation in some manner.
- Finally, a disadvantage of this optimisation could be that the guided travellers are shifted too much to future intervals, shifting the ‘problems’ with the departure time assignment onward.

Right now, quite some assumptions and simplifications were made to give departure time advice to the event visitors to counteract spillback. Further improvement of this optimisation can be made with regard to the dependency of the travel time on the assigned traffic and the use of fixed split fractions for the definition of the number of requests per path. Integration between route guidance and departure time optimisation would be interesting to increase the accuracy of the optimisations.

The mentioned extensions for both the route guidance and the departure time advice are possible research directions for future developments of the ITM controller.

4.6 Conclusion

In this chapter, the requirements for the design of an ITM controller for large-scale events have been defined, after which the controller design was presented. Figure 4.9 shows the conceptual working of the designed ITM controller and the interaction between the optimised control signal and the actual traffic process:

- The controller is started some time before the beginning of the event;
- It measures the real-time traffic conditions on the links in the network (cumulative counts);
- Based on these counts, the network properties and the expected demand, the LTM makes a prediction of future traffic states (for a certain prediction horizon). The LTM uses shockwave theory and information about the network and the demand scenario to compute the future development of the traffic conditions in the network;
- If route guidance must be given in the current time interval, the controller will optimise the individual advice (split fractions at decision nodes in the network) based on the predicted traffic states;
- If departure time advice must be given in the current time interval, the controller will optimise the individual advice (departure time shifts) based on predicted traffic states;
- The results of the optimisations are communicated to the travellers, which may then adapt their choice behaviour due to the individualised advice;
- The adaptation of the travellers behaviour (including possible disturbances as compliance or actual traffic demand levels) is taken into account in the update of the traffic states in the network;

- The Key Performance Indicators (KPIs) of the traffic conditions and the controller's actions are saved every time step, to enable the analysis of the working of the ITM controller and its effects on the traffic performance around events;
- This procedure repeats every control interval, until the start of the event. The controller ceases its operations when no event-bound traffic is left in the network.

In a simulation environment, the propagation of traffic in the network can be modelled with the LTM (applied for one time step): the real-time traffic states can then easily be retrieved by the controller from the simulation process. In reality, the traffic process will simply react to the advice that is given to individuals: this individual advice is based on the macroscopic outputs of the controller. The traffic states must then be retrieved from traffic data sources as loop detectors or floating car data.

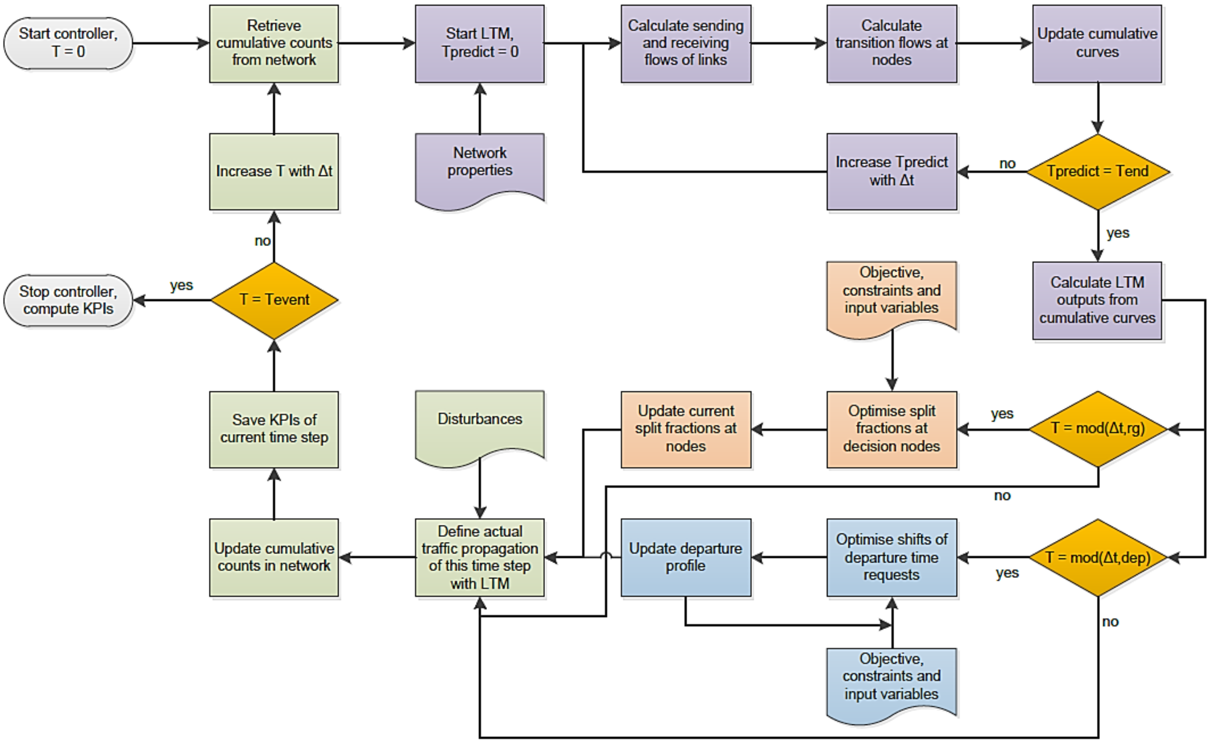

Figure 4.9: Flowchart of ITM controller actions and interaction with the traffic process at an event

This concludes the (mathematical) design of the ITM controller for large-scale events. In the next chapter, the design is simulated and evaluated: this will indicate whether the designed controller is able to reduce the delays in a network around an event venue and under what circumstances the controller design is suitable to achieve such benefits. The results of the simulations will also be used to find out what improvements and extensions are necessary to increase the potential effects of ITM in practice.

5 Simulations

In this chapter, the simulation phase of this Master thesis research is presented. Firstly, the setup of the simulations is described. Afterwards, the results of the simulations of the controller are presented and discussed, in order to evaluate the effects of the ITM controller design on traffic in a virtual network.

5.1 Introduction

The design of ITM for large-scale events will be evaluated using simulations. The main purpose of the simulations is to determine whether the controller design is behaving as expected. With this information, some input variables of the controller can be tuned as well. Another goal of the simulation is to identify and analyse the effects of the ITM controller design on traffic in a virtual network: the simulations are used to evaluate to what extent the ITM controller is able to reduce the total delay in the network by preventing spillback from bottlenecks at an event venue. The effects of the ITM controller on traffic will be compared to reference situations or scenarios. Furthermore, the (input) factors that influence the effectiveness of the controller will be analysed: this way, the sensitivity of the controller's performance to the various assumptions in the design and the simulation scenario setup is assessed.

For the simulations, the mathematical formulation of the controller is used, composed of the traffic flow prediction model and the optimisation. The optimisation of the control signal in MATLAB (the simulation environment) will be done with a CPLEX (optimisation software) plugin of MATLAB. The advantage of MATLAB as a simulation environment is that there is quite some flexibility for the simulation possibilities, including the possibility to incorporate optimisation problems in the script.

5.2 Simulation setup

In this paragraph, the setup of the simulations is described. Firstly, the networks are presented, in which the controller will be evaluated. Secondly, the input scenarios will be discussed. Finally, the method for evaluating the sensitivity of the controller to its inputs is described.

5.2.1 Studied networks

The working of the controller is tested in synthetic networks. The goal of the simulations in the synthetic networks is to evaluate the basic working of the ITM controller design. The synthetic networks are simple, and the demand scenario leads to some traffic issues (spillback) at the large-scale event. The simulations of the controller in these networks will therefore indicate whether the controller design is effective in reducing total delay in the network and if it has potential to work in other networks as well. Three synthetic networks have been designed:

- A network with two alternative routes to the event, where only route guidance will take place. One route is partially used by background traffic, which shouldn't encounter too much congestion caused by the event. In this case, the event visitors will only receive route guidance. The departure profile of the traffic is fixed.
- Secondly, a very simple network is created, with only one route from the origin to the event location. In this network, the event visitors receive departure time advice. This is the only way for the controller to achieve a better traffic performance in the network, as there are no route alternatives.
- Finally, a network is designed where both route guidance and departure time advice may be used to counteract the spillback from the event bottleneck to the main road. The results

of this simulation may be used to check the interaction between the route advice and the departure time shifts.

The networks are defined with unidirectional links. Since the LTM is used (the version as formulated in the design chapter), the nodes will not have more than three incoming and outgoing links in total. There is one origin in the network and two destinations. One of these destinations is the event location, the other is for the through traffic. The other destination will have one route between the origin and the destination, to simulate the background (through) traffic. This through traffic should be affected by the event-bound traffic in a minimal way.

The layout of the synthetic networks is depicted in Figure 5.1.

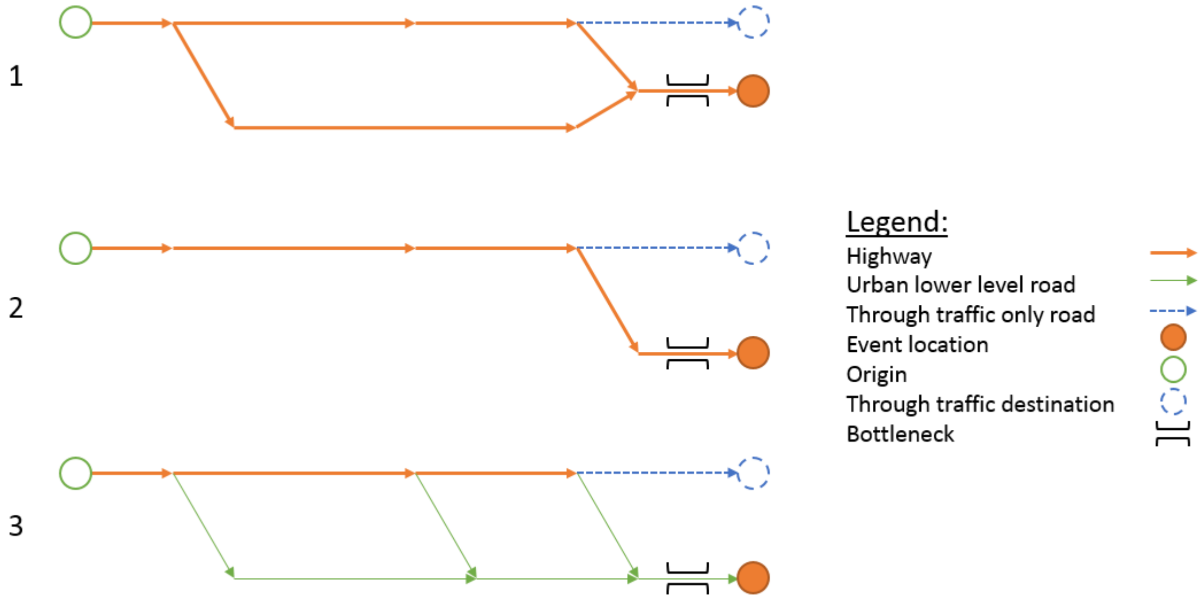

Figure 5.1: Synthetic networks used in the simulation phase. (1) Route guidance only; (2) Departure time advice only; (3) Integrated individual traffic management

Preferably, the simulated network has some resemblance with the road network at an actual event location in the Netherlands. This enables a better comparison between the results of the theoretical simulation, and any (future) observations of traffic and ITM at events in practice. Therefore, the area around the *Amsterdam Arena* (recently renamed to *Johan Cruijff Arena*) is chosen as the event location that will be represented in the case study simulation network. These simulations are performed in addition to the simulation of the synthetic networks. Close to the Arena, there are also other event venues like the *Ziggo Dome* and *AFAS Live*: these venues host concerts with a significant number of visitors as well. The following reasons are behind the choice for this event venue as case study.

- Many events are hosted in this area, meaning that there are quite some situations to refer to. A future practical application of ITM at the Arena could be compared to the simulations.
- As observed in a qualitative analysis, the off-ramps, traffic lights and parking facilities cause queues and spillback to the motorways surrounding the Arena before an event. Thus, the defined problem of traffic at large-scale events can be observed here.
- The venues are close to Amsterdam and motorways of national importance, which means that there is quite some through traffic during an event. For this through traffic, the hindrance should be reduced as much as possible.

- There are many approach routes for the venues, meaning that there are detour possibilities as well. This gives opportunities to ITM to improve the overall traffic performance.

A minor disadvantage of the Arena (and surroundings) as the chosen event location is that visitors might be fairly familiar with the route alternatives, as some events hosted there are recurrent (e.g. football matches). Therefore, a situation with a large concert should be simulated, meaning that less visitors will be familiar with the network and the traffic dynamics.

The network that is used in the simulations is shown in Figure 5.2. The network covers Amsterdam (the ring road) and the Arena and its surroundings. The idea of the Arena-network and the synthetic networks is similar: bottlenecks on urban roads close to the event location can lead to queue spillback onto the motorways, causing unnecessary delays for background traffic. Per origin, there are a number of alternative paths that an individual can choose (or can be guided on), in order to reduce the chance of spillback to main roads. Note that both the synthetic network and the Arena-network only contain nodes that do not have more than three incoming and outgoing links in total. This way, it is compatible with the LTM (as formulated for the ITM controller).

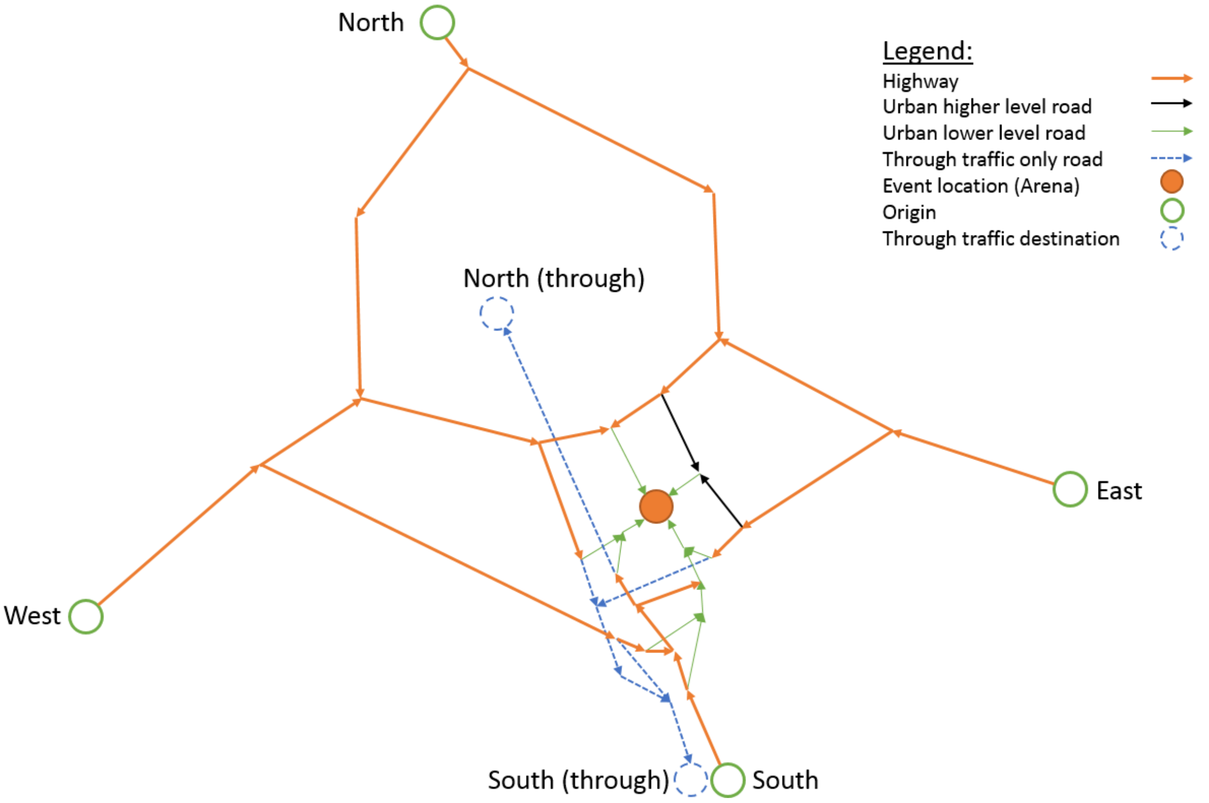

Figure 5.2: Simulation network for the Arena as event location, including through traffic in the simulation

Regarding the traffic demand, for both unguided and guided travellers the demand between the origins and the destinations is varying over the simulated time. This will enable the simulation to model the build-up of the peak in demand and the degradation of traffic performance in the network. Note that the guided OD-demand can be shifted over time with the departure time advice feature of the controller. The initial demand profile of the simulations is based on real loop detector data[3] of traffic dynamics before the start of an event in the Arena.

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[3] Acquired with ViVa-Viewer software

5.2.2 Evaluated scenarios in the case study simulations

Different scenarios will be simulated to analyse the influence of different controller configurations. This way, the influence of the departure time advice and the on-route route guidance on the traffic performance can be determined separately. It is also evaluated how the design would perform if the IRG would be calculated *pre-trip* in an offline manner. This is more similar to the current practice of IRG: the optimisation of the advice is done beforehand using simulation, without any real-time knowledge of the traffic conditions. During the hours before the event, the optimised advices are fed forward into the traffic system.

The base case scenario is a situation where no information is provided to the travellers. In this scenario, the event-bound visitors will follow a split fraction which is fixed over time. The departure times of the travellers cannot be influenced either. This simulation is basically one run of the LTM prediction model with fixed inputs.

A scenario that represents the current practice – non-predictive route guidance with VMS – will also be formulated. Compared to the ITM controller, the number of information access points will however be reduced in this scenario, as well as the ability to give a split fraction to routes other than 0 or 1. The locations of these DRIPs (Dynamic Route Information Panels) can be modelled realistically in the case study network of the Arena and surroundings (Figure 5.2). The DRIPs will base their advice on the current traffic conditions in the network, and will advise the travellers to take the path with the shortest travel time to the event venue. In Table 5.1, all scenarios are presented that will be evaluated and compared using the simulations.

Table 5.1: Controller design scenarios to be evaluated in the Arena-network simulations

Scenario	**Description**	**Controller elements included**		
1	Base case, no information			
2	Current practice, route guidance with DRIPs	Prediction model	Departure time shifts	Route guidance
3	Non-predictive individual route guidance	no	no	on-route
4	Predictive departure time advice	yes	yes	no
5	Predictive individual route guidance	yes	no	on-route
6	Pre-trip computation of individual route guidance (applied real-time)	yes	no	pre-trip
7	Predictive integrated individual advice[4]	yes	yes	on-route

To quantify the effects of the ITM controller in the scenarios, the following KPIs are used:

- Queue length on links over time;
- Travel times on different paths from a node to the destination (event venue);
- Total travel time in the system (TTS) and vehicle hours lost (VHL), also differentiated for event-bound traffic and background traffic separately;
- Number of departure time shifts to future control intervals;
- Route split fractions over time at the decision nodes.

These KPIs indicate the solving power of the controller design (components). This is the extent to which the ITM controller is able to guide the traffic in such a way, that total delay is significantly reduced and that less spillback towards the main roads in the network occurs.

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[4] This is the full design, as formulated in the previous chapter

5.2.3 Uncertainty of simulation variables

The results of the simulations will depend on the exact inputs into the controller optimisation. Literature and real traffic data are used to estimate inputs of the simulation, but these estimations still remain uncertain. Therefore, a sensitivity analysis will be executed to assess the influence of several parameters on the performance of the designed controller. This sensitivity analysis is only performed for scenario 7 (see Table 5.1), where the full design of the ITM controller is simulated. Important input parameters of which the effects of uncertainty must be evaluated are:

- Traffic demand of event visitors: this also influences the number of departure time advice requests from event visitors (R_p^t). The distribution of the requests over (future) time remains fixed, but the number of requests will vary according to the variation in the demand;
- Effective penetration rate (ε), which is the controller penetration rate times the compliance rate;
- Relative value of shifting time versus travel time in the departure time shift optimisation (φ);
- Penalty factor of assigning guided departures to paths with queues (δ_p);
- Unfairness thresholds for system optimal departure time advice and route guidance (H_i/H_n).

The sensitivity of the results to these variables is evaluated by performing different runs for each variable. The value of the variable will differ per simulation run (high value, medium value and low value) and the results for the varying variables are saved. The extent to which the performance of the controller changes with the variation of the input variable indicates the sensitivity of the controller design to this variable. The simulations have a deterministic nature. The inputs are fixed and will not be drawn from a probability distribution, which would make the simulations stochastic. Stochastic simulations are left for future research efforts.

In conclusion, the simulations will work as depicted in Figure 4.9 (flowchart): every time step, the ‘real’ traffic process is updated with the LTM. This working is reflected in the MATLAB script that is used for the simulations. The script varies slightly per network and per scenario that is being investigated. The results of the simulations lead to conclusions about the quality of the design – the extent to which it helps to solve the spillback problem – and possible improvements of the design in future research. Furthermore, the simulations lead to the description of points of attention for any future analyses of ITM controllers in practice.

5.3 Simulation results: synthetic networks

For all the different networks, a comparison has been made between a scenario with fixed route choice and a scenario wherein the designed controller (or a component thereof) is applied. The results of the simulations of the synthetic networks are meant to illustrate the solution power of the controller design.

5.3.1 Synthetic network 1: individual route guidance

To investigate the working of the route guidance component of the controller, a small network was defined. For the event visitors, there are two alternative routes towards the event location. One is slightly shorter in terms of free flow travel time, and therefore preferred by the majority of the event visitors. Using this route too much will however lead to spillback from the event location to the main road, causing hindrance for the background traffic. The other route also has to pass the bottleneck, but queues forming on the alternative route do not affect the through traffic immediately. Therefore, route guidance might enable improving traffic performance by steering traffic towards routes that cause less hindrance for the through traffic.

In this scenario, it is not possible to shift the departure time of the event visitors. This way, the performance of only the IRG can be evaluated. The network layout, including the link numbers, is depicted in Figure 5.3. The exact inputs for the network and the optimisation of this simulation are shown in *Appendix B*.

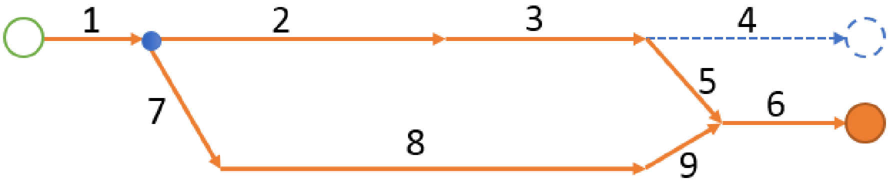


Figure 5.3: Synthetic network 1: route guidance only

The simulation gives the following results:

- In the base case scenario, 80 % of the event visitors chooses the shorter route (via links 2, 3, and 5), while 20 % opts for the other route via links 7,8 and 9. The bottleneck at link 6 causes queues, which propagate upstream on link 5 and 9. Due to the fact that most of the event visitors use the upper route, the queue will grow faster on link 5 than on link 9. Eventually, the tail of the queue reaches link 3, causing queues on link 3 as well. Now, the background traffic is also hindered by the queues caused by the event bottleneck.
- When IRG is applied in this network, the guided event visitors that reach the bifurcation node will receive an advice about the route that they should take: this advice is updated every 30 seconds (the LTM prediction module also has this step size). The route guidance identifies the future spillback of queues from link 5 to link 3, and will send some of the traffic over the lower route, trying to prevent the imminent spillback. This is done until the queue on link 5 is not threatening to spill back anymore, and the split fraction at the node will guide some or even all traffic over the upper route again.

Firstly, the queues in both situations are compared. In Figure 5.4, the queues in the network are shown. Clearly, the IRG prevents any spillback of queues to link 3 from happening. The queues on link 5 and 9 are much more balanced if the IRG is applied. This is done by changing the split fraction at the upstream decision node every time step.

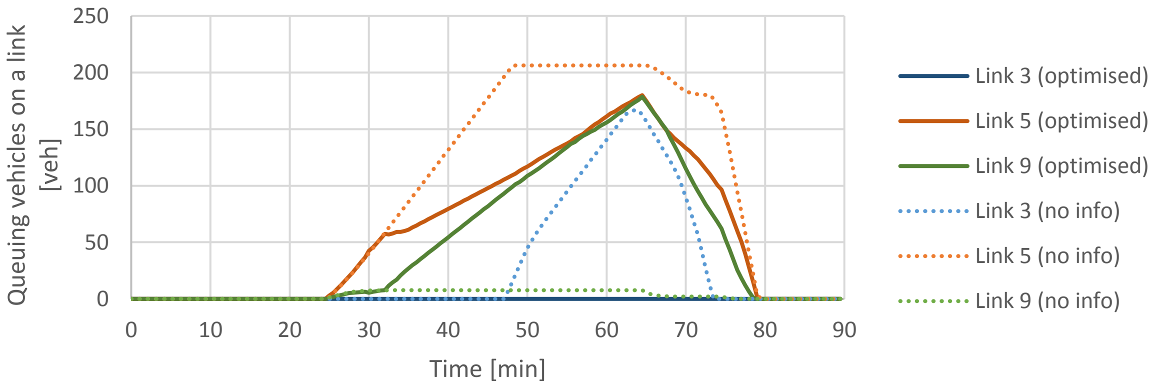


Figure 5.4: Queues in the network during the base case and the IRG simulation

In Figure 5.5, the optimised split fractions that the controller has computed during the simulation are depicted. At the start of the simulation, the upper route has the lowest travel time, since free flow traffic conditions apply then: the controller computes the optimal advice as an all-or-nothing assignment then. As time advances and the demand increases, the queue on link 5 grows. Then, the controller will intervene by sending more and more *guided* traffic over the lower route. For many time steps, the split fraction is 0 or 1, but for others a value in between is better. As can be expected from theory, the controller will eventually achieve a balance between the travel times and queues on both routes (see Figure 5.6). In the no information case, the travel times on the alternative routes deviated a lot (until the end of the simulation where a spike in the travel time exists on the lower route due to the LTM modelling). This balancing of travel times on alternate routes can be seen as an advantage of the individual route guidance again. When there is no event-bound traffic left in the network, the controller stops its computations.

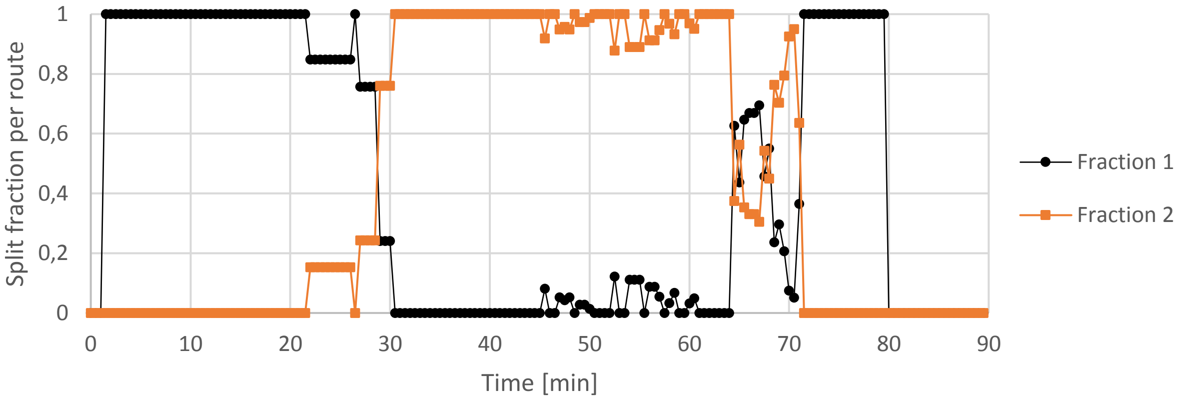


Figure 5.5: Split fractions at the decision node for the upper (1) and the lower (2) route

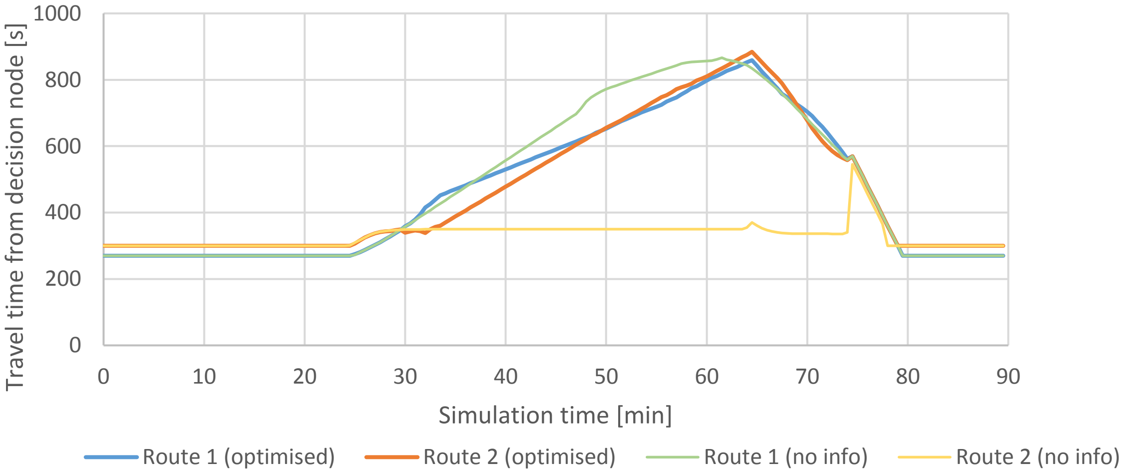


Figure 5.6: Instantaneous travel times on the routes (1: upper route, 2: lower route) from the decision node to the event venue

Table 5.2 shows the delay indicators (TTS and VHL) for both the event visitors and the through traffic in the network. The application of IRG leads to a small decrease in the TTS in total, which is felt more by the background traffic than the event visitors. The difference for the event visitors is basically zero. This is can be declared by the fact that the event visitors enter the network at the same time for both the base case and in the IRG scenario. This means that the same flow will have to pass the bottleneck. Irrespective of the route that they take, they will receive the same delay as without the route guidance, since they will enter a queue on the alternative route as well.

The benefits of the optimised route guidance are mostly for the background traffic, that isn't hindered by spillback from the event. Their VHL becomes equal to zero: the absolute difference is not that high (possibly because there is relatively less background traffic than event-bound traffic), but the relative difference in VHL is a 100 % reduction. Besides, the controller is able to equalize the route travel times to the destination, which is interesting for the event visitors as well from an equality point of view.

Table 5.2: TTS and VHL for the base case scenario and the IRG scenario

Target group	**TTS [veh*h]**		**VHL [veh*h]**	
	Base case (no info)	*Route guidance optimisation*	*Base case (no info)*	*Route guidance optimisation*
Event visitors	408.4	407.6	171.2	166.5
Background traffic	240.6	230.1	10.5	0
Total	**649.0**	**637.6**	**181.7**	**166.5**

5.3.2 Synthetic network 2: individual departure time advice

For testing the departure time advice component, a simple network was defined, in which the event visitors have only one route available from the origin to the event venue. The demand scenario leads to queue formation at the bottleneck at the event location, causing spillback to the main road that the background traffic uses as well. The only way to reduce this queue spillback is to change the departure behaviour of the event visitors. The synthetic network layout, including the link numbers, is depicted in Figure 5.7. The exact inputs for the network and the optimisation of this simulation are shown in *Appendix B*.

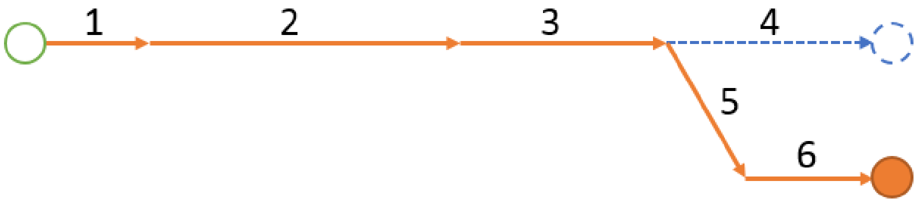


Figure 5.7: Synthetic network 2: departure time advice only

The simulation yields the following results:

- In the base case scenario, the event visitors have a fixed departure time. Because during some time, the demand for the event location is larger than the capacity of the bottleneck there, a queue will start to grow. After some time, the tail of this queue reaches the main road, where background traffic is present as well. This traffic will then also start to queue, until the event-bound demand reduces again and the queue will dissolve.
- When individual departure time advice is used (advice is calculated every 5 minutes, LTM has a step size of 30 seconds), the controller shifts some of the guided vehicles to earlier and later departure times than the preferred departure time of the individuals. This is because the predicted traffic conditions at the start of the simulation are better than the future traffic conditions (queueing starts). This way, the controller achieves a better distribution of departures over time, keeping the queue at the bottleneck in control and preventing it to spill back as much as possible.

In Figure 5.8, this evolution of the queues is depicted, for both the base case with no guidance and the departure time optimisation case. In the base case, the queue on link 5 grows steadily until the link is full, causing queues on link 3 as well. The optimised departure time advice shifts the event visitors to an earlier departure time in the first stages of the simulation, leading to an acceleration of the queue growth. This is because the optimisation uses the predicted traffic states. It foresees the spillback, and reduces the demand peak by shifting individuals to an earlier departure time.

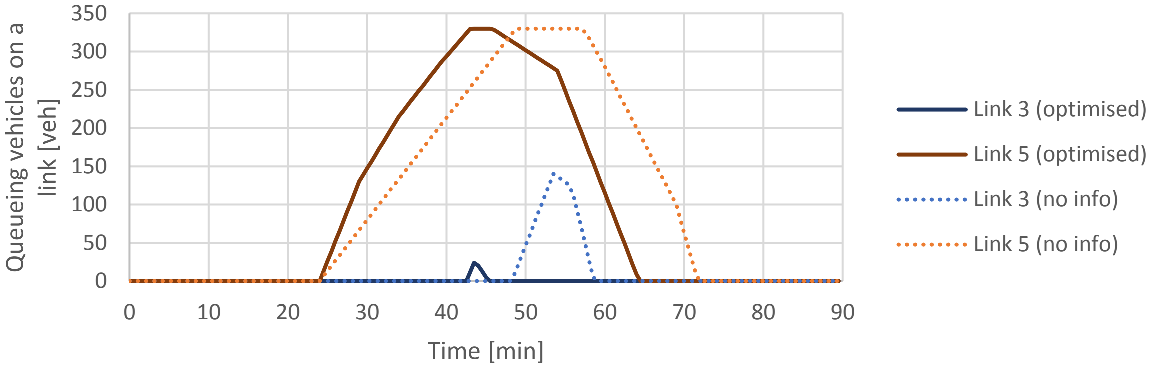


Figure 5.8: Queues on link 3 and 5 in the base case and the departure time advice scenario

In Figure 5.9, the departure time shifts are broken down per optimisation interval (every 5 minutes). It shows that the a large portion of the individuals that request departure time advice are assigned to their preferred departure time interval. However, there is also quite some shifting behaviour, especially to a few intervals earlier and very late intervals. In the first stage of the simulation, the controller has the tendency to shift travellers to an earlier interval (and of course their preferred departure time). This is reflected in the queue build-up as shown in Figure 5.8. In the later stages of the departure time control simulation, the individuals will all be shifted later in time, still respecting the maximum arrival time of the event visitors. Probably, this is caused by the reduction of the traffic demand at the end of the optimisation. This leaves space for additional traffic, which can be shifted to these late departure times.

A comparison between the initial, expected demand profile and the realised departure time profile (with optimised departure times) is shown in Figure 5.10. It reveals the shifts of the event visitors to the late stages of the simulation, where less (or no) demand is present in the base case.

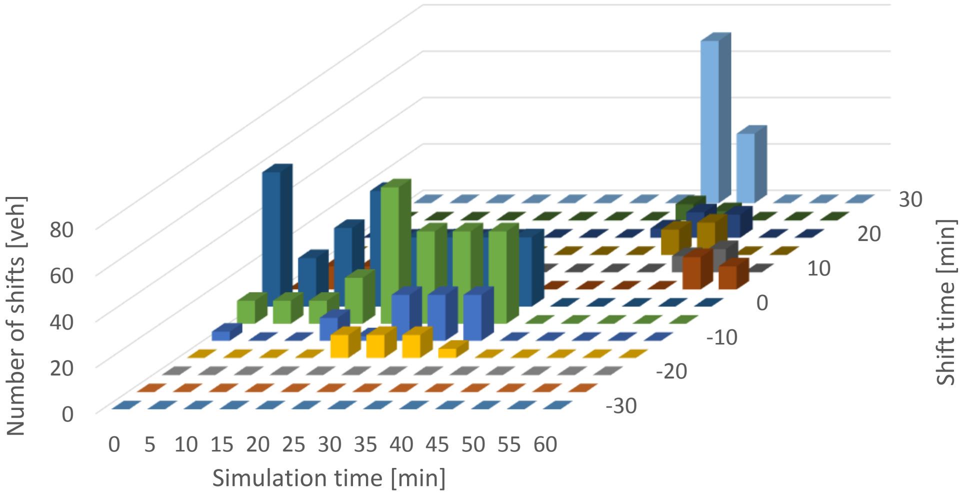


Figure 5.9: Departure time shifts during the simulation, as computed at every optimisation interval

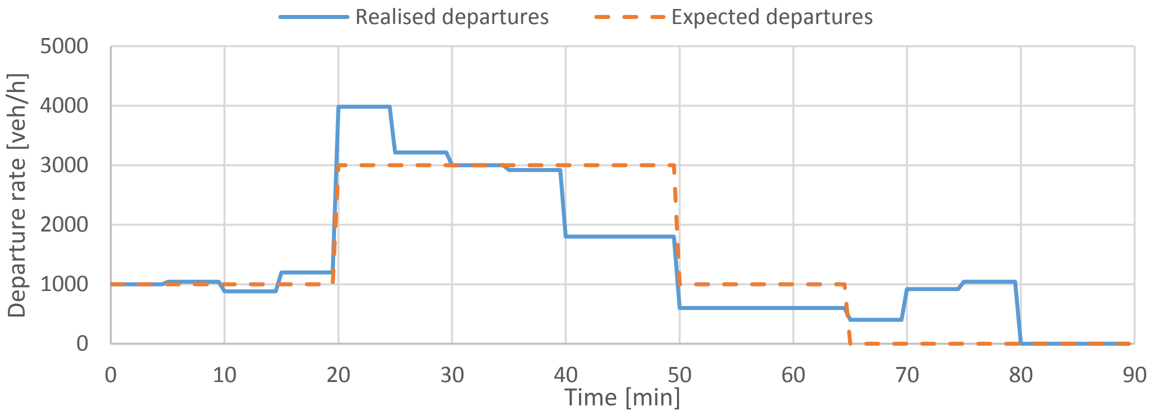


Figure 5.10: Initial departure profile versus optimised departure profile by departure time shifts

The effect of the controller on the TTS and VHL is clear: the reduction of by the departure time optimisation is shown in Table 5.3. The absolute reduction is not that high, but in relative terms the background traffic delay approaches a 100 % reduction. This would be even higher if more through traffic would be present, as the optimised departures are able to prevent spillback. Note that the total shift time of the travellers can also be seen as a disbenefit. However, this shift time is perceived to be better than in-vehicle travel time by travellers. The total shift time during this simulation is 115.9 vehicle hours, which is quite high. Possibly, the inputs to the simulation made the departure time optimisation focus too much on preventing spillback instead of reducing total travel costs (including total shift time).

Table 5.3: TTS and VHL in the base case and the departure time optimisation case

Target group	**TTS [veh*h]**		**VHL [veh*h]**	
	Base case (no info)	*Departure time optimisation*	*Base case (no info)*	*Departure time optimisation*
Event visitors	373.1	348.1	164.8	141.6
Background traffic	352.3	342.6	8.9	0.3
Total	**725.4**	**690.7**	**173.7**	**141.9**

5.3.3 Synthetic network 3: integrated travel advice for individuals

In the final synthetic network, event visitors can be shifted over time *and* space in the network. It is expected that these possibilities combined lead to an even better performance caused by the controller's operations. The synthetic network layout, including the link numbers, is depicted in Figure 5.11. The exact inputs for the network and the optimisation of this simulation are shown in *Appendix B*.

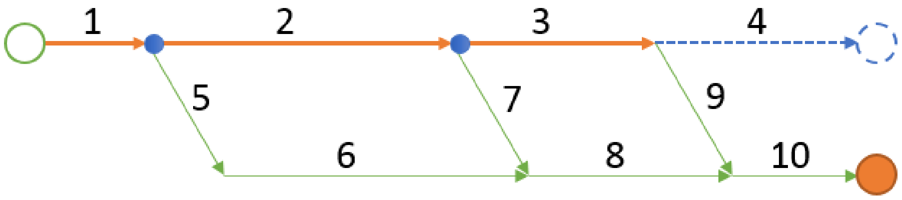


Figure 5.11: Synthetic network 3: integrated route and departure time advice

The simulation yields the following results:

- The base case is designed in such a way, that spillback occurs from the bottleneck (link 10) via link 9 to the main road, link 2 and 3. This is because the traffic is uninformed: 72 % of the event visitors will follow route 1 (via link 1,2,3,9 and 10), and only 18 % follows route 2 (via link 1,2,7,8 and 10) and 10 % follows route 3 (via 1,5,6,8 and 10). The event visitors do not change their departure time.
- If the integrated individual guidance is applied, the controller makes use of any room that is left in the network, in both the space and time dimension. The controller uses the split fractions at node 1 (downstream of link 1) and node 2 (downstream of link 2) to prevent the spillback from occurring. The individual departure advice strengthens the effects of the route guidance, although less shifts are performed than in the case where only departure time advice was possible. The step sizes of the control intervals and the LTM are the same as in the networks discussed before.

Figure 5.12 shows the formation of queues in the base case scenario and the effects of the controller on queues in the network. Similar to the route guidance only scenario, the split fractions at the decision nodes lead to a balance in the queues on the links directly upstream of the bottleneck. Spillback onto link 2 or 3 is prevented.

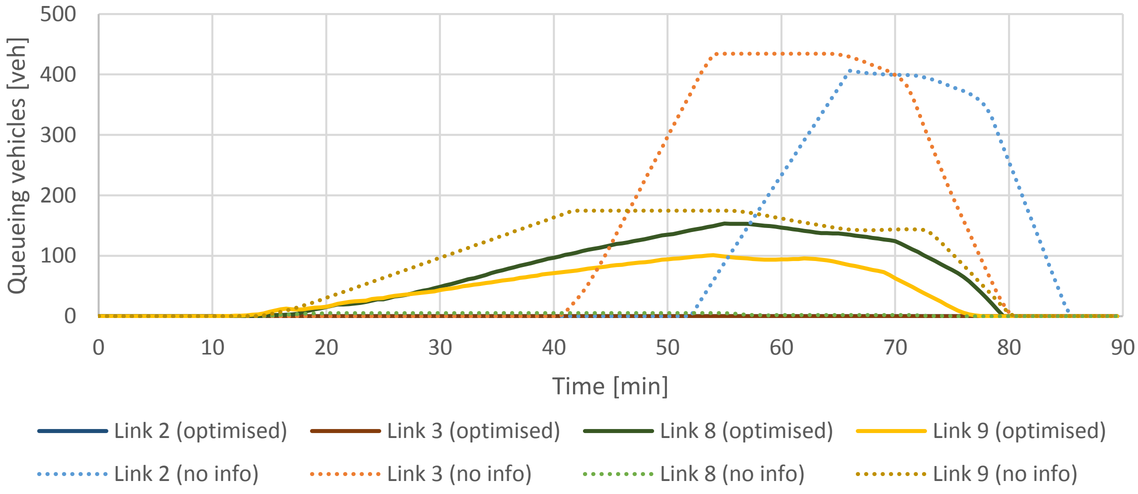


Figure 5.12: Queues in the network, in the base case and the integrated advice scenario

The split fractions during the simulation at the second split node are depicted in Figure 5.13. In the earlier stages of the simulation, route 1 receives the largest portion of the guided traffic. When the queue on link 9 is increasing, the controller will start sending traffic to the alternative route. The number of all-or-nothing assignments is quite low in this scenario, at many time steps *individual* advice is given. Note that the controller balances the queues on link 8 and 9 by adapting the split fraction roughly every few minutes.

Figure 5.14 depicts how the controller manages to keep the route travel times from the decision nodes to the event fairly equal, although the traffic on route 1 benefits the most. This is also a benefit for the event visitors, since the advice enables them to optimise their travel times, compared to the situation in which they are uninformed and have a fixed route choice distribution.

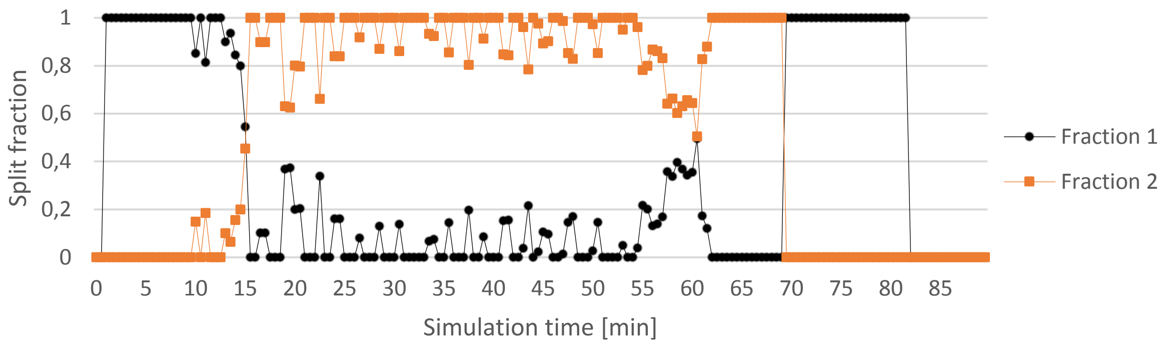


Figure 5.13: Split fractions at the second node in the integrated advice scenario

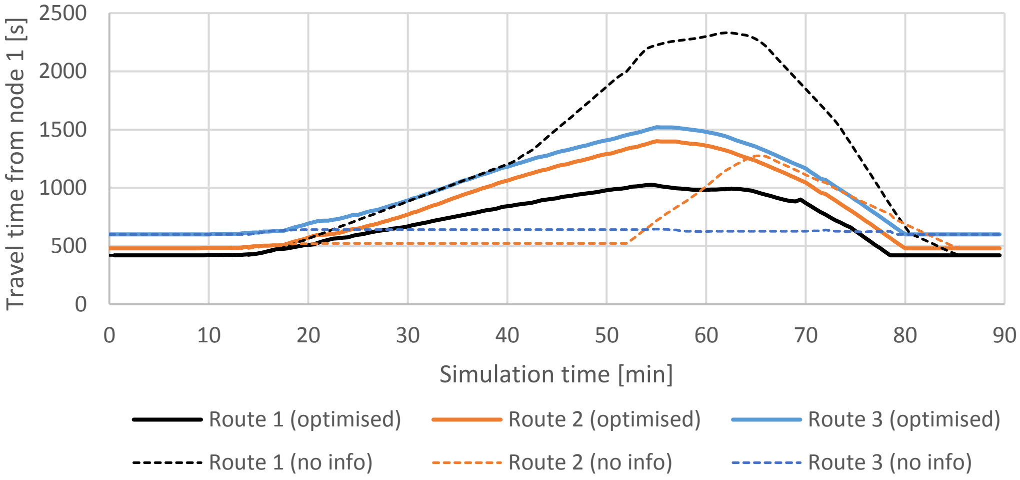


Figure 5.14: Route travel times from decision node 1 to the event venue for both the controlled and uncontrolled scenario. Route 1 via link 2,3,9; Route 2 via link 2,7,8; Route 3 via link 5,6,8

The departure time advice seems to have a supporting role for the IRG in the ITM controller. The departure time shifts are often small and the majority of the requesting individuals will be advised to use their preferred departure time (see Figure 5.15). This is caused by the lower demand, compared to the departure time advice only case (section 5.3.2). The shifts to earlier departure times occur mainly at the start of the simulation, while shifts to later departure times are performed relatively more in later stages of the simulation (see Figure 5.15). The demand profile changes slightly due to these shifts: in Figure 5.16, the difference between the initial and the optimised departure profile is not that large.

This can be explained by the fact that the route guidance affects the traffic in a beneficial way as well: there is less need for the controller to adapt individuals' departure times. Another reason could be that there is less room at the end of the simulation to shift event visitors to late departure times. This could possibly cause them to arrive late at the event, which is not allowed.

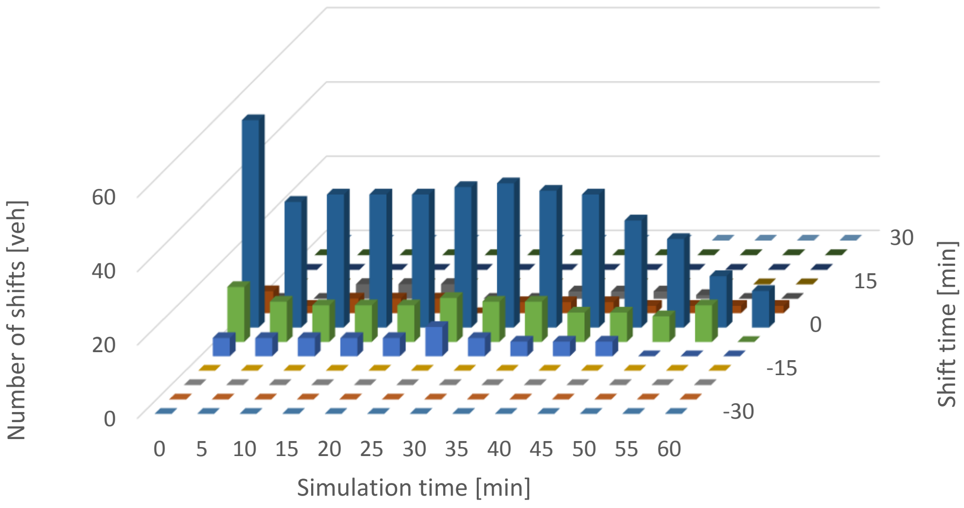


Figure 5.15: Departure time shifts in the integrated advice scenario, broken down per optimisation interval

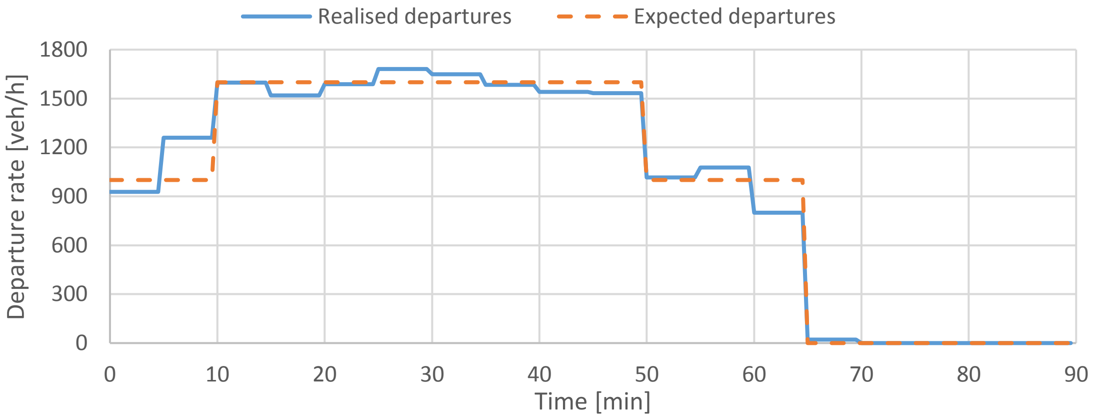


Figure 5.16: Initial and realised departure profiles in the integrated advice scenario

The base case scenario lead to serious congestion on the main road, which is also used by the background traffic. The improvement that the controller induces is large. In Table 5.4, the TTS and VHL are compared for the base case and the integrated optimisation scenario. The results are evident: the controller prevents delays for background traffic in this case, and is able to reduce the hindrance for event-bound traffic at the same time. Similar to the departure time only case, some of the traffic performance improvement (reduction in VHL) is compensated by the total shift time by the departure time guidance. The total shift time in this simulation is 24.8 veh*h.

Table 5.4: TTS and VHL in the base case and the integrated optimisation case

Target group	**TTS [veh*h]**		**VHL [veh*h]**	
	Base case (no info)	*Integrated optimisation*	*Base case (no info)*	*Integrated optimisation*
Event visitors	376.6	371.8	167.0	159.5
Background traffic	555.1	245.3	309.8	0
Total	**931.7**	**617.1**	**476.8**	**159.5**

An important criticism on the results of the ITM controller's performance in the synthetic networks is that the propagation of traffic is modelled in exactly the same way as the LTM prediction component of the controller. This means that there are barely discrepancies between the prediction model and the actual traffic process. In reality, the process might be significantly different than the prediction model and the assumptions in the optimisations of the advice. Clearly, large differences will degrade the benefits of applying the ITM controller, as the controller will base its decisions on wrong assumptions. The actual effects of differences between traffic process and modelling in the designed controller is left for future research.

5.4 Case study simulation results: Amsterdam Arena network

Finally, to evaluate the controller's effectiveness in a more realistic way, a network has been defined that represents an actual event location in the Netherlands, the Amsterdam Arena. Spillback issues in practice have been identified here. To some extent, the simulated network around the Arena is representative of the real inflow situation of an event there. However, the actual properties of the links are simplified to make the simulation feasible for the LTM and transparent for the analyses. The simulated network is depicted in Figure 5.17.

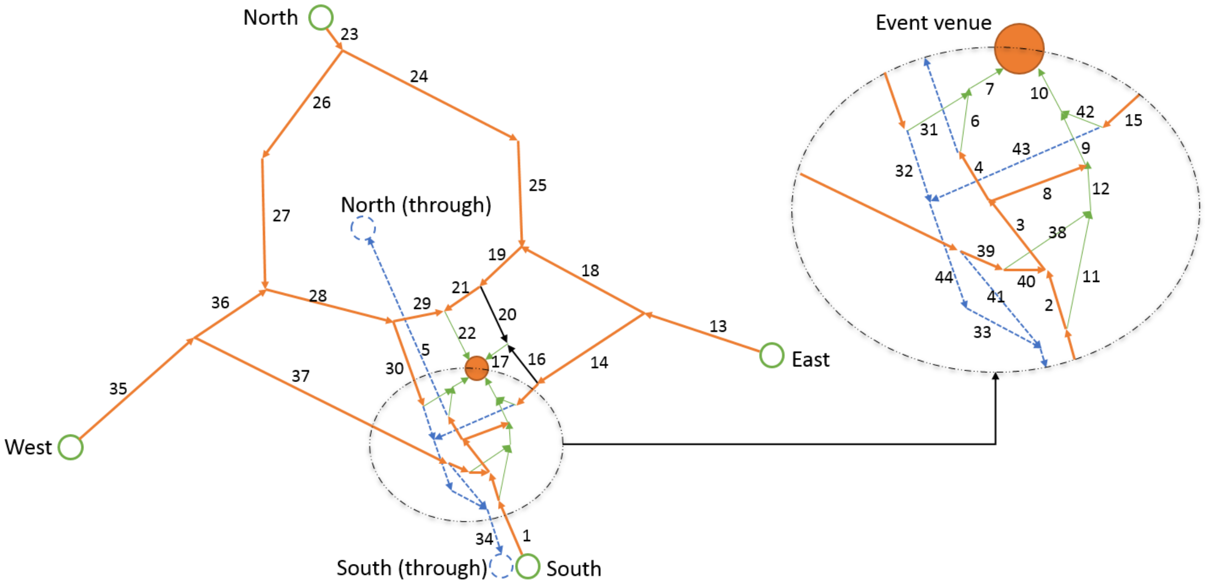


Figure 5.17: The case study network around the Arena event venue, including the link indices

5.4.1 Base case scenario: no information, fixed route and departure time choice

In the base case, all traffic follows a fixed route and departs at a fixed departure time. The traffic is not influenced in any way by a controller or the prevailing traffic conditions in the network (since they are uninformed).

The simulation results in very heavy congestion on the north-south corridor of the network (which is the A2 motorway in reality). This is caused by spillback from the western entrance of the event location. The fixed route choice of the drivers is suboptimal, which leads to the oversaturation of this link (link 7). Queues form on the links directly upstream, link 6 and 31, which are the off-ramps of the motorway. Eventually, the queue will spillback onto the motorway (links 4 and 30). This motorway contains background traffic that is travelling from north to south and vice versa. Right at the moment the queue spills back to the motorway, the damage is done and cannot be reversed. The queue will keep propagating upstream, affecting traffic from other origins as well. After a while, the event visitors have arrived and have left the network: then, the queue will dissolve. Figure 5.18 and Figure 5.19 present how the queue will propagate towards the motorway during the simulation.

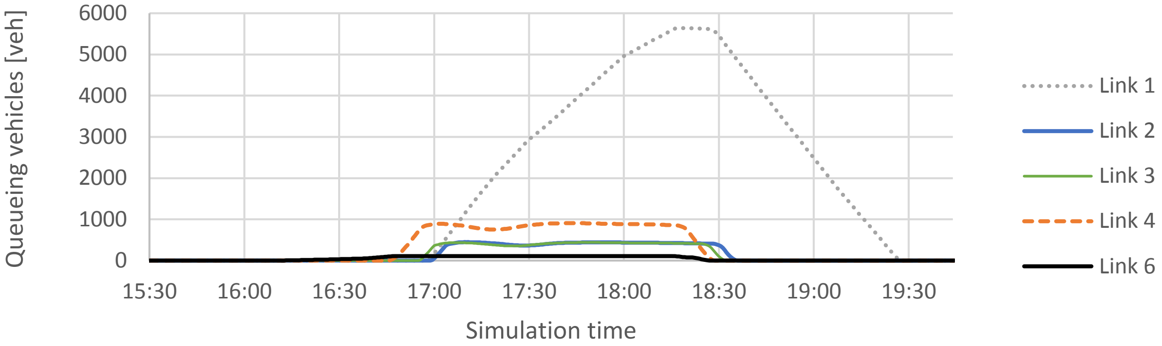


Figure 5.18: Queue propagation from the western event entrance to the northbound motorway A2

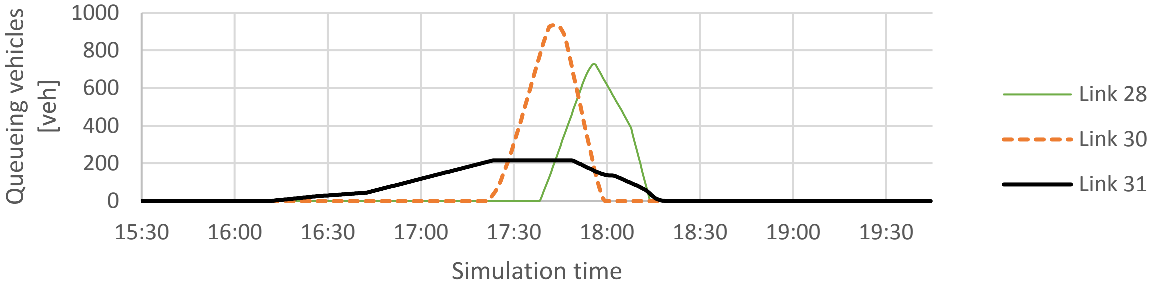


Figure 5.19: Queue propagation from the western event entrance to the southbound motorway A2

These queues are all due to poor decision making by the event visitors. The queues cause very large travel times, but the travellers will not change their route since they are uninformed about the downstream traffic conditions. This leads to very large differences in travel times among the alternative routes. An example of this is given in Figure 5.20, where route travel times are compared from node 2 (at the end of link 1) to the event location. This is the most upstream node on the A2 motorway, at the end of link 1. Route 1 follows the motorway over link 2, 3, 4, 6 and 7, route 2 uses link 2, 3, 8, 9 and 10. Initially, the most unattractive route is route 3, via 11, 12, 9 and 10: this route is chosen by a limited amount of traffic. Eventually, this leads to the fact that this route has the shortest travel time. If any information would be provided to the event visitors, more visitors could possibly use this route, reducing overall travel times in the network.

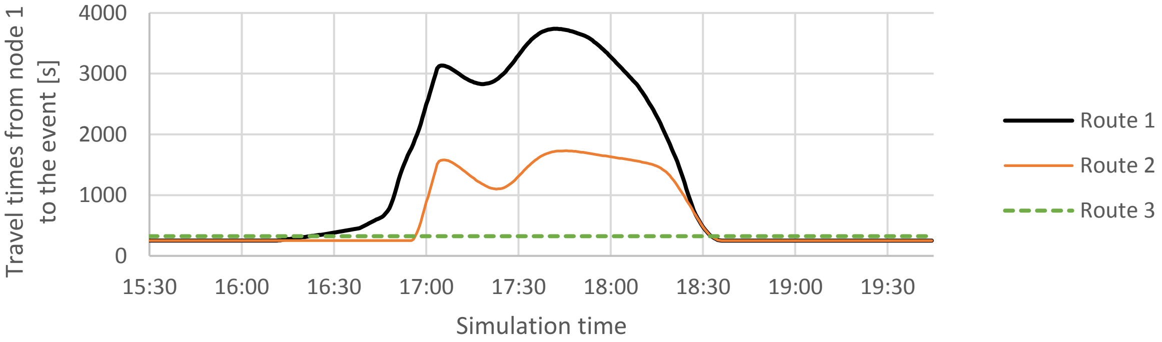


Figure 5.20: Travel times from the end of link 1 to the event venue over the alternative routes. Route 1 via links 2-3-4-6-7; Route 2 via links 2-3-8-9-10; Route 3 via links 11-12-9-10

The fact that the congestion affects the background traffic, is also reflected in the TTS and VHL performance indicators (see Table 5.5). Although there is of course more through traffic than event-bound traffic, the hindrance of the congestion delays the background traffic disproportionally. While the through traffic demand is about 5 times as high as the event traffic demand, the delay experienced by the through traffic (measured in VHL) is about 10 times higher than the delay for the event-bound traffic.

Table 5.5: TTS and VHL for all target groups in the reference case

Target group	***TTS [veh*h]***	***VHL [veh*h]***
Event visitors	3,134	997
Background traffic	25,119	10,590
Total	**28,253**	**11,588**

5.4.2 Current practice scenario: DRIPs influencing route choice

The latter scenario, in which all the drivers are uninformed and have a fixed route choice, is not very realistic. In reality, drivers will react to the traffic conditions, especially if they are informed. The current practice of road authorities is to operate message signs, which inform travellers about the traffic situation on the alternative routes to the destination.

These DRIPs are located at a few bifurcation nodes in the network. In the simulation, every origin and every path is serviced with at least one DRIP: these locations are based on the real locations of these message signs (see Figure 5.21). The DRIP will give the advice to all event visitors that pass the DRIP, but not all event visitors will of course comply to the advice (a compliance rate of 60 % is assumed). The advice that the DRIP gives in the simulation is based on the travel times on the different routes from the DRIP to the event venue. The route with the shortest instantaneous travel time will be recommended to the event visitor by the DRIP: the advice is updated every 3 minutes. It is important to note that the advice is not computed in the same way as is done in the designed ITM controller (no optimisations are used).

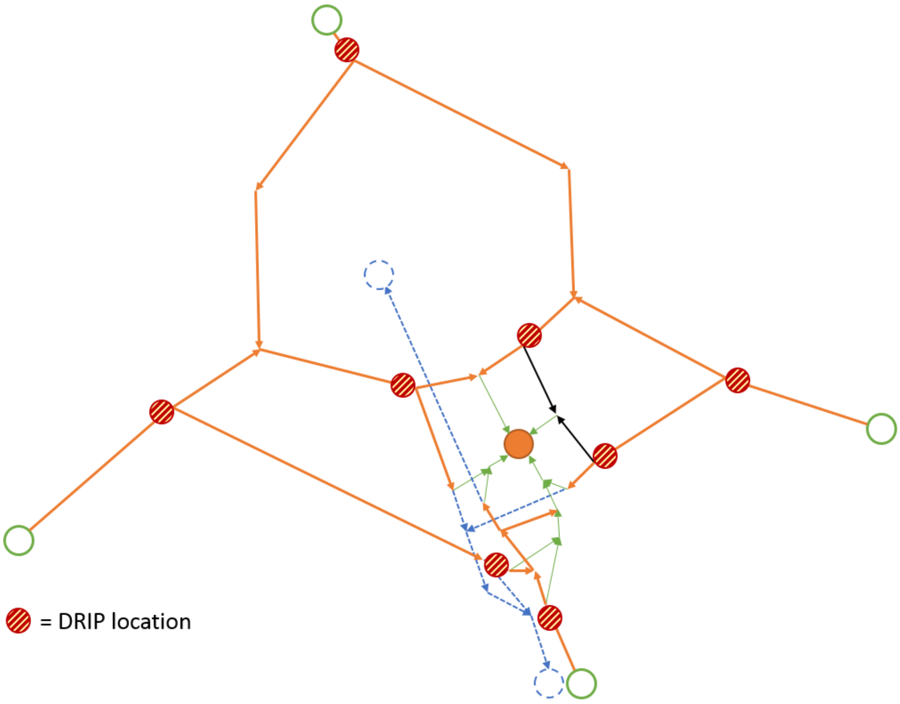


Figure 5.21: Locations of DRIPs in the case study network

The working of the DRIPs in the simulation is shown in Figure 5.22. The two DRIPs that influence the queues on the motorway the most, are the DRIPs at the end of link 1 and 39 (in reality this would be the junction of the motorways A2 and the A9). The advice given by these two DRIPs also differs over time in the simulation. As the queues (and the travel times) increase on the motorway, these DRIPs will redirect travellers via upstream exits of the motorway. The more the queue lengthens, the earlier travellers will be advised to exit the motorway and follow the lower level network to the Arena. For all other DRIPs, the route with the shortest travel time remains the same throughout the simulation time. Therefore, those DRIPs will not alter their advice.

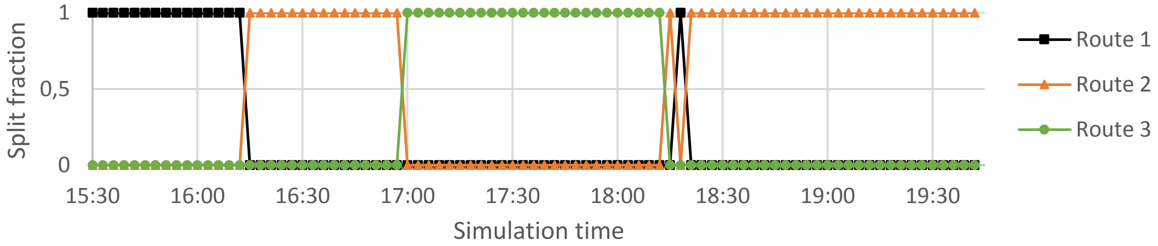


Figure 5.22: Split fractions induced by the DRIP at the end of link 1. Route 1 via links 2-3-4-6-7; Route 2 via links 2-3-8-9-10; Route 3 via links 11-12-9-10

Deviating the event traffic from the bottlenecks has a positive effect on queueing on the motorway. Although the DRIPs cannot prevent spillback from the event location to the motorway, the queue length is significantly reduced. This is shown in Figure 5.23, where the queues on some links of interest in the reference scenario and the DRIP-scenario are compared. The route guidance of the DRIPs does not cause any oversaturation of the other entrances of the event location (e.g. link 10), meaning that the spillback stays limited to the A2 corridor.

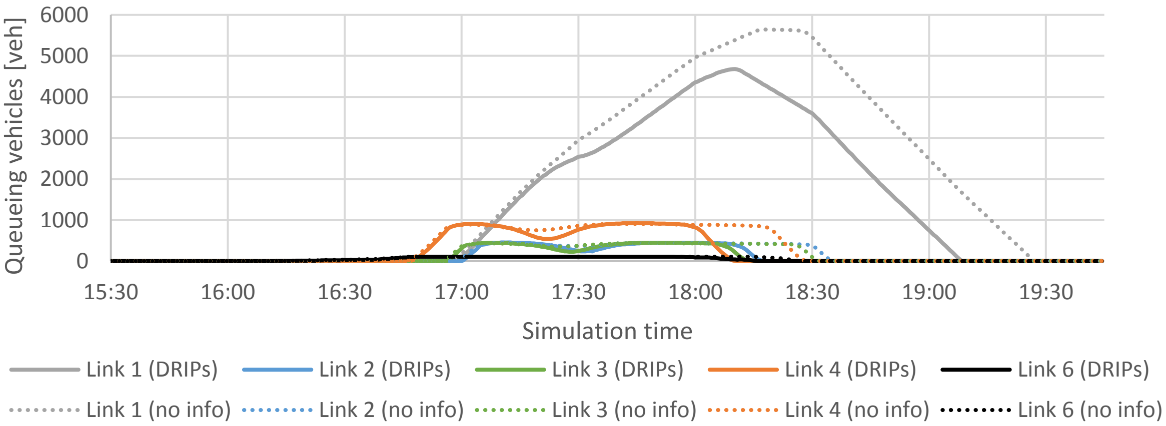


Figure 5.23: Comparison between queues on the A2 corridor (northbound), in the base case and the DRIP-scenario

These effects of the DRIPs on queue formation are reflected in the delay indicators of the simulations. The TTS and VHL of the reference scenario and the DRIP-scenario are compared to the no-information case in Table 5.6. This comparison reveals that the DRIPs are able to induce a significantly lower level of delay in the network. Both the event visitors and the background traffic benefit from the DRIPs' effects.

Table 5.6: Comparison of TTS and VHL between the base case and the DRIP-scenario

Target group	***TTS [veh*h]***		***VHL [veh*h]***	
	No information	*DRIPs*	*No information*	*DRIPs*
Event visitors	3,134	2,701	997	573
Background traffic	25,119	21,996	10,590	7,322
Total	**28,253**	**24,698**	**11,588**	**7,895**

5.4.3 Effects of the designed ITM controller and its components

The controller design, including traffic prediction and advice optimisations, is applied to the Arena-network as well. For the full design, all results will be reported. It will also be discussed what the effect of applying the three components of the controller *separately* is: the prediction module, the route guidance optimisation, and the departure time advice optimisation are simulated separately in different scenarios. The results of these simulations are compared to the results of the reference cases and the results of the simulation of the full design.

Performance of the full controller design compared to the reference scenarios

For the simulation of the ITM controller in the Arena-network, the following inputs are important:

- Effective penetration rate: 40 %
- LTM step size: 36 seconds (minimum link travel time), prediction horizon: 40 minutes
- Route guidance step size: 72 seconds
- Departure time advice step size: 15 minutes
- Maximum departure shift time: 30 minutes
- Event start time: 18:45 (simulation starts at 15:30, ends at 19:45)

Applying the controller design to the Arena-network leads to a huge improvement of the traffic performance in the network. There is no spillback from any of the approach routes of the event venue to the surrounding motorways. The controller is able to balance the queues on these different approach routes in such a way that the queues do not spill back, contrary to the reference scenarios. This is shown in Figure 5.24 and Figure 5.25. The queueing ends also earlier in the simulation of the ITM controller than in the reference cases. While at 19:00 queues are still present in the network (on link 1) in the reference cases, during the simulation of the ITM controller there are no queues left in the network at that time.

The DRIPs update their advice every three minutes. This causes some oscillations of the queue length on link 31. On link 6, the queue grows nearly as fast as in the base case, eventually causing spillback to the northbound A2 motorway.

Application of the controller in the Arena-network leads to a better distribution of the event visitors over the various approach routes of the event area (mainly the western, northern and southern approaches). This is also reflected in the queue build-up figures, which show that the controller accepts only a small queue length at the western entrance of the Arena (the key bottleneck), before deviating the event visitors to another approach route. This explains the oscillatory behaviour of the queues in the optimised scenario: when the queue exceeds a certain threshold, the controller identifies another route to be better. Event visitors (or a fraction of them) will then be advised to use an alternative route by the IRG component of the controller, so that the queue will diminish until the initial route is more attractive again.

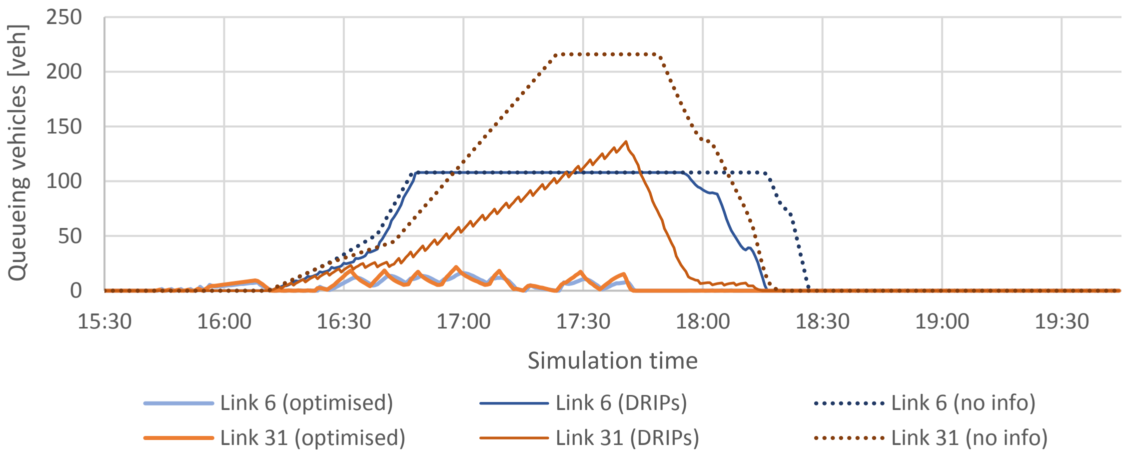


Figure 5.24: Queue formation at the western entrance of the Arena in the different scenarios

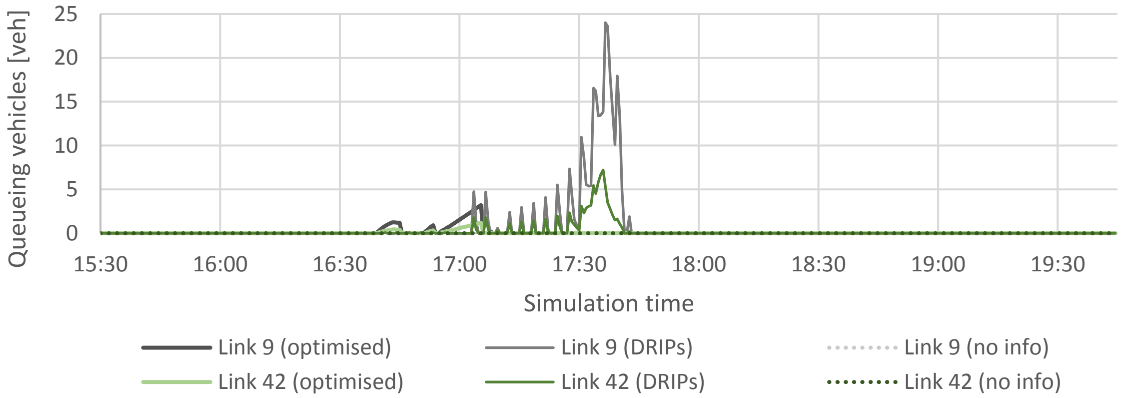


Figure 5.25: Queue formation at the southern entrance of the Arena

The VHL of the through traffic is reduced to (nearly) the absolute minimum: there is no significant delay for the through traffic (their VHL during the simulation is shown in Table 5.6). Clearly, the event-bound traffic benefits as well, since there is no congestion on the motorway anymore.

Table 5.7: TTS and VHL in the simulation of the ITM controller

Target group	***TTS [veh*h]***	***VHL [veh*h]***
Event visitors	2,121	29.8
Background traffic	14,720	17.3
Total	**16,841**	**47.1**

In the base case or the DRIP-scenario, the congestion on the motorway was so heavy that event visitors were caught in these traffic jams as well, regardless of the route that they were taking. The ITM controller enables the event visitors to make smarter routing decisions, which leads to a better use of the various approach routes by the visitors. In Figure 5.26 and Figure 5.27, it is shown how the controller uses split fractions to distribute the visitors over the approach routes: the route guidance is updated every 72 seconds (the LTM has a step size of 36 seconds). Once the (predicted) queue or travel time on a certain approach route becomes too large, the controller will guide the traffic to another entrance of the event venue. Since the *total* capacity of all approach routes is sufficient for the event bound traffic, the controller is able to fully prevent any spillback to motorways through the individual advice that it gives.

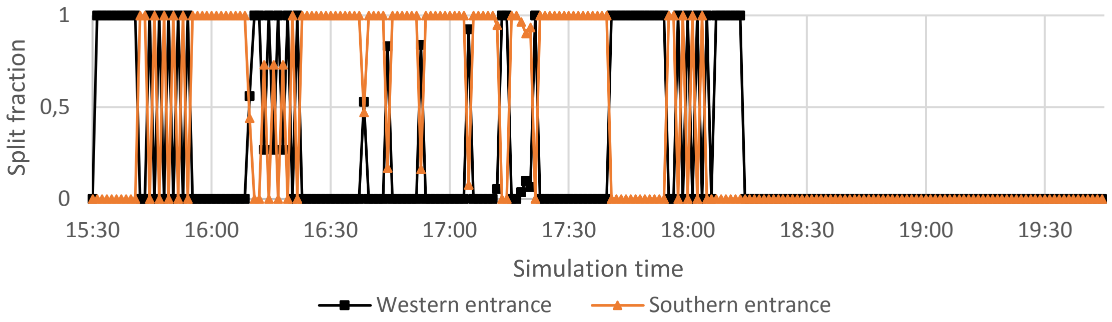


Figure 5.26: Split fractions at decision node 1 to the different approaches of the Arena

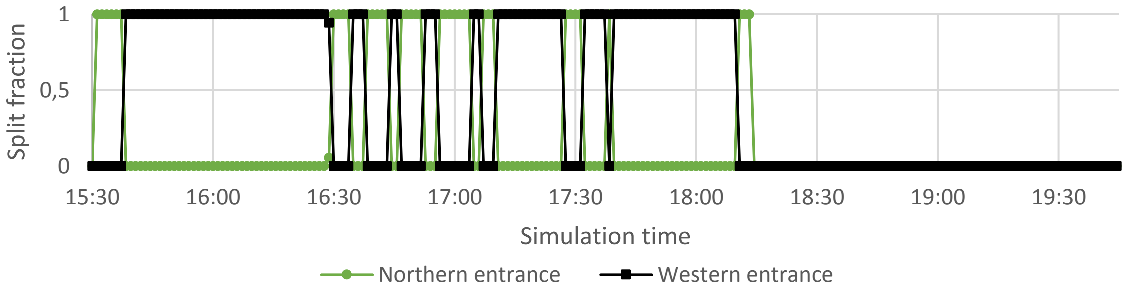


Figure 5.27: Split fractions at decision node 8 to the different approaches to the Arena

This alternating strategy of the route guidance component of the controller is not only reflected in the queue build-up, but also in the travel times over different routes to the event location. Figure 5.28 depicts how the travel times over the alternative routes from a split node remain close to each other. The travel time on the main route oscillates quite strongly due to the actions of the IRG, but the travel time never becomes unacceptably large. The difference between the travel times of the alternative routes remains acceptable as well, meaning that the travellers will not perceive their advice to be unfair.

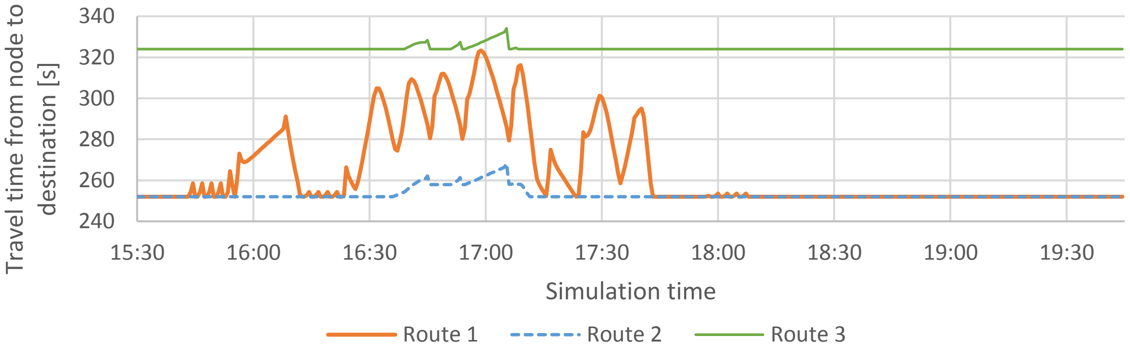


Figure 5.28: Route travel times from decision node 1 to the Arena. Route 1 via links 2-3-4-6-7; Route 2 via links 2-3-8-9-10; Route 3 via links 11-12-9-10

In Figure 5.29, the departure time shifting behaviour of the controller during the simulation is presented. This advice is computed every 15 minutes. Although the total number of shifts from the preferred departure time of users is relatively high, the controller seems to shift travellers both forward and backward during the whole simulation. The effect of the shifts is shown in Figure 5.30: although for some origins (especially those related to the western entrance of the Arena) some deviations from the expected departure time profile are visible, the effects of these shifts will likely be small. These small effects are caused by the fact that the realised departure time profile is alternating higher and lower than the expected departure time profile. This means that the controller is constantly correcting its own (departure time shift) actions during the simulation. This causes inconvenience for the event visitors, as they have to shift from their preferred departure time, while this will have a minor effect on the traffic conditions in the network.

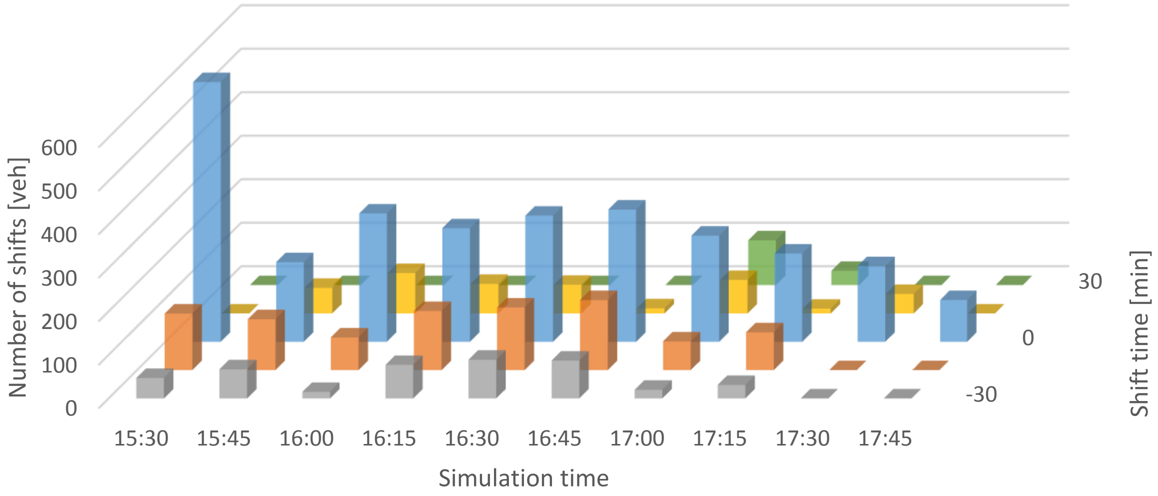


Figure 5.29: Departure time shifts (total of all origins) during the simulation

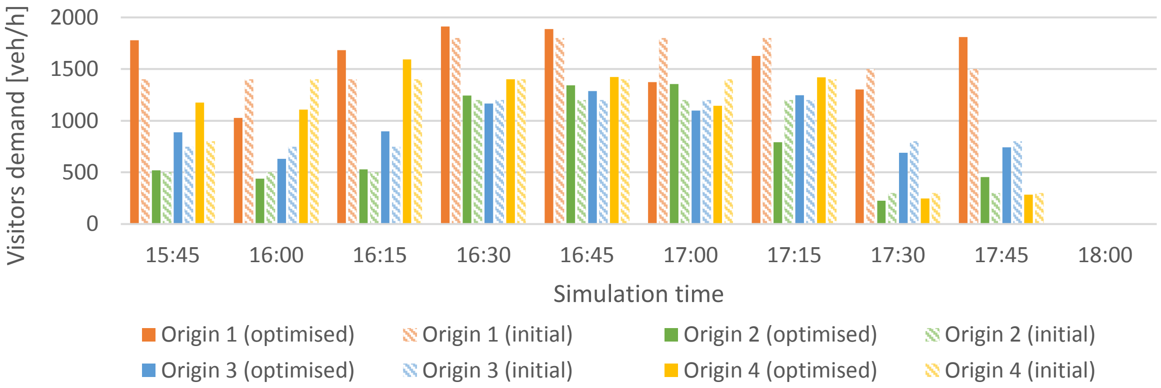


Figure 5.30: Initial and realised visitor departure time profiles (due to shifts) of all origins in the network. (1) A2 motorway; (2) A1/A6 motorway; (3) A8 motorway; (4) A4/A9 motorways

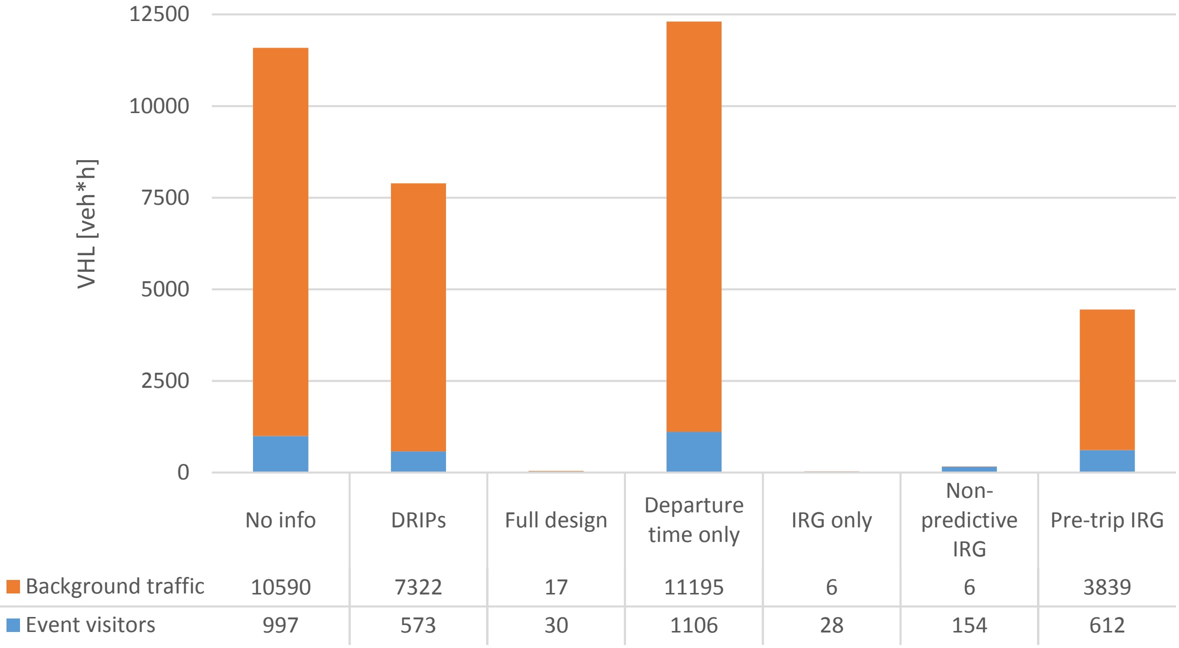
Note that there are no shifts to the time intervals where there is no demand in the initial scenario (later than 18:00). Apparently, the arrival time constraint prevents these shifts, as travellers would arrive too late at the event venue (the assumed event start is at 18:45).

The computation time of the advice is within acceptable bounds: the advice can be optimised within the time step of the simulation (36 seconds). 3 hours of individual traffic management and traffic propagation could be simulated within 40 minutes with an AMD A8-6410 quad-core processor (2.0 GHz, 12 GB RAM, Windows 10, MATLAB 2015b).

Influence of the separate controller components

Simulating the other scenarios, in which the separate controller components are evaluated, gives insight into the actual contribution of the components to the integrated results. In

Figure 5.31, the effects of all controller components (in terms of VHL in the network) are compared to the base case and the DRIP-scenario. In this section, the presented results are explained in more detail.



	No info	DRIPs	Full design	Departure time only	IRG only	Non-predictive IRG	Pre-trip IRG
🟧 Background traffic	10590	7322	17	11195	6	6	3839
🟦 Event visitors	997	573	30	1106	28	154	612

Figure 5.31: Comparison of VHL in reference scenarios and for different controller compositions

The most striking finding is that the route guidance is by far the most influential component of the controller, while the departure time advice even seems to have negative effects in terms of total vehicle delay. This holds for both the event visitors and the through traffic. This negative effect is on top of the shifts of travellers' departure times, that also cause some inconvenience. There are a number of explanations possible for the poor performance of the departure time advice component in the Arena-network:

- Many route alternatives from an origin to the destination for the event visitors. These alternative routes require the departure time advice to make an assumption about the split fractions in the network (since the departure time advice component does not interact with the route guidance component). If the number of alternative routes becomes too large, the split fractions will be very low. This leads to a smaller number of travellers that will be deviated from the congested time intervals. Possibly, this can be solved by making the assumption regarding the route fractions dynamic (dependent on the prevailing route advice), instead of fixed.
- The penetration rate of the departure time advice is not high enough. There is too much unguided traffic (both through traffic and event visitors) for the departure time advice component to have a significant influence on the traffic performance in this network setup (including the demand scenario). The departure time advice is simply too weak to counteract the queue formation on the approach routes and the spillback to the main roads. In the synthetic networks, the share of the guided departure times was higher: this led to a more positive influence of the departure time advice on the traffic conditions.
- The fit of the linear travel time function is poor. Since the used travel time function of the departure time optimisation is path-based, the properties of the links on a path are aggregated into one value. This value is then used in the travel time function and the objective function of the optimisation. Probably, this aggregation assumption leads to the

fact that the departure time advice negatively influences the traffic conditions in this network: the poor fit of the assumed objective function to the real traffic dynamics leads to sub-optimal decisions. The shifts of the departure time controller are very similar to the shifts of the integrated advice controller (Figure 5.29), although slightly more shifting behaviour can be observed.

This issue of sub-optimal guidance did not (noticeably) occur in the synthetic networks. The reason for this is that the synthetic networks are smaller and less complex than the Arena-network. The aggregated path-based values will therefore align much better with the real dynamics in the synthetic networks than in the Arena-network. Moreover, the damage – spillback to the main road – cannot be prevented by the departure time advice in the Arena-network. During the simulation it will try to counteract the issues, but the overreaction only leads to a small *increase* of delays in the network.

The effects of the IRG are not very dependent on the predictive nature of the controller. Removing the prediction model from the controller leads to an increase of VHL. The event visitors are affected by this, but the spillback to the main roads is contained to a minimum, which leaves the VHL at an acceptable number. Apparently, the reaction time of the controller and the reaction of the travellers to the computed advice is fast enough to prevent spillback, but the IRG is less capable of distributing the event visitors over the approach routes of the Arena optimally. Figure 5.32 shows how the non-predictive ITM controller reacts relatively late to the queue build-up at the western entrance of the Arena (compared to the full controller design). However, the controller is still in time to react to these queues and to deviate the traffic to another route. Again, a wave movement can be distinguished: the controller over- and undersaturates the bottleneck alternatingly, causing the queue to grow and diminish roughly every ten minutes. There is no queue at the southern entrance of the Arena in the non-predictive ITM scenario.

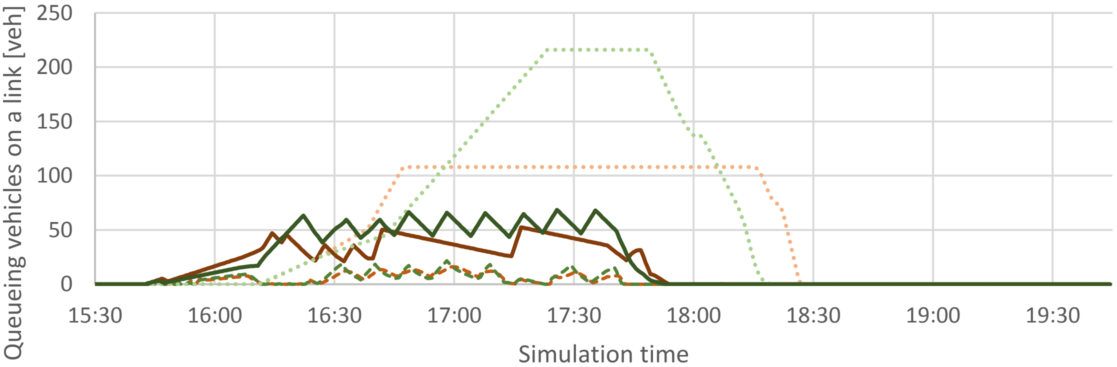


Figure 5.32: Queue formation at the western entrance of the Arena, for non-predictive ITM

Computing optimal advice offline for pre-trip advice purposes does not yield the high performance of the real-time and on-route IRG advice of the controller. However, the VHL were strongly reduced, comparing the pre-trip scenario with the reference cases. Figure 5.33 shows how the pre-trip advice influences the queue build-up at an approach route of the Arena (the main bottleneck). The offline computed advice causes the queue to build up faster, since the offline computation of the advice did not propagate the effects of the advice into that simulation. The spillback therefore occurs earlier. However, the pre-trip advice is able to undersaturate the bottleneck for a while, so that the queues reduce temporarily (also on the motorway, see Figure 5.34). Furthermore, the pre-trip advice leads to an earlier diminishing of the queues at the end of the simulations. This reduces the total delay suffered by the traffic in the network.

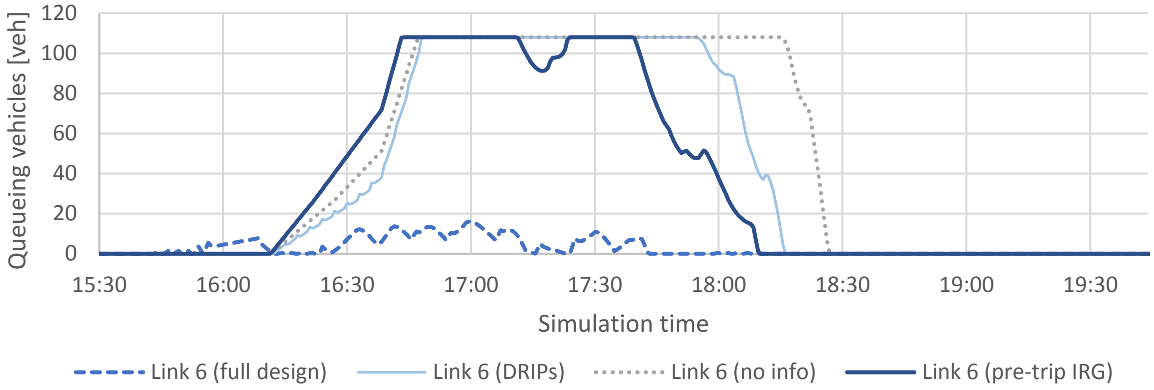


Figure 5.33: Queue formation at the western entrance of the Arena in different scenarios

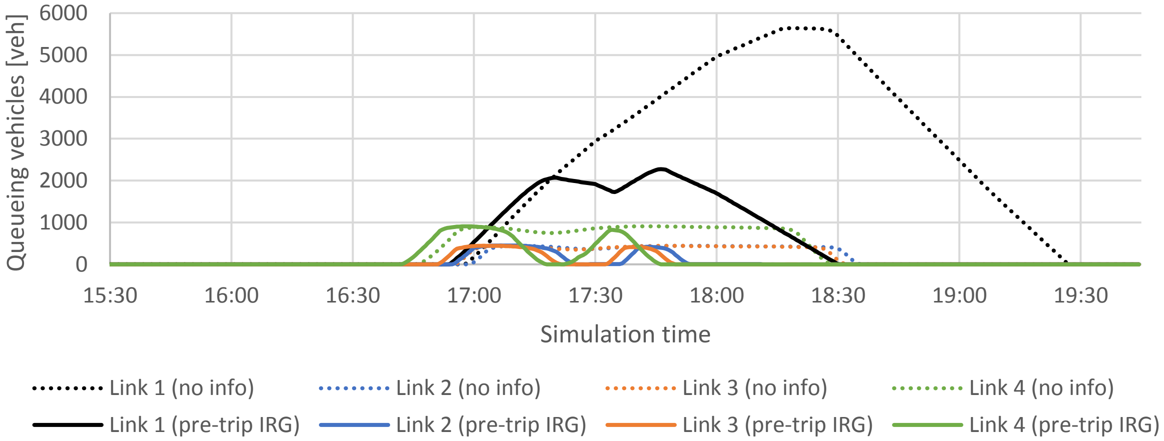


Figure 5.34: Queues caused by spillback from the Arena in the base case and the pre-trip advice computation scenario

Although such pre-trip computation of the IRG is not as effective as the real-time optimisation, it is much closer to the current practice of an individual advice provider. This offline optimisation already has some positive effects on the traffic conditions (more than DRIPs) and can be used if real-time optimisation becomes too complex and therefore technically not feasible.

As identified before, the applicability of this pre-trip computation of the advice is dependent on the extent to which the model and the real traffic process will match. Large deviations of the model from reality will lead to advice solutions that are not optimal. This should be handled with care if the controller will be applied in practice, both for real-time and pre-trip offline computation of the route and departure time advice.

5.5 Sensitivity analysis of the controller's performance in the Arena-network

The results of the case study simulations are of course dependent on the inputs into the simulation, e.g. the demand and the optimisation variables. The sensitivity of the performance of the *full design* of the controller to the inputs will be evaluated in this section. Every simulation, the value of one input variable is changed, while the value of the others is equal to the initial value of the full ITM controller design simulation. In Table 5.8, the absolute and relative values of the variable variations are presented. These will be used in the sensitivity analysis simulations. Combining variations of different inputs is out of the scope of this research, as this will generate many more scenarios and requires many more simulations.

Table 5.8: Variations of input variables in the sensitivity analysis

Input variable	Low value	Medium (initial) value	High value
Demand of event visitors	0.80 (relative value)	1.00 (relative value)	1.20 (relative value)
Effective penetration rate	0.20	0.40	0.60
Departure time shift penalty	0.50	0.70	0.90
Link queue assignment penalty	0.50 (relative value)	1.00 (relative value)	2.00 (relative value)
Alternative unfairness threshold	0.50 (relative value)	1.00 (relative value)	2.00 (relative value)

5.5.1 Overall results of the sensitivity analysis

In Figure 5.35, the results of the sensitivity analysis are presented: the figure depicts the change in total VHL in the network for a certain *relative* change of the input variable. The controller seems to be sensitive to the traffic demand (of event visitors) and the penetration rate, because the VHL differs quite strongly when the value of these inputs is changed. The controller is less sensitive to the value of the departure time shift penalty, the link queue assignment penalty and the unfairness threshold.

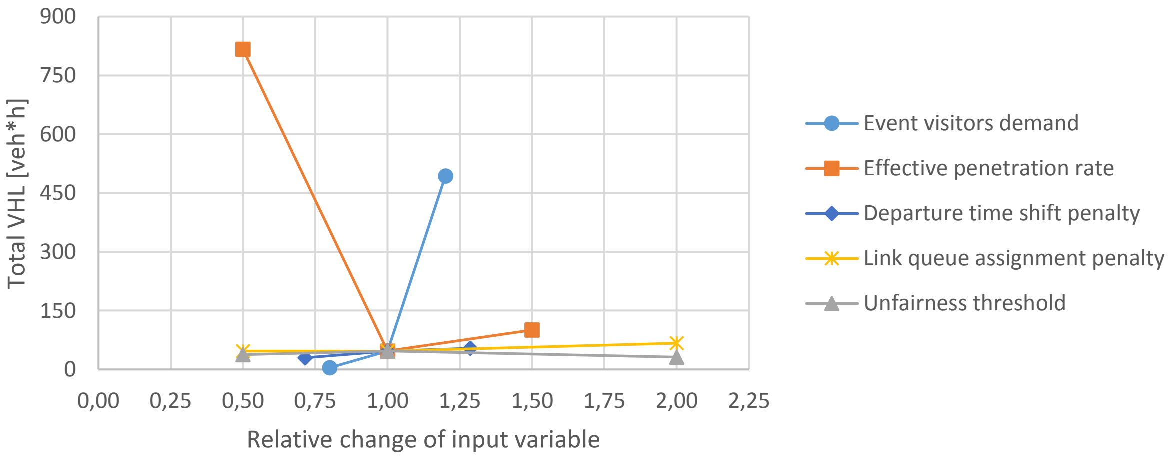


Figure 5.35: Sensitivity of the performance of the controller (in VHL) to the relative change of different input variables

The remainder of this paragraph will focus on the variables to which the controller is the most sensitive, namely the visitor demand and the penetration rate.

The distribution of the VHL over the two target groups in the sensitivity analyses is depicted in Figure 5.36. Note that changing (especially reducing) the effective penetration rate affects the background traffic more than the event-bound traffic. This could indicate that spillback occurs at one of the entrances of the event venue, resulting in a higher delay for the through traffic. For the demand, the relative change in VHL for the event visitors and the background traffic does not differ significantly. In the coming sections, the reason for the sensitivity of the controller's performance to the demand and the penetration rate are discussed.

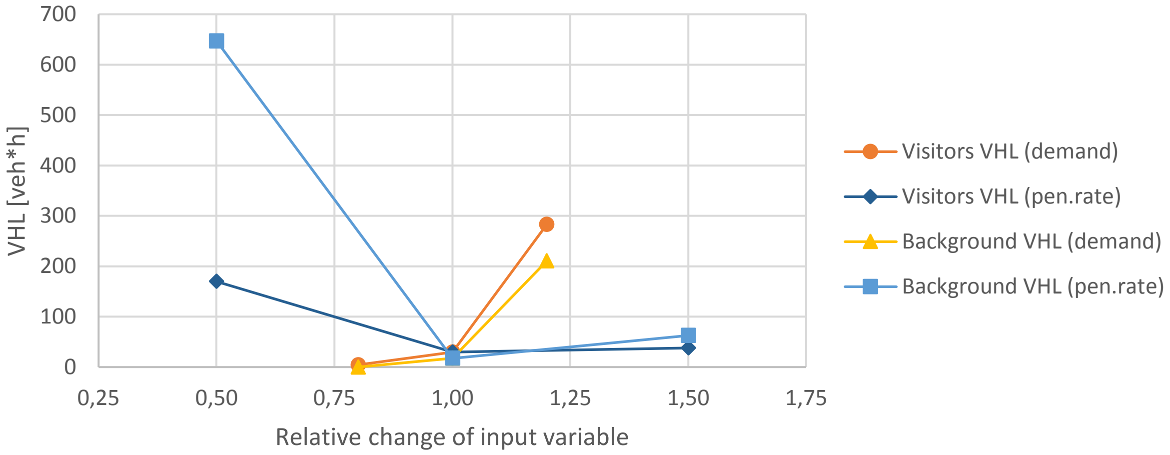


Figure 5.36: Sensitivity of the VHL of the target groups to visitor demand and penetration rate

5.5.2 Sensitivity to event visitor demand

The effects of increasing the event-bound traffic demand in the simulation are straightforward: more demand leads to a faster queue build-up and more oversaturated bottlenecks, while a lower demand decreases these issues. Figure 5.37 shows that the queues at the western entrance of the Arena build up much faster than in the reference case: still, the controller can prevent any spillback onto the motorway. This is done by steering more traffic over the alternative routes and making the advice more individualised (see Figure 5.38, compare to Figure 5.26). The individual route guidance results however in significant queues at the southern entrance of the Arena (Figure 5.39). The ITM controller tries to prevent spillback from the western entrance as much as possible, but at the same time the southern entrance is congested as well (spillback to link 8 and 12, but no delay for through traffic over there).

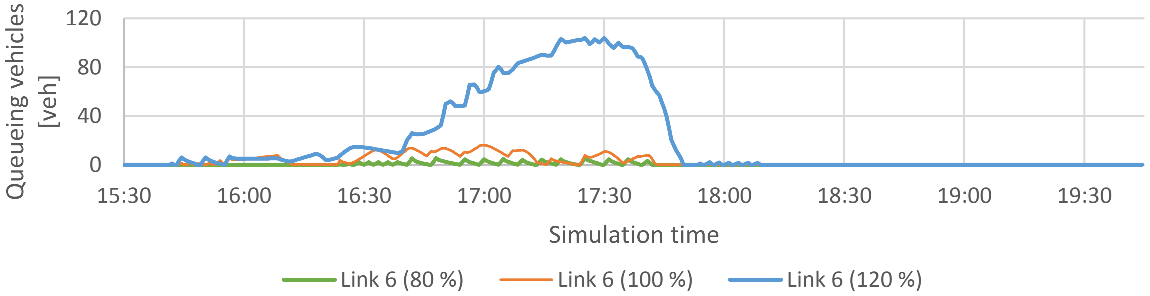


Figure 5.37: Queues at the western entrance of the Arena in different demand scenarios

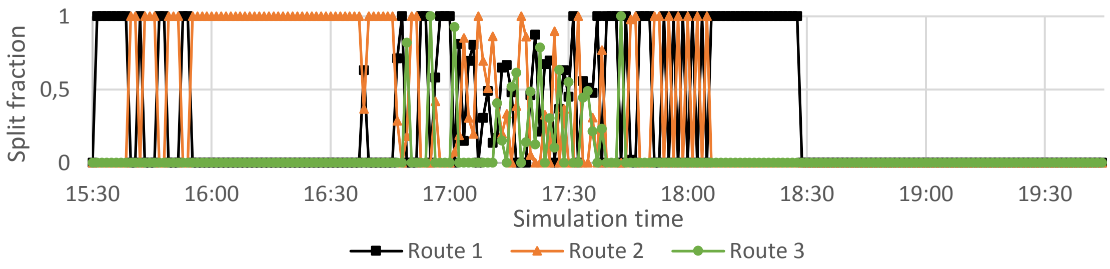


*Figure 5.38: Split fractions induced by the controller at the first A2 decision node in the **high demand** scenario. Route 1 via links 2-3-4-6-7; Route 2 via links 2-3-8-9-10; Route 3 via links 11-12-9-10*

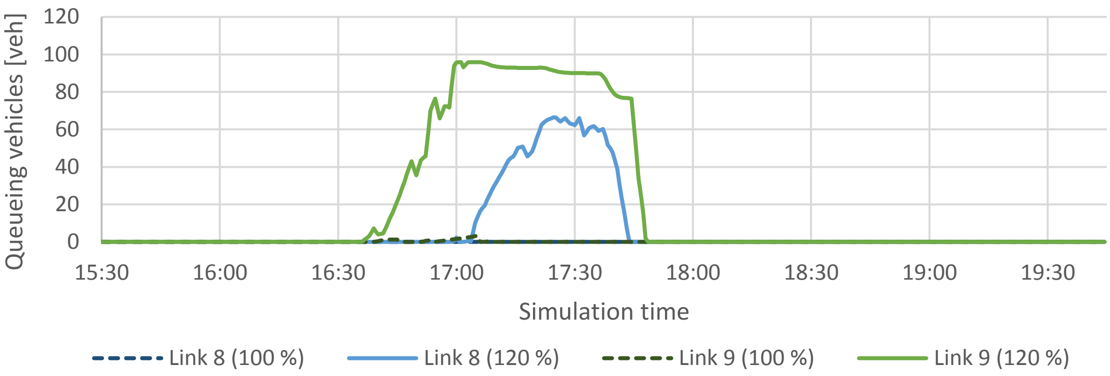


Figure 5.39: Queues at the southern entrance of the Arena in the initial and high demand scenario

The longer queues on the entrance links are reflected in the VHL figures of the event visitors. However, delay for the background traffic was reported as well, while no spillback occurs from the event venue to the main roads containing background traffic. This VHL is caused by bottlenecks that exist on the *motorways*. For instance, the merge of the A9 and the A2 motorway towards the Arena normally causes no problems for traffic, but with the increased traffic demand this becomes a new bottleneck. This causes queues, in which background traffic is caught as well. These queues could be prevented by the controller, if a capacity constraint would be incorporated in the optimisation model. The applied design does not contain a capacity constraint: this means that the controller will not foresee if its actions lead to a too high inflow for a bottleneck somewhere. A serious downside of the capacity constraint is possible infeasibility of the general optimisation model. This has been discussed more elaborately in chapter 4 (the design phase).

Note that also the background traffic demand can be varied: this has not been researched, as the controller is not able to influence the behaviour of this traffic directly. However, the results of increasing the through traffic demand would be that spillback leads to more severe congestion on the main road and that more sections on the motorway would be oversaturated by the through traffic demand, causing congestion regardless of the controller's actions.

5.5.3 Sensitivity to penetration rate

The effective penetration rate has also been identified to be an important factor in the performance of the controller in the simulation. This effective penetration rate is composed of the penetration rate of the advice among event visitors and the compliance of the advised visitors.

Reducing the effective penetration rate implicates that the controller has less power of changing the behaviour of the traveller population that is in the system. As the VHL-figures show, a lower penetration rate will lead to more delay: the event visitors will suffer relatively less from this delay than the through traffic. The reason for this delay is spillback: the maximum queue length of link 6 - western entrance of the Arena - is reached (Figure 5.40), leading to queues on the A2 motorway as well. This causes delays for the background traffic, and also some delay for the event bound traffic. The queue figure shows how the controller's actions have limited influence on the build-up of the queue. Although the controller identifies this queue and steers all event-bound traffic to alternative routes, the penetration rate is too low. This means that a vast majority of the event visitors will stick to their fixed route fraction, which causes this spillback.

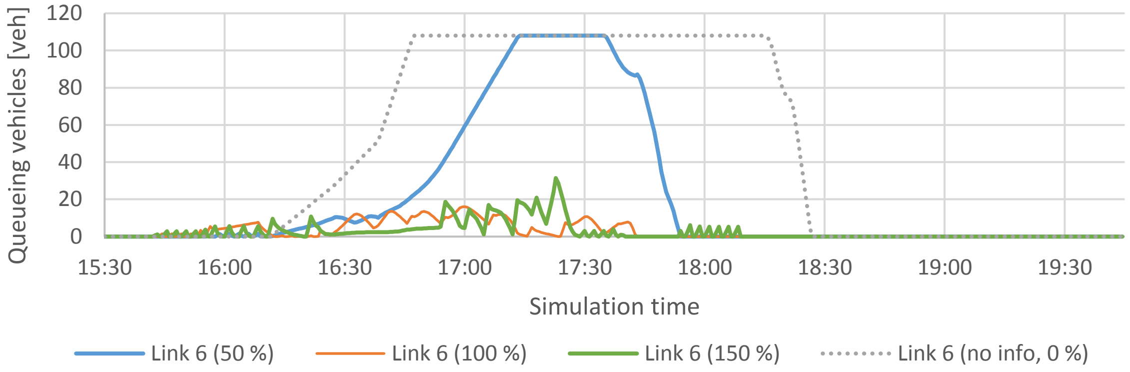


Figure 5.40: Queues at the western Arena approach in different effective penetration rate scenarios

The queue propagates upstream over the whole A2 corridor, as it does in the no-information reference case (Figure 5.41). But clearly, the queues are much less serious than in the reference case: although the effective penetration rate of the controller is low, the ITM is still able to stall the formation of queues at the approach route of the Arena by steering the traffic over the alternative routes.

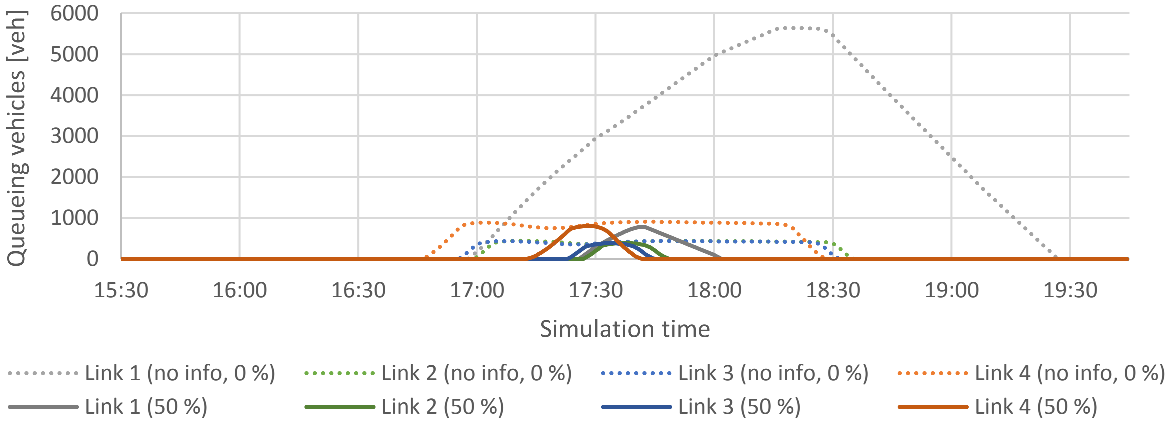


Figure 5.41: Queues on the A2 corridor in the no information case and the low effective penetration rate scenario

Increasing the (effective) penetration rate leads to more oscillatory behaviour of the controller. This higher penetration rate also ensures that the controller is able to prevent spillback from any of the entrances of the Arena to the main roads. However, Figure 5.36 shows that both event visitors and background traffic suffer from more delay, if the penetration rate is increased. This is remarkable, since no spillback was observed at the event venue. The increased VHL figures with the increased penetration rate can be explained as follows:

- The increased penetration rate leads to controller decisions, which can cause congestion. This was also observed in the analysis of the sensitivity to the demand: the controller basically overshoots with the advice, by steering a too large portion of traffic to a certain route. This does not cause spillback at the event location, but congestion on the main roads at a bottleneck over there. The lack of the capacity constraint means that the controller does not take these bottlenecks directly into account in the route guidance optimisation.
- The performance of the departure time advice is not optimal, due to the assumptions in the optimisation model. This was already identified in the previous paragraph. Increasing the

penetration rate of the individual advice (and thus also the departure time advice) might lead to an increase in the sub-optimal effects of the departure time advice, causing the VHL to increase as well.

For application of the controller in practice, the sensitivity of its effectiveness to the (effective) penetration rate might be an issue: this external factor is difficult to influence in practice. The controller design takes an assumed penetration and compliance rate into account in its calculations for the route guidance, so it can account for a low (or high) effective penetration rate. Nevertheless, the sensitivity to compliance and penetration rate is an important attention point if the controller would be applied at a real event. In some way, it must be ensured that the (effective) penetration rate is high enough to achieve benefits by the application of the ITM.

5.6 Discussion

The simulations in the synthetic network show that the designed controller and its components (theoretically) are able to reduce delay by preventing spillback. The formulated optimisation models are accurate enough to achieve a better traffic performance in small and simple networks. Of course, these synthetic networks and demand scenarios were formulated in such a way that this resulted in a solvable problem. Furthermore, the modelling of the traffic process in the simulations did not deviate from the modelling in the controller's computations. Still, the simulations indicate the working and the potential effects of the ITM controller design.

In a more complex network (Arena and surroundings), the effects of the controller design are promising as well. The integrated controller design achieved an almost perfect score by preventing spillback very effectively. This was mainly due to the route guidance component of the controller, the departure time component seemed to have small negative effects on the total delay in the network. A few reasons for this were presented earlier. These reasons - and possible solutions - are discussed here.

1. Complexity of the network, many routes available for the event-bound traffic. This causes more distribution in the departure time shift optimisation, as a fixed route fraction is used there.

A possible solution is to make the route fraction assumption dynamic, instead of fixed. To do this, some kind of interaction between the departure time advice and route guidance components of the controller is needed: the most recent split fractions at nodes can be used to calculate route fractions from the origins to the event venue. This is simply a feed-forward process, which can be implemented without too much effort: no iterative interaction between the optimisation components is needed. A disadvantage of this solution can be that the most recent route advice does not lead past the bottleneck queues (which are spilling back), causing the optimisation to perform no shifts, while these might be beneficial. Choosing one fixed route as 'risky for spillback' - similar to the synthetic network for departures only - has the benefit that the departure time advice becomes more powerful. However, if spillback threatens to occur on the alternative route, the departure time advice can do nothing about it. Therefore, a dynamic spilt fraction as input for the departure time advice seems to be a suitable solution for the complexity issue, provided that this interaction between the route fractions and the departure time advice is modelled accurately.

2. Penetration of the advice into the whole traffic system. A relatively low number of travellers could be shifted, so that the spillback problem could not be handled by the departure time advice alone.

The occurrence of this issue is very dependent on the demand scenario in the simulation. If the share of the background traffic is lower, the departure time advice for event visitors is more able to reduce the speed of the queue formation on main roads. The traffic demand distribution over the two target groups can however not be influenced. Of course, a higher penetration rate of the advice could help as well, but only if the accuracy of the optimisations (especially the departure time optimisation) is increased: this requirement can be derived from the sensitivity analysis of the controller.

Modelling-wise, there are not many solutions to this problem. One option could be to make the split fraction assumption at the origins dynamic (this is the proposed solution at 1.). This would lead to a more realistic assumption of the traffic propagation in the optimisation model, which might lead to more effective and accurate shifts: this increased number of effective shifts leads to a higher share of the advice in the traffic system.

3. Assumptions are needed to simplify the departure time optimisation model. The optimisation is path-based, which requires aggregation of conditions on the links on a path. This might cause sub-optimal actions, which the controller will try to correct again during the simulation.

The accuracy of the formulated departure time optimisation can be increased by using another method for the aggregation of the path-based variables that are used in the travel time function. For instance, the queues on the links of a path are simply summed for each time interval, which then represent the queues on a path. This assumption can be made more realistic by also taking the travel times on links into account to aggregate queues that a departing event visitor will encounter on its route. Other variables of the travel time function can be approximated more realistically as well.

It might also be possible to change the nature of the departure time optimisation from path-based to link-based (similar to the route guidance). The fact that the route guidance performs excellently, indicates that the link-based approach is accurate and might work for the departure time advice as well. However, changing the optimisation to a link-based model is quite complex, since the objective function and the constraints will all have to be adapted.

Another solution, requiring more effort, is iterating between the advice optimisations and the prediction model. This will change the control strategy into iterative predictive control: the accuracy of the advice will be high, but the computation time increases.

Despite the issues with the departure time advice in the Arena-network, the overall performance of the controller is very good. In the synthetic networks, all the components of the controller are effective, while the IRG is able to make a great difference in the simulated Arena-network. Although this simulated network is of course a basic representation of the network and the traffic around the real Arena (and parking lot choice is not taken into account in the simulation), it can still be derived from the results that the controller design has great potential to improve the traffic conditions at large-scale events. The exact effects of the controller (and its separate components) depend on the network in which it will be applied, the traffic demand (of event visitors and background traffic) and the initial split fractions of the event-bound traffic.

This dependency on external factors has to some extent been evaluated in the sensitivity analysis, where also the optimisation inputs were analysed. Many factors in the traffic system are however stochastic: they vary over time, sometimes even during the course of a trip. It might be interesting to evaluate the controller’s performance in a stochastic simulation environment (e.g. Monte Carlo analysis), to understand more how the controller will react to unexpected variations in the traffic process. Capacities, demands, departure time advice requests, route fractions of unguided traffic, etc. are examples of stochastic inputs that can be analysed.

Furthermore, a crucial factor for the success of application of the ITM controller in reality is the gap between the real traffic process and the modelling in the controller's components. If this difference is large, the controller will not be functioning optimally, leading to a poor performance. In the worst case, the controller could even have negative effects on the traffic situation around large-scale events. This difference between the traffic process in reality and the predictions and optimisations of the controller must therefore be analysed thoroughly in future research before the ITM controller is applied in practice. Another attention point is the choice for a prediction horizon and step size of the optimisations in reality. The effects of these variables have not been assessed in this study, but these might have significant influence on the controller's performance as well. This is also left for future research efforts.

5.7 Conclusion

In this chapter, the simulation of the controller design was discussed. For different networks, the controller was evaluated. In simple synthetic networks, the working of the controller and its components was tested. Both the route guidance and the departure time advice achieved a reduction of delays in the network by preventing spillback from the event bottleneck to the main road.

In a case study network (Arena event venue), the controller's performance was compared to the performance of DRIPs. While the DRIPs tended to overshoot with their advice, the controller was able to take its own effects into account (to some extent). Therefore, the individual route and departure time advice controller was able to give proactive and more effective route advice.

Pre-trip calculation of the route guidance also had positive effects, compared to the no information case and the DRIP-scenario. Although it was not able to prevent spillback, pre-trip advice will delay the start of severe congestion. This offers opportunities for the practical application of the controller. The predictive component of the controller mainly influences the total delay of the event visitors, a non-predictive controller was still able to prevent spillback in the Arena-network (and thus also delay for the through traffic). It is likely that the effects of the prediction model increase when the network to which the controller is applied becomes larger and more complex.

Most importantly, it can be concluded that the effects of the integrated controller design and the separate components are dependent on the situation to which they are applied. The simulations have shown that networks with only one or two routes from the origins to the event location are suitable for departure time advice. Application to more complex networks requires some adaptations to the departure time optimisation model. The route guidance component seems to be very effective in complex networks, but its effects on total delay ultimately depend on the demand of both the event-bound and the background traffic. This was also identified in the sensitivity analysis, where also the effective penetration rate was acknowledged as an important factor in the application of the controller. Increasing the penetration rate to very high levels requires very accurate representation of the traffic dynamics in the model and the optimisation, to ensure optimal decisions by the controller in simulation and reality.

In the next chapter, the application of the controller in practice will be discussed. Although the results of the simulations are promising, there is a gap between a controlled simulation environment and the current and future practice of (individual) traffic management. The implementation of the designed ITM controller will encounter several barriers and limitations. The discussion of the practical application explains how the controller can be implemented technically in the traffic system and what stakeholders, limitations and developments can be important in this process.

6 Practical application of the designed controller

In this chapter, the applicability of the controller is discussed: this is done for both the current situation and the expected future characteristics of the traffic system. This chapter gives indications about how the steps must be made from the theoretical design and analysis of the controller (as described in this thesis) towards its application in real individual traffic management. A distinction is made between the application of the controller in the current traffic system and in the future state of the traffic system. Firstly, the implementation possibilities in the current traffic system are identified, as well as barriers for the application. Secondly, interesting extensions of the controller design for future application of ITM are proposed, to enhance the controller's influence on the traffic system and its applicability in practice.

6.1 Application of the controller in the current traffic system

The controller is designed to reduce hindrance at large-scale events, also for the properties of the current traffic system. The simulation of the ITM controller has identified its potential to improve the traffic situation at events. However, this does not mean that application of the presented work is directly possible. Presumably, adaptations to the controller or the prevalent traffic management methods are needed to fit the design into traffic management in current practice. For applying the controller in practice, two approaches are distinguished:

- **Offline** application of the design: for a given network and a given demand, the controller's actions and effects are simulated in a virtual environment. There is no interaction with real road users. Such an offline modelling approach is similar to the simulations of the previous chapter. The offline simulations can be used to perform what-if analyses, in order to find the optimal traffic management measures in certain situations. The ideal target group for ITM in reality can be identified as well. This offline application is not very far away from the presented simulation methodology. However, the use of the offline computed advice in reality is risky: to achieve a good performance of the offline computed advice, there must be a strong match between the real traffic process and the model of the ITM controller. Therefore, it is likely that offline simulation of the controller's actions will be used to derive more qualitative traffic management measures that can be taken regarding the route and departure time advice to event visitors.
- **Real-time** application of the controller: the controller uses the current traffic states to predict future traffic states, in order to optimise its route and departure time advice. This advice is calculated in an online manner and is sent through to real individuals, which will change their route and departure time choice behaviour. It is important that the computation time of the controller is low enough to enable the real-time optimisation of the advice. The computation time of the controller will depend strongly on the complexity of the network: more links and more alternative routes mean that the optimisations will have to take much more variables into account. This might be a barrier for the real-time implementation in complex networks. However, for simple or simplified networks, the controller should be able to compute its individual advice in time (as was observed in the simulations).

These two different approaches to the application of the controller also have different requirements: applying the controller offline is technically rather straightforward (not very different than the already performed simulations), while real-time application requires more effort and management of different stakeholders that are involved.

6.1.1 Requirements for application in the current situation

The requirements to apply the controller are different for the offline and online situation. For offline application, the following data is needed:

- Network properties, including all sorts of data about the network's links;
- OD-matrix over time, distinguished for different target groups;
- Estimations of split fractions at decision nodes.

The accuracy of this information determines the extent to which the offline computations can be used in reality. It is likely that quite a number of assumptions is needed to run the offline simulation model. Therefore, it might be needed to calibrate and validate the (base case) simulations first, comparing the results to real traffic data (e.g. from loop detectors). If the model is validated, the results of the simulations are more persuasive for real-time application of the controller's simulation results.

The current design of the controller is able to handle only one destination for the guided traffic. An extension of the optimisation model is needed if multiple destinations are taken into account in the offline simulation of a network. Furthermore, improvements to the ITM controller that were proposed in the design and simulation chapters can be implemented to increase the accuracy of the controller's actions.

It is important to note that the simulations were performed for specific networks and demand scenarios. Although the mathematical formulation of the ITM controller makes it very flexible – it can be adapted in many different networks and with many different demand scenarios – the scripts used for the simulation still contain situation-specific elements. If one would wish to develop the mathematical formulation into a software application, additions and adaptations to the current script are needed. Probably, other programming languages and other optimisation software is more suitable to create such an application. This program should have a user interface, where network and demand inputs can be uploaded (e.g. from Excel) and optimisation inputs can be adapted (for deeper analysis). This development of a situation-independent program is key for the flexible offline use of the ITM controller simulation. A possible architecture for such a tool is presented in Figure 6.1.

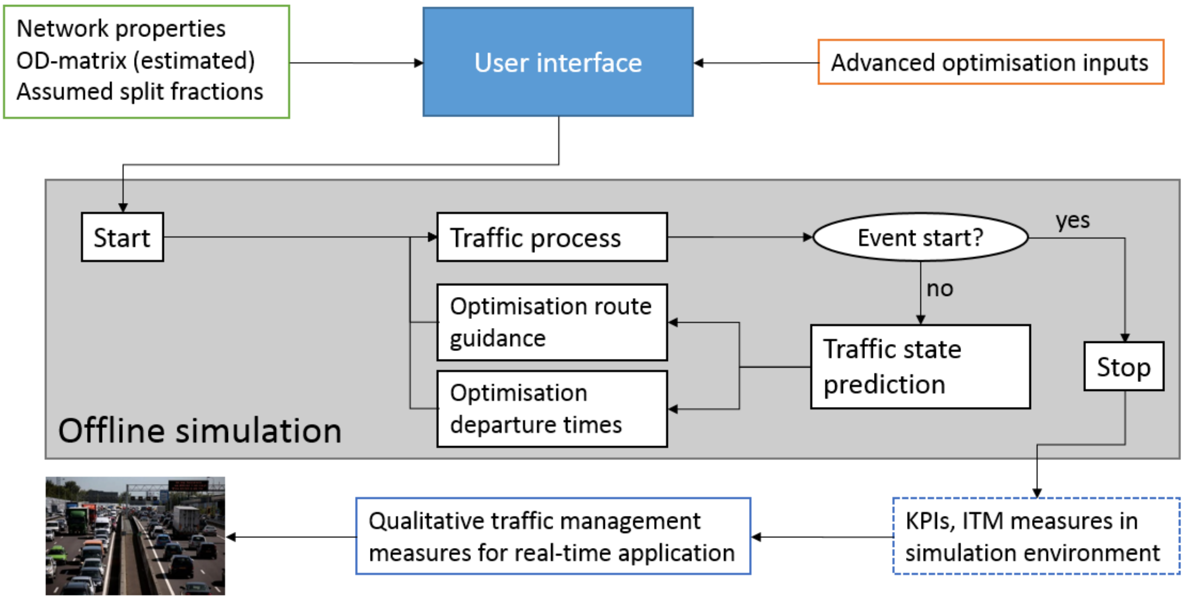


Figure 6.1: Conceptual architecture of an offline ITM simulation tool

The figure depicts the working of the controller and its interaction with the inputs that are uploaded via the user interface. The results of the offline simulation are saved (KPIs, just as in the simulation phase of this thesis). The ITM measures that were taken during the simulation can be translated into all sorts of (qualitative) traffic management measures that one could apply in real-time to improve the traffic conditions at an event.

Another option for the offline application is to integrate the simulation tool into an already existing dynamic traffic modelling software package, as some sort of plug-in: this increases the convenience for possible users of the tool.

In addition to the offline application of the ITM controller, real-time use of the controller requires the following:

- Real-time information about cumulative counts on the start and end of all links in the network. This could be derived from loop detector data. This information is used for the traffic state prediction and the advice optimisations. The update interval should be roughly every minute. A barrier for the real-time implementation of the ITM controller could be that the real-time data is not sufficiently accurate or complete. The accurate estimation of the traffic states was outside the scope of this thesis, but for the online application of the controller it is valuable to investigate whether the measured states will be accurate enough and how the quality of the measurements can be improved;
- An interface between the controller (back-end) and the individual users requesting and receiving advice. This can be any provider of in-car route guidance (e.g. Flitsmeister, Waze, Livecrowd). Possibly, this service provider can help increasing the effective penetration rate of the controller;
- Arrangements between the advice provider, the road authorities and the event organisation, to streamline the interaction between conventional traffic management methods (DRIPs) and the individual traffic management. The interests of the stakeholders involved should be incorporated in the design of each case-specific individual guidance controller. Furthermore, these arrangements should contain the set of alternative routes that the service provider is allowed to use. This prevents that travellers are routed via undesirable routes (for environmental or safety reasons).
- In future situations, the controller’s computations and actions could be *integrated* with road-side systems, so that the in-car and road-side traffic management systems fully take each other’s actions into account. However, this requires additions to the optimisation models, as well as adaptations to the current methodologies of the road-side systems. Furthermore, the operator of the road-side systems must participate in such an integration process.

This way, the controller’s calculations can be implemented in the operations of a central traffic control centre. The interaction between the ITM tool user, the traffic, the service provider and the controller’s operations are depicted in Figure 6.2. Again, inputs regarding the simulated network and demand, as well as the optimisation inputs, can be uploaded using a user interface. Every control interval, the controller predicts the traffic states, based on measurements of the real states. This leads to the optimisation of the advice, which is communicated to the users of the service. The traffic conditions over time are saved in KPIs, for later evaluation of the controller’s performance in real-time

Note that the proposed architectures (also the offline simulation application) can be built-up in steps: one could develop the route guidance component of the controller first for offline application, before proceeding to a tool that is able to compute the route advice in an online manner. If the results are good, the departure time advice can be added as well.

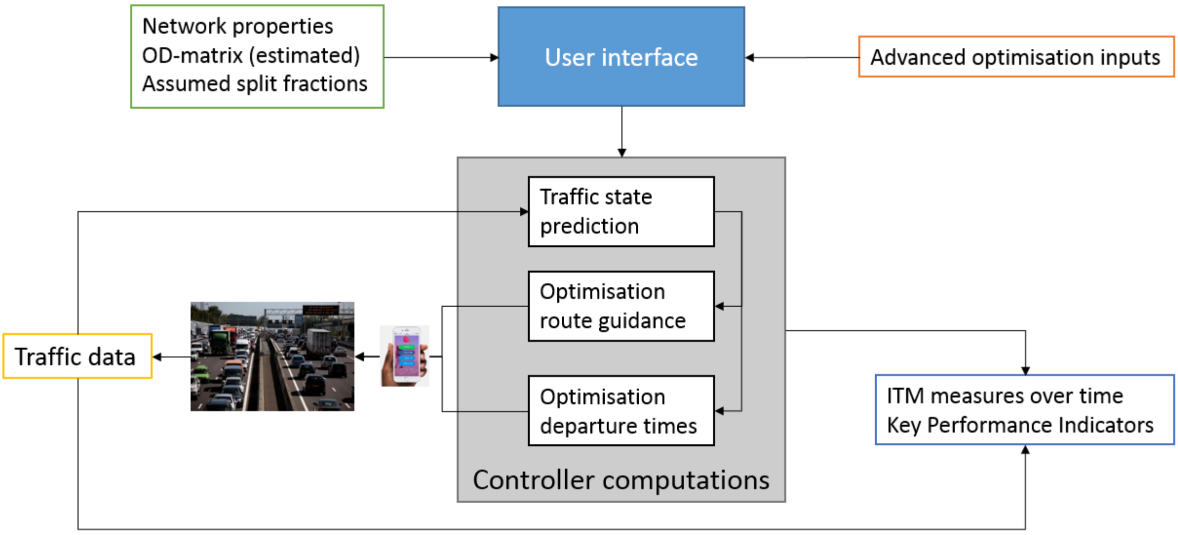


Figure 6.2: Conceptual architecture of real-time application of the ITM controller design

6.1.2 Event-like conditions to which the controller could be applied

The individual travel advice controller might not only be applicable to large scale-events. Other situations in which the controller can be applied, are road works and incidents. In these cases, the traffic situation is non-recurrent and spillback to other parts of the network can occur as well. This spillback delays traffic that is not routed via the bottleneck (for instance caused by a lane closure due to the incident or road works). This makes road works and incidents to some extent similar to large-scale events.

- **Road works**. Road works are planned: in most cases, planned road works are prepared in a traffic management context as well, with the so-called *scenarios*. Due to the capacity reduction that arises as a consequence of the road works, queues might form. To prevent these queues from spilling back, ITM can be applied: the designed controller is possibly able to target the traffic that will have to pass the bottleneck and to give these individuals optimised advice. Road works are also excellent cases for offline simulation of the controller, to evaluate what traffic should be steered in what manner during the actual road works.
- **Incidents**. Incidents are more sudden capacity reductions. To apply the controller to incident management, the controller must be able to target the traffic causing the queues quickly. Probably, route guidance is the most effective at incidents, as departure time advice requires more long-term planning: incidents are difficult to predict. In an offline context, simulations could be performed to do a ‘what-if’ analysis to evaluate how the (individual) traffic management should react to incidents at a specific location.

These other possibilities for the application of the ITM controller are taken into account in the analysis of the involved stakeholders.

6.1.3 Involved stakeholders and their interests

An important aspect in the application of the controller design to a practical situation is the stakeholders that would like to work with the controller or that will be affected by the controller’s actions. What stakeholders will be involved with the individual guidance controller, depends on the situation to which the controller is applied. The design of the controller (with the mathematical optimisations) is flexible: this means that the specific wishes of a stakeholder can be incorporated in the operation of the controller whenever it is applied in an offline or online sense. This makes the ITM controller design fit-for-purpose, and a possible software application should give the opportunity to change inputs in the controller simulations or real-time operations. The following stakeholders for the controller's implementation and application are identified to be the most important:

- Road authorities and operators;
- Traffic information service providers;
- Event organisations;
- Contractors;
- Road users, specifically users of the ITM.

Both the benefits for these stakeholders and the possible barriers of the implementation of the designed controller will be discussed in this section.

Road authorities and operators

The road authorities and operators (Rijkswaterstaat, provinces and municipalities in the Netherlands) are key stakeholders for the implementation of ITM at large-scale events, road works and incidents. They play a big role in the planning of the (dynamic) traffic management measures for these situations, and controlling the traffic management in real-time during these events. Therefore, both offline and online application of the controller by road authorities is possible.

The design of the ITM controller suits road authorities well: the design is characterised by the (constrained) system optimal goal of the advice. Furthermore, the controller is centralised, meaning that it computes the individual advice based on the traffic states in the whole network. It has been shown in the simulations that the controller is able to predict and prevent spillback from (event) bottlenecks towards important links in the network, reducing the delay of through traffic significantly by shifting users to other routes or departure times. Mainly the predictive nature of the controller and the influencing of departure times of travellers is quite new for road operators. The high performance level of the controller design is attractive for road authorities: the controller is able to use the network in a more optimal way, so that expensive infrastructural changes would not be needed.

Another benefit for the road authorities and operators is that the controller design enables them to stay in charge of the information provision to individual drivers in the network. With the growing importance of in-car navigation and information systems (especially on phones), the risk exists that road authorities will have less influence on how the traffic is steered in the network. The service providers will become more and more independent, using traffic data that they gather themselves. Regarding traffic management, it is debatable whether these service providers are able to achieve a situation on the road that is desired from a societal perspective. Centralised guidance by road authorities would mean that the goal of the advice would be more unified over the driver population than if many service providers would influence a small portion of the traffic system with their own methodologies.

These benefits of the controller design don't mean that there will be no issues with implementing such a controller in the usual operations of the road authorities. Currently, road operators make use of traffic management *scenarios*, which are basically a large set of if-then rules to influence the traffic in the network. On first sight, these rule-based control scenarios seem to mismatch with the automatic nature of the designed ITM controller. The complexity of the controller design and possibly also less transparency of the controller's computations might be a barrier for road operators to implement the controller design for individual advice. However, the automatic nature of the controller has benefits as well for a road operator: the controller is able to do work on the background, keeping the traffic conditions on a high or at least acceptable level without any intervention of the operators in the traffic management centre. This means that the workload for the operators is lowered by the actions of the ITM controller. Furthermore, it might be possible to find a framework in which the controller can co-exist with the currently used scenarios. This framework would then consist of the conventional DTM systems being operated as usual, with in addition a component that describes the controller's influence on the traffic system by individual advice. This also enables incorporating the (expected) effects of road-side DTM systems into the optimisation of the controller, to enhance the quality and effectiveness of the advice.

Traffic information service providers

For any online application of individual route and departure time advice, a traffic information service provider is needed. These providers are the interface between the controller and the end user of the advice. Although road authorities could develop their own information and navigation application, it is probably better to use existing services for ITM. These services are already widely used and accepted by the road users.

For the service providers, the controller design is interesting as well: the controller enhances the quality of the advice (with respect to current steering methods), which means that the service will lead to better traffic conditions in the network. This quality increase might lead to more clients (event organisations, road work contractors) and a higher satisfaction of the users of the individual advice. The increase of the quality of the advice is caused by three properties of the controller:

- The automatic nature of the controller: this means that service providers are not bound to control scenarios anymore, if they would cooperate with a road authority to increase the network throughput at an event. Any cooperation could make use the ITM controller design, while keeping a connection with the existing DTM methods.
- The predictive nature of the controller: although traffic state prediction might not be very new for service providers, the methodology used by the controller is different than the conventional prediction method used by the providers. The controller bases its predictions on the current traffic states, estimated demand profiles and importantly, traffic shockwave theory. This method is an addition to the data-based prediction methods that are used in the current traffic system.
- The ability of the controller to optimise the departure times: this is a new aspect for traffic information service providers and therefore, this component of the controller design could be interesting for them.

The disadvantage for service providers of the controller's implementation at road authorities might be that road authorities gain more control of the actual advice that is given to the clients of the service provider. This might be a barrier for the service providers to cooperate with the road operators. Furthermore, the control goal of the design is a system optimum: this means that the advice for one individual can lead to a better travel time than the travel time of another advised individual (or even unguided users). Traffic information service providers would like to give each of their users the best advice – the route with the shortest travel time – leading to a user optimum in the network. The controller design tries to find a balance between the system optimum and the user optimum, by constraining the unfairness between advised alternatives with the indifference bands of the advised users. This way, the unfairness is limited and maybe not even perceived by the user of the service.

Event organisation

For the event organisation, the expected effects of the controller are also attractive: the controller will be able to reduce any traffic hindrance caused by the event. This reduction is for all target groups, so both the background traffic and the event visitors will benefit. Another advantage of the controller is that the departure time advice optimisation module ensures that event visitors will depart on time, so that they chance of them arriving too late at the event is small. However, the controller might shift travellers to departure times so that they will be *just* in time. This is of course a bit risky, and also the income of the event organisation in the direct surroundings of the venue might reduce, since visitors will have less time to buy food, drinks, merchandise, etc.

The use of individual advice will enable the event organisation to have a better connection with their users. Firstly, they will have a better knowledge of the flows of visitors towards the events: the number of visitors, their origins, the modal split, etc. Secondly, improving the experienced travel time of event visitors will make them more satisfied about the event, meaning that there is a larger chance that they will return for later editions of the event. On a higher level, the use of an ITM application (or another medium) will enhance the experience of the visitors of the event. It also offers opportunities for the event organisation to reach out to their visitors with surveys, in order to improve the quality of the event even more.

With some small adaptations, the controller might also be able to distribute the incoming traffic over various parking lots and arrival times at the event venue. This means that the workload for personnel at these parking facilities is spread. A disadvantage for the event organisation might be that they might have less parking earnings, as the more expensive parking facilities close to the event venue might not be fully filled. On the other hand, the controller might offer the opportunity to maximise the parking revenues by smart individual routing advice.

The event organisation might see a disadvantage in the system optimal goal of the ITM controller. The system optimal routing might mean that event visitors will benefit less of the routing (in terms of travel time delay) than the background traffic. The constraints of the system optimal routing optimisation try to reduce this unfairness as much as possible.

Contractors

Contractors could benefit from the ITM controller design by applying it at their road works. Including this controller in their plans will reduce the expected delay caused by the road works (especially if any relevant spillback can be prevented). Reducing the effects of the road works on the traffic performance in the network will offer the contractor a better chance to win the tender for the road works. The ITM controller is useful for the contractors in both an offline and online sense: an offline application can be used to determine the effects of their road works (temporary lane/road closures) and to find the optimal target group to give individual advice to. Online application is necessary when the contractor wants to steer the traffic based on the real-time effects of the road works.

A difficulty for the contractors would be to reach out to the target group that they would like to steer. Event visitors are much easier to reach, for instance via the ticketing services. If a navigation app would be used to offer the individual advice, the floating car data of that application can be used to target drivers that frequently use the road section that will be under construction.

Users of the individual travel advice

For the online application of the controller, the end user of the individual advice is the most important stakeholder. The proper usage of the individual advice controller by the users (event visitors or other target groups) is crucial for the success of the application of the controller design. The benefits for the users are clear: there are less delays in the network (also for the user group), and travel times over the different routes to the destination are influenced in such a way that the travel time difference remains within acceptable bounds. There are two factors that influence the controller’s performance strongly, which are determined by the behaviour of the users:

- Compliance to the individual route and departure time advice;
- Penetration rate of the individual advice in the traffic system.

Both these factors will be affected by the quality of the advice: if the quality of the advice is high, users are more likely to comply to it (since they will have positive experiences using it). Furthermore, high quality of the advice will lead to more usage of the individual advice, as event visitors might recommend the service to others. It is important to note that a higher compliance and a higher penetration rate will lead to better advice quality again (the controller will have more insight in the traffic system). This higher quality might again lead to better compliance and higher penetration of the service. Therefore, the quality of the advice must already be good at the early stages of the implementation of the ITM controller design, as this will lead to self-improvement of the ITM controller’s performance in the traffic system.

Note that achieving a high (enough) penetration rate of the controller’s advice in the early stages of the practical application might be challenging. A possible solution for this is to implement the ITM controller’s calculations in an already existing service for in-car advice (e.g. *Waze*, *Flitsmeister*, *Livecrowd*). These services have already a significant market share in the real-time provision of travel advice to road users. At an event for instance, these platforms could aid the road authorities with improving the traffic conditions by offering their services to provide ITM to the event visitors. The individual road user (visiting the event, or travelling past a key bottleneck) can be reached via a number of methods:

- Through ticketing services, the event organisation has knowledge about the event visitors. On the ticket and via the event website, the visitor can be encouraged to use the ITM service for their travel to the event;
- Via social media, there might be knowledge about the individual event visitors: with suitable advertisements, again the ITM service for the event can be offered. This also holds for e.g. road works: if one would know that an individual uses a certain road frequently or lives close, this individual can be approached to inform them about road works and what this implies for their travel choices.

Furthermore, integration between road-side and in-car systems would increase the penetration rate of the advice. However, the information shown on the DRIPs is not individualised: still, it can be used as a support for the in-car ITM.

6.1.4 Evaluating the controller's performance in reality

If the controller design will be applied in an online manner, it is important to evaluate its effects in the real traffic system as well. To do this, an ex-post data-analysis can be performed. In this data-analysis, the situation with the application of ITM is compared with one or more situations in which the controller was not applied at the same event. In this section, the objectives and a possible setup of such a data-analysis are discussed.

Objectives of the data-analysis

There are two perspectives from which the effects of the controller's online application can be analysed: the user perspective and the road authority perspective. The following objectives are defined for the respective perspectives of the data-analysis:

- Examine what the effects are of the controller on the behaviour of event visitors;
- Evaluate the effects of the controller's actions on the traffic throughput in the network, and whether it is able to prevent spillback from the event to the main roads.

From these evaluations, possible improvements of the controller design and working can be identified. These should be simulated and implemented in future online applications.

Data-analysis setup

A data-analysis of the effects of the online application of individual travel advice could have the setup, as described below. For both perspectives, another setup is needed.

1. User perspective: this part of the data-analysis should focus on behavioural changes of the user. After the users receive the individual advice (or after they arrive at their destination), a survey can be sent to them. If they participate, they will answer questions about their route and departure time choice, compliance to the advice, and the whether they actually took different actions because of the advice.
2. Road authority perspective: this part of the data-analysis focuses on the traffic states during the application of the ITM controller. These are compared to the states in a reference data set: this reference can be an event at the same location, but without the application of the ITM. As a reference to these both event cases, a conventional traffic situation (no event) can be used. This way, the relative improvement of traffic performance by the controller can be computed.

As data sources, loop detector data and floating car data are suitable to analyse the traffic states. With these data sources, the following important performance indicators can be computed: realised route fractions, link intensities and queues, (route) travel times and delays, relative utilisation of the lower level network. Other indicators might be suitable as well.

The results of the evaluation can be used to improve the design (settings) of the ITM controller, in order to achieve a higher quality of the individual advice.

6.2 Application in the future traffic system

The presented design of the ITM controller can be placed in a more general development in the traffic system. From the current situation – where road-side guidance still has a large role in the traffic management –, the traffic will evolve into a fully automated system in the future, with the expected implementation of autonomous vehicles. Drivers will take much less decisions: not only on the microscopic level (braking, accelerating, steering), but also on the macroscopic level (route choice). The first step in this development is by making traffic management more individual and fit-for-purpose. The designed controller takes this first step. With some adaptations, the controller is also suitable for application in later stages of the evolvement process. This suitability for future application is discussed in this paragraph.

6.2.1 Suitability of the controller for autonomous vehicles

In a system with a large number of highly automated vehicles, it is likely that routing decisions will be made by the vehicle or a central entity managing the vehicle fleet in the network (in the case that automated vehicles will be owned by companies/authorities and shared by civilians). The automated vehicles will of course comply to the guidance that is given to them. Furthermore, the penetration rate of the advice is very high, depending on the market share of the centralised agent controlling the vehicle fleet. A few characteristics of the ITM controller design make that the controller may be suitable for steering automated vehicles as well:

- The controller can be used from a fleet management perspective: the system optimal control goal can be used to minimise the total travel costs of the whole fleet, while the constraints ensure that the travellers will not perceive their trip to have an unfair duration (with respect to trips of other travellers).
- The controller can steer vehicles *individually*, meaning that each automated vehicle may receive its own unique advice. This enables very detailed steering of the traffic, making it as efficient as possible.

An advantage of the automated vehicles is that these vehicles can communicate all sorts of data to the traffic management centre of the fleet owner or the road operator. This data can then be used to make very accurate predictions of the traffic states and to enhance the quality of the route guidance.

Whether the controller design will be applicable in the future situation, will depend on the evolvement of the autonomous vehicles: there is a variety of scenarios, in which the usage of the autonomous vehicles will be different (Tillema et al. 2015). For instance, it cannot be predicted whether the autonomous vehicles will be owned by a large population of the individual travellers or that large companies will offer shared vehicle services with their fleet. A combination of both possibilities is also an option. Hence, the exact application of the ITM controller in the future depends on the vehicle system to which it will be applied.

6.2.2 Possible extensions of the controller

The arrival of fully automated vehicles in the traffic system will probably take a few decades. Until then, the current design of the ITM controller can be improved and extended. A few possible extensions of the design are discussed below.

- Including egress times from a parking lot: the controller could take the parking location of alternative routes to the event venue into account. The walking time from the parking lot to the event venue is related to in-car travel time and added to the objective function of the route guidance optimisation. Parking costs can be incorporated as well, by relating this to travel time with the value of time of the event visitors. Furthermore, parking lot occupation rate can be an interesting objective for some stakeholders.
- Including mode choice in the controller: an extra component can be added to the controller, to distribute event visitors over an additional dimension (modes). This requires complex modelling of traffic dynamics in public transport. Multimodal travel is an important factor at events as well. This can be considered as a separate mode, but route, mode, and departure

time choice can be integrated in one network as well. Supernetworks are suitable for this, but such an integrated network approach requires a lot of computational power of the controller. For more elaboration on the working of supernetworks, the contribution of Carlier et al. (2003) is a good example.
- The controller design can also be applied to other situations: for car traffic, incidents and road works have already been discussed. But for pedestrian flows, individual advice might be interesting as well. In situations where long queues might arise (hindering other pedestrians), it can be beneficial to steer pedestrians to other queues or to let them enter the queue at a later or earlier time. Examples could be queues at large-scale events (food stands, toilets), airports (check-in desks, customs, security), or large shops.

Extending the controller's possibilities requires additional modelling or adaptations to the existing optimisation models. This way, the ITM controller can be applied to more situations, as it will be suitable for personal traffic management. The commercial viability of the traffic management controller can then increase as well.

6.2.3 Personalised advice

This Master thesis research has focused on *individual* traffic management: advising individual travellers means that travellers at the same location and time might receive different advice, in order to optimise the flows in the network. Personalised advice is one step further: it entails that the individual advice is based on the personal preferences of the advised travellers. The differences are defined in Figure 6.3.

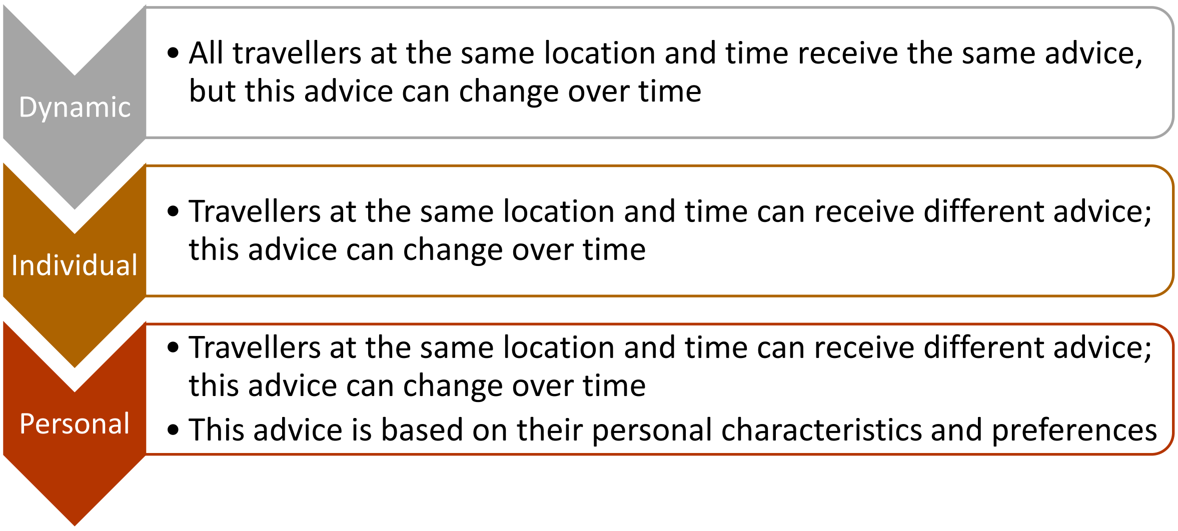


Figure 6.3: Different ways of influencing travellers' behaviour with traffic management

More personalised advice will likely increase the quality of the advice and thus, the satisfaction of the users and their compliance to the guidance. The advice will suit the individual characteristics of the travellers better. Furthermore, personal advice is also commercially attractive: service providers can advise the individual to use certain routes, stops, or parking lots that are close to facilities (e.g. shops, restaurants) that the traveller will like, according to its behavioural profile. Of course, this would require knowledge about the traveller's preferences and behaviour. To a limited extent, this knowledge is already available via data that is gathered via the internet and smartphone applications. However, the use of this (personal) data is not accepted widely, as it interferes with a person's privacy. If in the future privacy regulations would be relaxed, personal traffic management would benefit as well.

Technically, the controller design would also require some adaptations to facilitate personal traffic management. Making the advice more personal might mean that the controller will have to use a more micro- or mesoscopic approach. Another possibility is to differentiate between different target groups (based on age, gender, shopping behaviour, etc.) within the event visitor group.

It is uncertain whether the step from individual to personal traffic management will lead to a significant improvement of the traffic conditions or the commercial gains around the event venue, especially when the penetration rates remain relatively low. Most likely, the travellers will benefit the most from the personal guidance, as they will appreciate the service more because of this personalisation.

6.3 Conclusion: practical applicability of the controller design

In this chapter, a number of application possibilities have been identified, as well as the corresponding data needs and stakeholders. Firstly, the application in the current traffic system was discussed: on the one hand, the offline simulation of the ITM controller in a certain network during non-recurrent congestion events can aid road authorities, event organisations and contractors to optimise their traffic management plans. On the other hand, the controller can also be applied in an online manner, forwarding the optimised advice to the travellers via a service provider. Real-time application of the controller is more complex than offline application: it requires a high quality and completeness of traffic state measurements and a good match between the modelling in the controller components and the real traffic process.

A trial of real-time application at an event would enable an analysis of the controller’s effects using traffic data, possibly identifying future improvements of the ITM controller. A brief setup of such a data-analysis has been described in this chapter as well.

Furthermore, the application of the controller in the future was discussed. In a system of shared autonomous vehicles, the controller can be very useful. It is able to optimise the operations of the vehicles, minimising the costs or travel time of the whole fleet. Future extensions of the ITM controller have been proposed as well: incorporating multimodal traffic and parking lot choice will enhance the accuracy and the effects of the controller even more. Personalisation of the individual advice leads to more acceptance and appreciation of the service by the end users.

The application possibilities, as described in this chapter, can be summarized in a kind of timeline: the practical application, now and in the future, is a process. This is shown in Figure 6.4. Firstly, the current controller design needs improvements, to increase its accuracy and applicability in the current traffic system. An offline simulation tool can then be developed stepwise: application of the offline controller will indicate possible improvements, which will aid in the development. Similarly, the real-time application of the ITM controller can be done in a stepwise manner. Data-analysis of the application in reality might point out additional improvements or extensions to the controller design. Extensions as mode advice and personalised advice can also be implemented in the current ITM controller design, to make the controller ready for the future: a system of autonomous vehicles that can be steered by the controller.

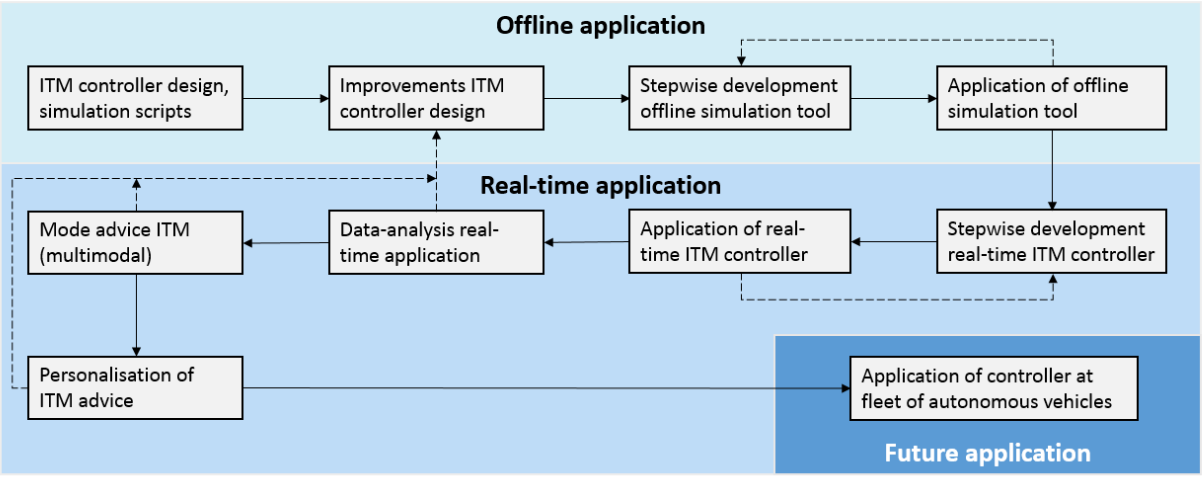


Figure 6.4: Steps for the practical application of the ITM controller. Dashed arrows indicate feedback steps in the development process

7 Conclusion

In this chapter, the conclusions of this Master thesis research are presented. Firstly, the research questions are answered. Secondly, recommendations for Antea Group and stakeholders of ITM at non-recurrent traffic events are formulated. Furthermore, the limitations of this research and future research directions are discussed.

7.1 Answering research questions

Three main research questions were formulated at the start of this research. These three questions can be answered by answering their associated sub-questions. The answers on these main and sub-questions follow from the literature study, the formulation of the ITM controller design and the simulation results respectively.

Theoretical analysis of control concepts

1. *What theoretical control concepts can be used to improve the current methods of individual route guidance?*
   1.1. *What are the possible control strategies for individual route guidance and their corresponding advantages and disadvantages?*

A number of control strategies has been studied: predictive and non-predictive control, iterative optimisation control, fuzzy logic control, artificial neural networks, and multi-agent systems. An important trade-off for all these strategies is between computation time and accuracy or performance of the route guidance controller. For example, a non-predictive strategy requires less computational effort, but is less accurate than an iterative predictive controller. An iterative predictive approach is however more complex and needs accurate prediction models to ensure good performance. Fuzzy logic control and neural networks are based on the representation of traveller behaviour. Although this can yield powerful controller performance, a lot of knowledge is needed about drivers' route choice behaviour in different situations. A multi-agent system is a very distributed way of route guidance, which is suitable for individual routing. However, the distributed nature of multi-agent systems means that it is more difficult to reach a (system) optimal assignment on the network. A summary of the (dis)advantages is given in Table 7.1.

Table 7.1: Summary of control strategy (dis)advantages

Control strategy	**Controller properties**				
	Optimality	Accuracy	Complexity	Data needs	Flexibility
Non-predictive	-	-	+	+	+
Predictive	+	0	0	0	+
Iterative (predictive)	+	+	-	0	+
Fuzzy logic	0	+	0	-	0
Neural networks	+	+	-	-	-
Multi-agent systems	0	0	+	+	0

   1.2. *What are the possible control objectives for individual route guidance and their corresponding advantages and disadvantages?*

The main control objectives for route guidance are the user equilibrium and system optimum assignment of traffic on the road network. A user equilibrium follows from the natural behaviour of fully informed travellers, making the travel times for each traveller between a certain ODpair equal. This is optimal for the individual level, but not on a larger (network) scale. To achieve optimal assignment on the network scale, a system optimum control objective is needed. This leads to the absolute optimum solution, minimising the total travel time of all traffic in the network. The downside is however that the system optimum leads to unfairness regarding the travel times among the driver population. The consequence of this unfairness is a lower credibility of the advice and less compliance to the route advice. Various approaches have been discussed that find a middle way between the user and system optimum. Making use of the indifference band of travellers seems to have quite some potential in approximating a system optimal assignment, while also not harming the perceived route utility of the drivers. Furthermore, the input (travel time, queueing time, emissions) into the optimisation can be adapted to fit the control objective to the specific purpose of the ITM controller. A summary of the possible objectives and their (dis)advantages is given in Table 7.2.

Table 7.2: Summary of control objective (dis)advantages

Control objective	Advantage	Disadvantage
User equilibrium	Follows natural route choice behaviour of drivers	Suboptimal solution on the network scale
System optimum	Highest level of assignment optimality on network level	Unfairness of travel times among drivers, leading to lower compliance
Hybrid system-user optimum	Seeking balance between user equilibrium and system optimum	Knowledge about travellers' indifference bands needed

1.3. What methods can be used to integrate departure time advice with route advice for individuals and what benefits do they have for car traffic in non-recurrent congestion?

Influencing the departure time of travellers has a significant impact on the traffic conditions in the network over time. Since travellers have a perception error regarding the time-dependent travel times in the network, offering departure time advice can help them making decisions for both the long and short term. Often, descriptive information is given to travellers, so that they can adapt their departure behaviour. Prescriptive information (advice or guidance) is more persuasive. This can be combined with prescriptive information about route choice of the individual travellers. The departure time advice can be determined integrated with the route guidance, or in a separated manner. An important aspect of the departure time advice is the preferred arrival time of the users. Travellers do not want to deviate too much from this preferred arrival time, unless shifting their departure time (and consequently their arrival time) has significant benefits for their total travel costs.

Both a system optimum and user equilibrium objective can be chosen for the departure time advice (a hybrid variant is possible as well). This is also possible if the departure time would be integrated with the route guidance. The optimal value is then found by assigning the drivers over both time and space. Although it is questionable whether departure time advice can be applied for the very short term (non-recurrent congestion), it is expected that it can help to avoid the very sudden peaks in demand on the network during large-scale events. Therefore, it might also be possible to counteract spillback from bottlenecks at events with departure time advice.

Applying the theoretical concepts to a controller design for large-scale events

2. *How can the theoretical concepts of individual traffic management be used in a controller design specifically aimed at car traffic at large-scale events?*
    2.1. *What requirements does an individual traffic management controller for large-scale events have?*

The requirements are based on the problem statement and the specific characteristics of traffic around large-scale events. The requirements that are formulated, defined what the controller must be able to do and how it should do it. In short, the requirements are as follows:

- The controller must give *individual* advice;
- The controller gives both pre-trip and on-route route advice to the individuals requesting guidance;
- The controller design also includes possibilities to give individuals pre-trip departure time advice;
- To counteract spillback, the controller has predictive capabilities;
- Unguided traffic is accounted for in the prediction of the traffic states and the calculation of the individual guidance;
- The controller induces a system optimal route and departure time assignment, or an approximation thereof;
- For the requirement above, a centralised control structure is needed;
- The controller doesn't heavily rely on historical databases;
- The traffic state predictions are based on the current traffic states;
- The only event visitors are guided from their origin to the event location (one destination);
- The event visitors are distributed over fixed route sets by the controller.

These requirements are the basis of the controller design, and already give a clear direction for the choice of building blocks (elements) of ITM.

    2.2. *What theoretical concepts and methodologies are the most suitable for an individual traffic management controller for large-scale events and how must these be implemented mathematically in the controller design?*

The formulated requirements indicate the use of the following building block elements:

- Control strategy: **predictive** (as required). A non-iterative procedure is used to reduce the complexity of the controller, at the cost of some accuracy of the control signal.
- Control objective: **constrained system optimum**. An approximation of a system optimal assignment was required. To reduce the experienced intrinsic unfairness of the system optimum by the travellers, this objective is constrained with a maximum detour time of travellers.
- Integration with departure time advice: as required, **departure time advice is included** in the controller. A mathematical optimisation is used to compute how the departure times of requesting individuals should be shifted (to the future, and if possible to earlier control intervals). There is no direct interaction between the departure time advice and the route guidance, although these advices do influence each other in reality.

The three components of the controller (prediction model, route guidance, departure time advice) are mathematically defined as follows:

- Prediction model;
    - The LTM of Yperman (2007) is used. This model uses shockwave theory to calculate traffic flows and future states in the network.
- Route guidance optimisation;
    - The objective function minimises the total travel time all vehicles on all links, taking a linear link travel time function into account
    - The optimisation is constrained by a maximum travel time difference between used route alternatives, to limit the unfairness of the system optimal assignment
- Departure time optimisation;
    - The objective function minimises total travel time of departing vehicles, including shift time of individuals and a time penalty for assigning traffic to departure time intervals with queues
    - The optimisation is constrained by a maximum shift time of individuals from their preferred departure time, a maximum arrival time (to prevent late arrivals at the event), and a maximum unfairness between departure time alternatives

The result is a flexible controller design, which can be applied in many networks and situations. The predictive abilities, the optimisation-based advice and the influence of the controller on departure times are all features that can make a significant difference with the common operation of route guidance systems.

Evaluating the controller design through simulations

3. *What are the quantitative effects on traffic performance of individual traffic management at large-scale events?*
    3.1. *What is the performance of the theoretical design of the ITM controller in a simulation environment?*

The performance of the controller was tested in fictive, synthetic networks and in a case study network, namely the Arena event venue and the surrounding road network (simplified). In the synthetic networks, a base case scenario – in which spillback from the event bottleneck would occur due to poor fixed route and departure time choice – was compared to a situation in which the controller (or a component thereof) was applied. The effects of the application of the ITM controller in the synthetic networks are large: both the individual route guidance and the departure time advice separately are able to fully prevent spillback to the main road (which is used by through traffic). This is reflected in the amount of vehicle hours lost (VHL): the VHL of the through traffic is nearly equal to zero, while the event-bound traffic benefits from the controller as well. Compared to the no information scenario, the travel times on alternative routes were equalised as well. This is achieved by the individual route guidance, that distributes traffic optimally over routes, aided by the departure time advice component of the controller.

In the Arena-network, the performance of the full controller design was again compared to a base case with fixed routes and departure times. Furthermore, a reference case with the application of DRIPs (guiding traffic to the shortest route towards the event) was simulated. Again, the controller design is able to reduce the delays in the network - of both through traffic and event visitors – greatly (~ 99 % reduction) with respect to the reference cases. The ITM controller prevents large queues at the exits of the motorways by distributing the event-bound traffic over the entrances to the Arena event area. Spillback is therefore reduced to a minimum.

3.2. *How do the different components of the controller design affect the simulated traffic performance?*

In the synthetic networks, the route guidance and departure time advice optimisations were tested separately. For both the components, this led to benefits for the event-bound traffic and the through traffic in terms of delay, compared to the base case.

In the Arena-network, the full design of the ITM controller was compared with simulations of the 'partial' designs, in which components of the full design were left out:

- Predictive on-route route guidance only: the route guidance component seems to have the greatest contribution of all the controller's components. The VHL during the simulation of the route guidance only are even lower than during the full controller design simulation in the Arena-network: again, the VHL for both background traffic and event visitors is reduced with more than 99 % in the simulation.
- Predictive departure time advice only: the results of the departure time advice only simulation in the Arena-network are poor. The effects are even slightly negative: the VHL are higher than in the no-information case. Probably, this poor performance is caused by a combination of factors. Firstly, the structure of the Arena-network is very complex, with many routes to the destination per origin: the strength of the departure time optimisation reduces strongly when it has to take multiple routes into account. This leads to no significant effects of the departure time advice. Secondly, the negative effects are caused by the slight inaccuracies in the path-based objective function of the optimisation.
- Non-predictive on-route route guidance: leaving the traffic state prediction model out of the controller's route guidance calculations slightly reduces the performance of the controller: still, the individual route guidance is able to prevent spillback to the motorways, but it is not able to distribute the queues over the entrances as nicely. Therefore, mainly the event-bound traffic in the Arena-network suffers (in terms of VHL) from leaving out the prediction component of the controller. Apparently, the prediction model does not give strong benefits in this specific case: the system optimal control goal can also be induced to some extent with myopic steering. However, in a different demand case or a totally different network the prediction component may be crucial to avoid spillback and to keep the delay for both target groups relatively low.
- Pre-trip calculation of route guidance: in this case, a traffic prediction of the whole simulation time is made, which is used to compute the optimal IRG actions. These IRG actions are input into a simulation of the 'real' traffic situation. This pre-trip calculated advice leads to a reduction in VHL of roughly 60 %, but still the through traffic suffers from spillback. However, such calculation of advice might be good starting point for application of the controller design in reality.

3.3. *What is the influence of the input variables on the performance of the designed controller in the simulations?*

A sensitivity analysis has been executed to evaluate the influence of the input variables on the performance of the full ITM controller design. Five factors were analysed by variating their value to a high and low value in separate simulations.

- Event visitor traffic demand
- Effective penetration rate of the controller
    - This variable is composed of the penetration rate and the users' compliance

- Relative penalty of departure shift time with respect to travel time
- Queue assignment penalty
- Alternative unfairness threshold

Of these variables, only the event visitor demand and the effective penetration rate have a significant influence on the ITM controller's performance. These are external factors, which are difficult or even impossible to influence. Logically, a low demand (- 20 %) led to less delay in the network, while an increased demand (+ 20 %) resulted in some spillback from the event entrances to the motorway: the controller was not able to prevent the fast growth of the queues there. Thus, the ITM controller is useful in cases where there is not too much congestion: this has also been identified in the literature study. In situations with very heavy congestion, the alternative routes may become congested as well, which leads to a state where route advice cannot make a difference anymore.

The effective penetration rate (combining penetration rate and compliance) also has noticeable effects on the performance of the full controller design. Decreasing the effective penetration rate from 40 % to 20 % leads to a large increase in the VHL during the simulation. Increasing the effective penetration rate to 60 % also results in an (unexpected) increase in VHL. Possibly, this is caused by an overreaction by the route guidance component of the ITM controller. On the other hand, sub-optimal actions by the departure time advice component could be amplified by the higher penetration rate or compliance. An increased effective penetration rate (compliance and/or penetration rate) is therefore only useful if also the accuracy of the controller increases as well.

This leads to the conclusion that the effectiveness of the ITM controller design depends strongly on the network and the demand profile to which it will be applied. The departure time advice seems to be applicable in relatively simple networks where there are only one or two approach routes for the event. In complex networks with a large amount of through traffic demand, the performance of this component degrades. The IRG component is however very effective in a complex network as the Arena-network. However, the effectiveness in other networks depends on the ratio between the event-bound traffic demand and the total capacity of the approach routes to the event.

Main conclusions of this Master thesis

Summarizing the answers to the research questions, the following can be concluded from this research.

- For the design of an ITM controller, there are many options for the control strategy, structure, objective and inclusion of departure time advice. For the specific application of ITM to large-scale events, trade-offs are needed regarding the complexity (computation time), accuracy and historical data needs in the choice for certain design elements.
- To apply ITM at a large-scale event to improve the traffic conditions there, a centralised one-shot predictive controller is needed. This controller induces a constrained system optimum on the road network by optimising the on-route route guidance and pre-trip departure time advice for individual event visitors.
- Simulation of this controller design in a representation of the network around the Amsterdam Arena (event venue) has revealed that ITM at large-scale events has potential to solve traffic issues like spillback. In complex networks, the individual route guidance by the controller affects the traffic conditions the most, while in more simple networks (e.g.

limited number of approach routes to the event venue) the departure time advice can be effective as well. The effectiveness of the implementation of the ITM controller vary for the network and demand scenario to which it is applied.

- A sensitivity analysis of the performance of the ITM controller shows that its effectiveness mainly depends on external factors such as demand, penetration rate and the network layout. Therefore, application of the ITM controller in a real-time manner should be done with care.
- To apply the ITM controller design in practice in the current traffic system, this research has proposed the development of an offline simulation tool, as well as a tool to apply the controller in real-time at an event.

7.2 Recommendations for the practical application

In the simulations, the ITM controller design has proven to have potential to solve traffic issues (such as spillback) at large-scale events. The hindrance for both event visitors and through traffic can be reduced drastically by offering individuals route guidance and departure time shift advice, based on predicted traffic conditions. Following the conclusions on the technical aspects of the ITM controller and the discussion of its application in practice (chapter 6), a number of actions are recommended that follow-up on the final report of this Master thesis research:

- Firstly, it is recommended to implement some minor improvements to the working of the controller, such as the use of a more detailed node model in the LTM, or making the split fraction assumption in the departure time optimisation dynamic. This will enhance its accuracy (especially for the departure time advice optimisation). Secondly, the model can be extended for usage at other sorts of non-recurrent ‘events’ like road works and incidents. This requires that the controller can handle multiple destinations for the guided traffic instead of only one destination (the event venue).

  With these minor improvements, the designed ITM controller can be made ready for *offline* application. It is advised to develop a simulation tool, which can be used by road operators, contractors and service providers to compute optimal ITM measures in an offline manner. The setup of this simulation tool is basically a generalisation of the simulation scripts that were used for the ITM controller simulations for the Arena-network. In addition, a user interface is needed to upload the inputs for the simulation conveniently. The outputs of the simulation tool can be used to qualitatively determine traffic management measures that are needed in a certain case. In this newly developed tool, the improvements of the model can be implemented as well. An important factor in this offline implementation of the controller is the match between the modelling in the controller’s components (prediction and optimisation) and the real traffic process. A strong similarity might be needed to achieve significant benefits from the ITM controller’s actions.

- The promising results of the ITM controller design in a simulation environment serve as a persuasion for road operators and service providers to apply the concept of individual route and departure time advice in real-time at large-scale events. As was shown in this report, ITM (and especially individual on-route route guidance) has potential to make a large difference in delays in a network around an event venue. Application of a developed offline simulation tool – and the usage of its outputs in reality – might confirm these benefits. This might give rise to the development of a tool that will perform the ITM controller’s calculations in *real-time*. Again, the network properties, the optimisation inputs and more can be defined before the start of the event (traffic) with a user interface. During the hours before the large-scale event, the tool will obtain real-time traffic data from sources as loop detectors, floating car data and license plate registration cameras. This data is input into the traffic state prediction module of the ITM controller: the prediction is used in the optimisation of the individual route and departure time advice, which is communicated to the traveller via in-car service providers. There are two possible limitations for the real-time application of the controller: its computational time in complex networks and the quality of the real-time measurements of the traffic states. It is important to assess whether these limitations will actually form a barrier for the successful implementation of the ITM controller in practice. Similar to the offline implementation, the match between the modelling in the controller design and the real traffic process is vital for the real-time application as well.

- It is recommended to develop both the offline simulation tool and the online application stepwise. First, the route guidance should be implemented in the offline simulation tool; then, the computed optimal IRG should be applied some way in practice, so that the working of the IRG in reality can be evaluated and improved. Afterwards, the (improved) departure time advice optimisation can be implemented in the simulation tool. With the finalisation of the offline simulation tool, the online controller can be developed in a similar stepwise manner as well. The advantage of such a development approach is that it enables to develop the tools within projects, together with stakeholders as Rijkswaterstaat, service providers, event organisations and possibly in later stages also contractors.
- To evaluate the use of the ITM controller in practice, it is advised to execute a data-analysis. This analysis will give information about the controller's effects on the traffic conditions in the network and the behaviour of the guided users in reaction to the given individual advice. This information is useful for further improvement of the ITM controller design and the developed tools.

The design of the ITM controller can be seen as a first step from the current way of traffic management to the future with a system of automated vehicles, steered by a central entity. With small but sure steps, this future is approaching, and the main stakeholders in the traffic system can join in these advancements by individualising their traffic management measures. Now, the controller design is only suitable for large-scale events; in the future, this can be extended to road works, incidents and eventually the everyday rush hour traffic.

7.3 Limitations and future research directions

As every research, this Master thesis work is limited by the available time and the scope of the research. Specifically, the following limitations apply to this research:

- The analysis of mobility around large-scale events has only focused on car traffic travelling towards the event: the spillback problem affects inbound car traffic, but similar mechanisms could affect exiting car traffic or even public transport modes as well.
- The design of the ITM controller is bound to a number of assumptions and simplifications, to prevent a very complex design of the controller components. However, this leads to some inaccuracies in for instance the network representation, the objective function of the departure time optimisation, the parking lot choice and the interaction between the guided users and the controller.
- From the simulations in the synthetic networks and the Arena-network, it can be concluded that the effects of the ITM controller design are promising, potentially preventing large delays for through traffic passing large-scale events. However, the results of ITM

application are also rather dependent on the size and complexity of the network, the demand scenario, and the penetration rate of the controller in the traffic system. The simulation results might also be difficult to compare to any future data-analysis of real-time application of ITM at the Arena, since the simulation network is a strongly simplified version of the real network. Furthermore, it might be interesting to evaluate the influence of stochastic simulation inputs on the controller's performance.
- For the practical application, some limitations have been identified, such as computation time and the similarity between the model and reality. This research has not evaluated the influence of these limitations and assumptions on the effectiveness of the ITM controller in practice.

Because of these limitations, the following research directions for future research efforts are suggested:

- Improvement of the presented ITM controller design
    - Usage of a more accurate node model of in the Link Transmission Model prediction component of the controller, so that the network can be represented more accurately
    - Link-based departure time advice optimisation, for a better fit of the objective function with reality. Furthermore, the departure time advice optimisation can use a dynamic assumption for route choice. This is based on the results of the route guidance optimisation.
    - Other approaches to compute the (near-)optimal individual route and departure time advice, to avoid complexity and computation time of optimisations in large networks. The designed control structure and strategy can be retained, but the actual design of the components can be adapted. For instance, one could study the possibilities for another prediction model, that is even more capable of representing the traffic flows in a more advanced manner. Furthermore, the route and departure time advice could be based on more simple control rules: the split fractions and the departure time shifts can be computed based on the deviation of (predicted) traffic states from an optimal value.
    - Iterative control procedure, with interaction between the route and departure time advice components and the prediction model, to increase accuracy at the cost of computation time
- Extensions to the ITM controller design
    - Addition of the ability to optimise the behaviour of guided travellers to multiple destinations, making the controller suitable for other non-recurrent traffic conditions
    - Addition of the ability of the controller to distribute individuals travelling to large-scale events over various modes
    - The ability of the controller to achieve an optimal distribution of event visitors over parking lots at the event venue, making the controller more attractive for event organisations
    - The ability of the controller to give certain advice to specific individuals, based on their personal preferences and characteristics: this increases compliance behaviour and appreciation of the ITM services.
    - The controller can be made suitable for the implementation of automated vehicles in the traffic system. Research is needed to determine what adaptations to the controller design are needed to use ITM in a system of shared autonomous

    vehicles, controlled by a central entity. Furthermore, studies could focus on the effects of the ITM controller in such a highly automated traffic system.

- Influence of a possible poor match between ITM controller modelling assumptions and the real traffic process
    - The extent to which the modelling in the controller (LTM, optimisations) is similar to the real traffic process and how any differences affect the ITM controller's performance for the offline and real-time application in practice
    - Computation times of the ITM controller in a real-time application, when applied in all sorts of conditions (e.g. network complexity and size)
    - Accuracy of real-time measurements of the traffic states in the network, the influence of this accuracy on the controller's performance, and methods for accurate traffic state estimation that are suitable for the ITM controller and the practical situation

For the shorter term, the extensions and the application of the ITM controller are the most relevant research subjects. Examples of main research questions for such future studies:

- *How can a theoretical ITM controller design be implemented in reality with the development of a software package?*
- *What are the quantitative effects of applying an ITM controller in real-time at a large-scale event?*
- *What is the influence of the differences between the modelling in the ITM controller and the real-traffic process on the effectiveness of the controller?*

These aforementioned research efforts will lead to the further development of individual traffic management, and will help in the evolution process from the current practice of dynamic traffic management towards a central control system of shared automated vehicles. This Master thesis has presented one of the first steps that can be taken in this development: presumably, more research steps will follow.

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Appendix A Event visitors and background traffic in the LTM

The event visitors (whether they are guided or unguided doesn't matter) and the through traffic are distinguished in the LTM by the use of multiple commodities. Yperman (2007) already developed the LTM with the application of multiple commodities to the various routing possibilities. The application of the LTM for the ITM controller is slightly different. In this appendix, the approach to compute the flows for both the event-bound and background traffic (two commodities) is explained. The variables that are used are shown in Table A.1.

Table A.1: Sets and inputs for the application of the LTM of Yperman (2007) to ITM control, taking different target groups into account

Sets	**Description**	**Unit**
V	Set of node indices, describing the nodes in the network	
A	Set of link indices, describing the links in the network	
I_n	Set of indices of incoming links of a node, I_n is a subset of A	
J_n	Set of indices of outgoing links of a node, J_n is a subset of A	
O	Set of all origin indices in the network. O is a subset of V	
T	Set of simulation time step indices. The maximum simulation time of the LTM can be fixed to a certain *prediction horizon*	
X	Set of space indices, describing space in the network	
P	Set of traffic commodity indices (event-bound and background traffic)	
Indices		
t	A certain time interval, $t \in T$	
n	A node in the network, $n \in V$	
r	An origin node in the network, $r \in O$	
a	A link in the network, $a \in A$	
p	A traffic commodity, $p \in P$	
i	Incoming link, $i \in I_n$	
j	Outgoing link, $j \in J_n$	
x	A point in space, $x \in X$	
x_a^0	Entrance point of link a	
x_a^L	Exit point of link a	
Model variables		
Δt	The amount of time between each time step of the controller's predictions	[s]/[min]/[h]
$v_{f,i}$	Free flow speed (forward shockwave speed) of link i	[km/h]
w_i	Backward shockwave speed (negative number) of link i	[km/h]
$q_{M,i}$	Link capacity of link i	[veh/h]
$k_{jam,i}$	Jam density of link i	[veh/km]
L_i	Length of link i	[km]
$N^p(x,t)$	The cumulative number of vehicles of commodity p at x at time t	[veh]
$N_r^p(t)$	The cumulative number of vehicles of commodity p at origin r at time t. This can be derived from the demand profile of both commodities	[veh]
$S_{ij}(t)$	Total sending flow from link i to j during a time interval	[veh]

$S'^{p}_{ij}(t)$	The uncorrected sending flow of commodity p from link i to j during a time interval	[veh]
$S^{p}_{ij}(t)$	Sending flow of commodity p from link i to j during a time interval	[veh]
$G_{ij}(t)$	Total transition flow between i and j during a time interval	[veh]
$G^{p}_{ij}(t)$	Transition flow between i and j of commodity p during a time interval	[veh]
β^{p}_{ij}	The split fraction at a node connecting link i and j for commodity p	

Note that the usual calculations (as discussed in section 4.4.1) of the LTM will also be performed. The following computations of the commodity flows occur in addition to the usual predictions.

1. Firstly, the disaggregated cumulative curves are used to determine the potential sending flows of the two commodities. These calculated numbers do not yet take the other commodity into account.

   $$S'^{p}_{i}(t) = \min([N^{p}(x_i^0, t + \Delta t - \frac{L_i}{v_{f,i}}) - N^{p}(x_i^L, t)], q_{M,i} * \Delta t)$$

   The sum of the commodities' sending flows *can* however still exceed the capacity with this formula. Therefore, the sending flow per commodity must be corrected by the total sending flow. Since the following must hold for all links:

   $\sum_{p \in P} S_i^p(t) = S_i(t)$, the calculated commodity sending flows are corrected as below.

   $$S_i^p(t) = \frac{S'^{p}_{i}(t)}{\sum_{p' \in P} S'^{p'}_{i}(t)} * S_i(t), \qquad \forall\, i \in I_n; p \in P$$

2. The sending flows per commodity are used to distribute the transition flows over the two commodities. If not all the sending flows can be sent due to downstream restrictions, the two commodities will be penalised equally. This holds for all node types, except for origin nodes (where there is no sending flow available)

   $$G_{ij}^p(t) = \frac{S_{ij}^p(t)}{\sum_{p' \in P} S_{ij}^{p'}(t)} * G_{ij}(t), \qquad \forall\, i \in I_n; j \in J_n\, ; p \in P$$

   This formula ensures that the sum of the transition flows per commodity is equal to the total transition flow at a node.

   For diverge nodes, the sending flows per direction are determined by using a split fraction. This split fraction enables the LTM to account for the through traffic, which uses a fixed route (meaning that the split fraction for this commodity is either 1 or 0). For the event traffic, the split fractions from the optimisation can be used in the traffic propagation model.

   $$S_{ij}^p(t) = S_i^p(t) * \beta_{ij}^p, \qquad \forall\, i \in I_n; j \in J_n\, ; p \in P$$

   For origin nodes, a slightly different method is proposed, although the concept is the same. All the demand is sent into the first link by the origin nodes, unless there is some restriction there. If the downstream link is not capable of receiving all the demand, the inflow from both commodities is restricted in a (relative) equal way.

$$G_j^p(t) = \frac{N_r^p(t+\Delta t) - N^p\left(x_j^0, t\right)}{\sum_{p' \in P}\left[N_r^{p'}(t+\Delta t) - N^{p'}\left(x_j^0, t\right)\right]} * G_j(t), \qquad \forall\, j \in J_n\,; p \in P$$

3. The transition flows per commodity are used to update the cumulative vehicle numbers. This is done in a similar way as the aggregated cumulative numbers.

$$N^p\left(x_i^L, t+\Delta t\right) = N^p\left(x_i^L, t\right) + \sum_{j \in J_n} G_{ij}^p(t), \qquad \forall\, i \in I_n; p \in P$$

$$N^p\left(x_j^0, t+\Delta t\right) = N^p\left(x_j^0, t\right) + \sum_{i \in I_n} G_{ij}^p(t), \qquad \forall\, j \in J_n; p \in P$$

   The sum of the disaggregated cumulative vehicle numbers must be equal to the total cumulative vehicle count.

Similar to the aggregated outputs of the LTM (see section 4.4.1), the outputs as travel times, queues and link counts can also be computed for the different commodities with the calculation of the disaggregated cumulative vehicle counts. Most importantly, the methodology discussed above enables the controller design to take the different (route choice) behaviour and the effects of any spillback on the commodities into account.

Appendix B Inputs into the simulated networks

Synthetic network 1: individual route guidance only

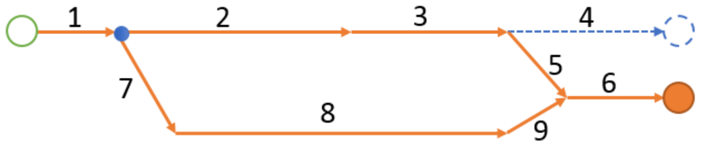

Figure B.1: Link IDs of the first synthetic network

Table B.1: Link properties of the first synthetic network

LINK ID	LENGTH [KM]	SPEED [KM/H]	CAPACITY [VEH/H]	K_{JAM} [VEH/KM]	T_{FREE} [S]	QUEUE PENALTY [S]
1	3.0	120	4,400	330	90	0
2	4.0	120	4,400	330	120	480
3	2.0	120	4,400	330	60	240
4	2.0	120	4,400	330	60	0
5	1.0	120	4,400	330	30	120
6	2.0	120	2,200	165	60	0
7	3.0	120	4,400	330	90	360
8	3.0	120	4,400	330	90	0
9	2.0	120	4,400	330	60	0

Table B.2: Optimisation input variables for synthetic network 1

INPUT VARIABLE	VALUE	UNIT
α_{route}	1.75	
ε	0.40	
H	360	s
Δt	30	s
T_{future}	2,400	s
w	15	km/h

Table B.3: Demand scenario for synthetic network 1

SIMULATION TIME [S]	EVENT DEMAND [VEH/H]	THROUGH DEMAND [VEH/H]
0-1200	1,000	1,800
1200-3600	3,000	1,800
3600-4200	1,000	1,800
4200-5400	0	1,800

Table B.4: Definition of paths for event visitors in synthetic network 1

PATH ID	LINK SEQUENCE	INITIAL SPLIT FRACTIONS	
		Split 1	Split 2
1	1,2,3,5,6	0.8	1
2	1,7,8,9,6	0.2	0

The background traffic uses links 1,2,3 and 4 to drive from the origin to their destination.

Synthetic network 2: individual departure time advice only

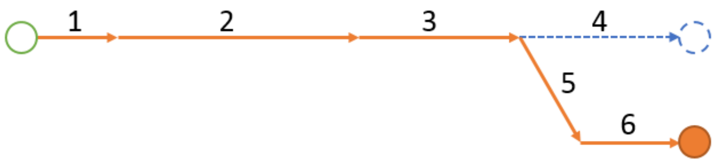

Figure B.2: Link IDs of the second synthetic network

Table B.5: Link properties of the second synthetic network

LINK ID	LENGTH [KM]	SPEED [KM/H]	CAPACITY [VEH/H]	K_{JAM} [VEH/KM]	T_{FREE} [S]	QUEUE PENALTY [S]
1	3.0	120	6,600	495	90	90
2	4.0	120	6,600	495	120	120
3	1.0	120	6,600	495	30	30
4	2.0	120	6,600	495	60	60
5	2.0	120	4,400	330	60	60
6	2.0	120	2,200	165	60	60

Table B.6: Optimisation input variables for synthetic network 2

INPUT VARIABLE	VALUE	UNIT
α_{dep}	1.38	
ε	0.40	
φ	0.70	
H	360	s
B	1,800	s
Δt_{LTM}	30	s
Δt_{dep}	300	s
T_{future}	2,400	s
M	180	intervals (5,400 s)
w	15	km/h

Table B.7: Initial demand scenario for synthetic network 2

SIMULATION TIME [S]	EVENT DEMAND [VEH/H]	THROUGH DEMAND [VEH/H]
0-1200	1,000	3,000
1200-3000	3,000	3,000
3000-3900	1,000	3,000
3900-4800	0	3,000
4800-5400	0	1,000

The guided event visitor demand will pose departure time advice requests for the designed ITM controller. The distribution of the requests over time is as follows:

- 30 % of the requests is sent to the controller at the preferred departure time of the guided event visitors
- 40 % of the requests is sent to the controller 5 minutes before the preferred departure time of the guided event visitors

- 20 % of the requests is sent to the controller 10 minutes before the preferred departure time of the guided event visitors
- 10 % of the requests is sent to the controller 15 minutes before the preferred departure time of the guided event visitors

The background traffic uses links 1,2,3 and 4, while event visitors use link 1,2,3,5 and 6.

Synthetic network 3: integrated individual traffic management by full controller design

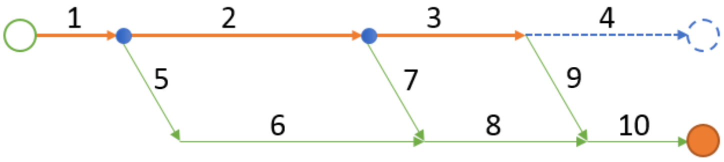

Figure B.3: Link IDs of the third synthetic network

Table B.8: Link properties of the third synthetic network

LINK ID	LENGTH [KM]	SPEED [KM/H]	CAPACITY [VEH/H]	K_{JAM} [VEH/KM]	T_{FREE} [S]	QUEUE PENALTY [S]
1	2.0	120	4,400	330	60	240
2	4.0	120	4,400	330	120	480
3	2.0	120	4,400	330	60	240
4	1.0	120	4,400	330	30	0
5	2.0	60	1,800	150	120	480
6	4.0	60	1,800	150	240	0
7	2.0	60	1,800	150	120	480
8	2.0	60	1,800	150	120	0
9	2.0	60	1,800	150	120	480
10	2.0	60	1,200	100	120	0

Table B.9: Optimisation input variables for synthetic network 3

INPUT VARIABLE	VALUE	UNIT
α_{dep}	1.38	
α_{route}	1.75	
ε	0.40	
φ	0.70	
H	360	s
B	1,800	s
Δt_{LTM}, Δt_{RG}	30	s
Δt_{dep}	300	s
T_{future}	2,400	s
M	180	intervals (5,400 s)
w	15	km/h

Table B.10: Initial demand scenario for synthetic network 3

SIMULATION TIME [S]	EVENT DEMAND [VEH/H]	THROUGH DEMAND [VEH/H]
0-600	1,000	2,500
600-3000	1,600	2,500
3000-3900	1,000	2,500
3900-5400	0	1,500

The guided event visitor demand will pose departure time advice requests for the designed ITM controller. The distribution of the requests over time is as follows:

- 30 % of the requests is sent to the controller at the preferred departure time of the guided event visitors
- 40 % of the requests is sent to the controller 5 minutes before the preferred departure time of the guided event visitors
- 20 % of the requests is sent to the controller 10 minutes before the preferred departure time of the guided event visitors
- 10 % of the requests is sent to the controller 15 minutes before the preferred departure time of the guided event visitors

Table B.11: Definition of paths for event visitors in synthetic network 3

PATH ID	LINK SEQUENCE	INITIAL SPLIT FRACTIONS		
		Split 1	Split 2	Split 3
1	1,2,3,9,10	0.72	0.80	1
2	1,2,7,8,10	0.18	0.20	0
3	1,5,6,8,10	0.10	0	0

Again, the background traffic only uses link 1,2,3 and 4.

Arena-network

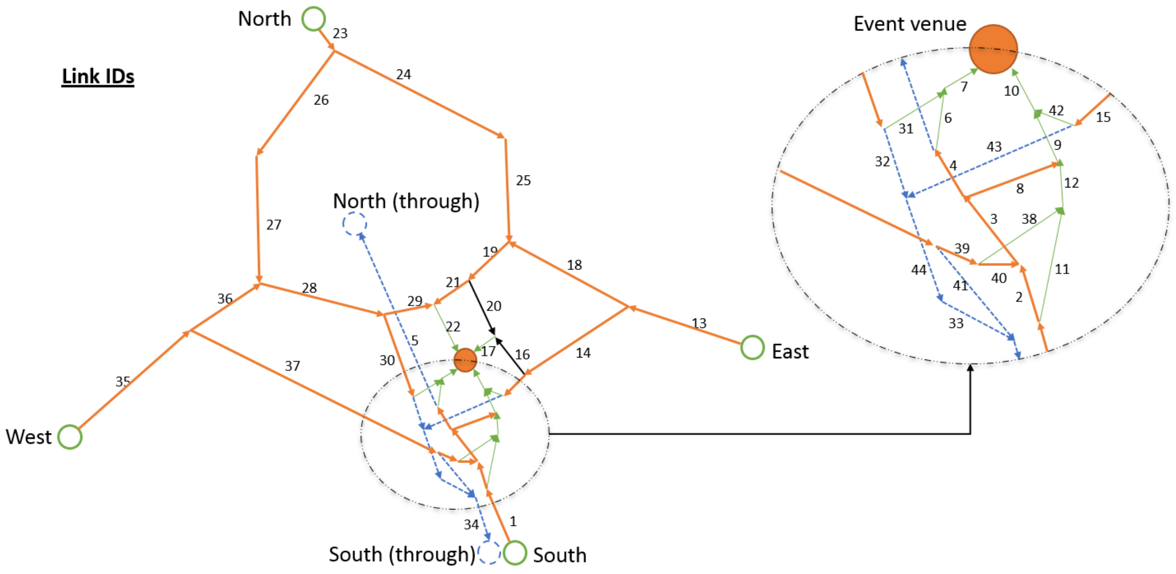

Figure B.4: Link IDs in the Arena-network

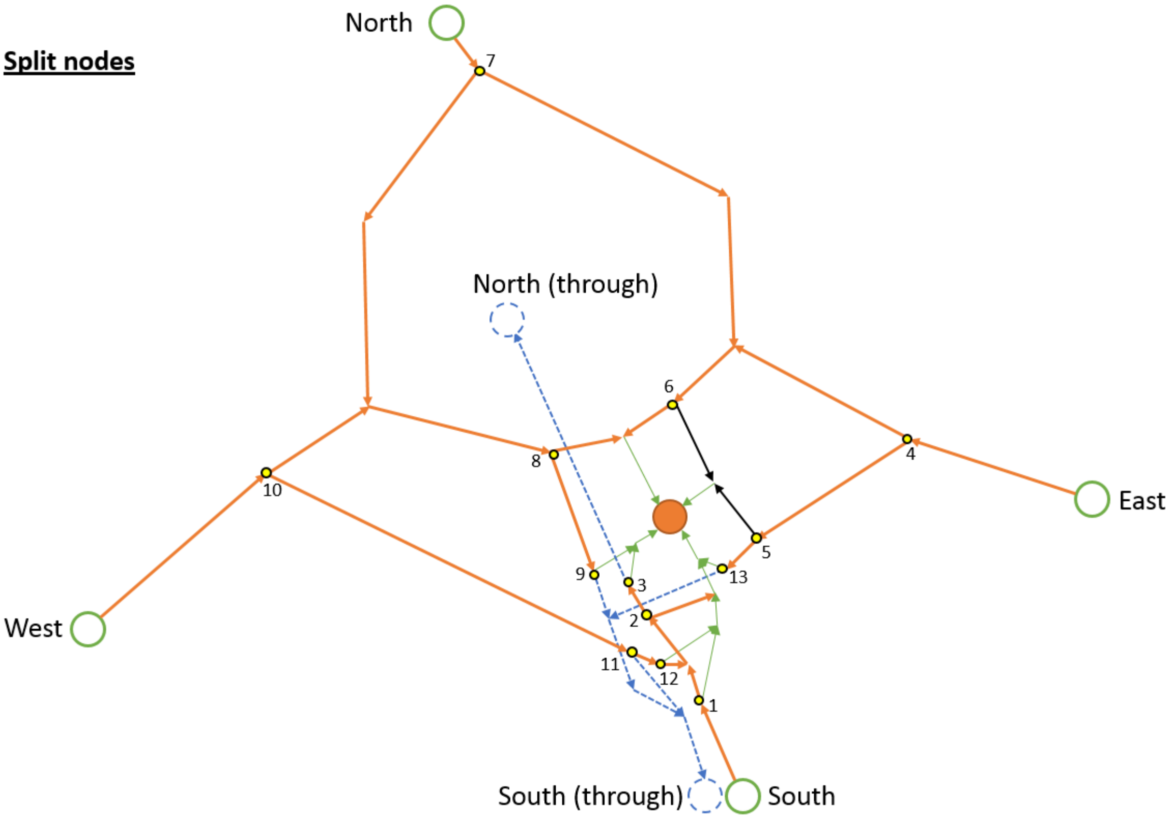

Figure B.5: Decision node IDs in the Arena-network

Table B.12: Link properties of the Arena-network

LINK ID	LENGTH [KM]	SPEED [KM/H]	CAPACITY [VEH/H]	K_{JAM} [VEH/KM]	T_{FREE} [S]	QUEUE PENALTY [S]
1	10.0	100	10,500	735	360	360.0
2	1.0	100	8,400	588	36	72.0
3	1.0	100	8,400	588	36	72.0
4	2.0	100	8,400	588	72	144.0
5	5.0	100	8,400	588	180	0.0
6	0.5	50	3,600	288	36	72.0
7	1.0	50	1,800	144	72	0.0
8	1.0	100	4,200	294	36	36.0
9	0.5	50	3,600	288	36	0.0
10	1.5	50	1,800	144	108	0.0
11	1.0	50	1,800	144	72	144.0
12	1.5	50	3,600	288	108	0.0
13	4.0	100	10,500	735	144	144.0
14	5.0	100	6,300	441	180	360.0
15	1.0	100	6,300	441	36	72.0
16	1.5	75	3,600	264	72	144.0
17	1.0	50	1,800	144	72	0.0
18	5.0	100	8,400	588	180	180.0
19	3.0	100	8,400	588	108	0.0
20	3.0	75	3,600	264	144	0.0
21	1.0	100	8,400	588	36	0.0
22	2.5	50	3,600	288	180	0.0
23	3.0	100	10,500	735	108	108.0
24	6.0	100	6,300	441	216	0.0
25	5.0	100	6,300	441	180	0.0
26	5.0	100	6,300	441	180	360.0
27	5.0	100	6,300	441	180	360.0
28	5.0	100	8,400	588	180	360.0
29	2.0	100	6,300	441	72	144.0
30	3.0	100	6,300	441	108	216.0
31	1.0	50	3,600	288	72	144.0
32	2.0	100	8,400	588	72	0.0
33	2.0	100	12,600	882	72	0.0
34	4.0	100	16,800	1176	144	0.0
35	5.0	100	8,400	588	180	180.0
36	5.0	100	8,400	588	180	180.0
37	10.0	100	6,300	441	360	720.0
38	1.5	50	1,800	144	108	216.0
39	1.0	100	4,200	294	36	72.0
40	1.0	100	4,200	294	36	72.0
41	2.0	100	8,400	588	72	0.0
42	0.5	50	1,800	144	36	72.0
43	2.0	100	6,300	441	72	0.0
44	2.0	100	12,600	882	72	0.0

Table B.13: Optimisation input variables for the Arena-network

INPUT VARIABLE	VALUE	UNIT
α_{dep}	1.38	
α_{route}	1.75	
ε	0.40	
φ	0.70	
H_{origin}	900	s
B	1,800	s
Δt_{LTM}	36	s
Δt_{RG}	72	s
Δt_{dep}	900	s
T_{future}	3,600	s
M	325	intervals (11,700 s)
w	16.67	km/h

Table B.14: Unfairness thresholds for the different decision nodes in the Arena-network

DECISION NODE	1	2	3	4	5	6	7	8	9	10	11	12	13
H_{NODE} [S]	600	300	300	600	360	420	600	600	300	600	300	600	300

Table B.15: Initial demand scenario for the different origins in Arena-network

SIMULATION TIME [S]	DEMAND SOUTH ORIGIN (1) [VEH/H]		DEMAND EAST ORIGIN (2) [VEH/H]		DEMAND NORTH ORIGIN (3) [VEH/H]		DEMAND WEST ORIGIN (4) [VEH/H]	
	Visitors	Through	Visitors	Through	Visitors	Through	Visitors	Through
0-1800	1,400	5,500	500	4,400	750	3,800	800	4,200
1800-3600	1,400	6,600	500	4,800	750	3,800	1,400	4,700
3600-5400	1,800	6,600	1,200	4,800	1,200	3,800	1,400	4,700
5400-7200	1,800	6,600	1,200	5,300	1,200	4,100	1,400	5,000
7200-9000	1,500	5,000	300	5,300	800	4,100	300	5,000
9000-10800	0	5,000	0	3,500	0	2,500	0	3,500
10800-15300	0	3,000	0	2,000	0	2,000	0	2,000

The guided event visitor demand will pose departure time advice requests for the designed ITM controller. The distribution of the requests over time is as follows:

- 30 % of the requests is sent to the controller at the preferred departure time of the guided event visitors
- 40 % of the requests is sent to the controller 15 minutes before the preferred departure time of the guided event visitors
- 20 % of the requests is sent to the controller 30 minutes before the preferred departure time of the guided event visitors
- 10 % of the requests is sent to the controller 45 minutes before the preferred departure time of the guided event visitors

Table B.16: Definition of paths for event visitors in the Arena-network

PATH ID	**LINK SEQUENCE**	**INITIAL SPLIT FRACTIONS**												
		1	2	3	4	5	6	7	8	9	10	11	12	13
1	1,2,3,4,6,7	0.64	0.8	1	0	0	0	0	0	0	0	0	0	0
2	1,2,3,8,9,10	0.16	0.2	0	0	0	0	0	0	0	0	0	0	0
3	1,11,12,9,10	0.20	0	0	0	0	0	0	0	0	0	0	0	0
4	13,14,15,42,10	0	0	0	0.56	0.7	0	0	0	0	0	0	0	1
5	13,14,16,17	0	0	0	0.24	0.3	0	0	0	0	0	0	0	0
6	13,18,19,20,17	0	0	0	0.08	0	0.4	0	0	0	0	0	0	0
7	13,18,19,21,22	0	0	0	0.12	0	0.6	0	0	0	0	0	0	0
8	23,24,25,19,20,17	0	0	0	0	0	0	0.2	0	0	0	0	0	0
9	23,24,25,19,21,22	0	0	0	0	0	0	0.3	0	0	0	0	0	0
10	23,26,27,28,29,22	0	0	0	0	0	0	0.1	0.2	0	0	0	0	0
11	23,26,27,28,30,31,7	0	0	0	0	0	0	0.4	0.8	1	0	0	0	0
12	35,36,28,29,22	0	0	0	0	0	0	0	0	0	0.12	0	0	0
13	35,36,28,30,31,7	0	0	0	0	0	0	0	0	0	0.48	0	0	0
14	35,37,39,40,3,4,6,7	0	0	0	0	0	0	0	0	0	0.096	0.24	0.24	0
15	35,37,39,40,3,8,9,10	0	0	0	0	0	0	0	0	0	0.024	0.06	0.06	0
16	35,37,39,38,12,9,10	0	0	0	0	0	0	0	0	0	0.28	0.7	0.7	0

Table B.17: Definition of origins and corresponding through traffic routes in the Arena-network

ORIGIN ID	**MOTORWAY IN REALITY**	**LINK SEQUENCE FOR BACKGROUND TRAFFIC**
1	A2	1,2,3,4,5
2	A1	13,14,15,43,44,33,34
3	A8	23,26,27,28,30,32,44,33,34
4	A4/A9	35,37,41,34