Modeling and control of congestion phenomena

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Publications

Author contributions

Chapter 2 is based on [144], and is a joint effort of N. Levering, M. Boon, M. Mandjes, and R. Núñez Queija. The original framework and some key ideas for the proof of the main theorem are due to Mandjes. Levering had the leading role in the analysis of the routing algorithms and, with guidance from Boon, the implementation of these algorithms. Whereas Levering was responsible for writing the original draft, the other authors were highly involved in the review and editing process.

Chapter 3 is based on [121], a joint work of R. Kamphuis, N. Levering, and M. Mandjes. The initial idea to study the optimal departure times came from Kamphuis and Levering, after which Kamphuis performed a literature review and identified the research gap. All authors contributed to defining the conceptual framework. In particular, Levering described how to model recurrent and non-recurrent effects using the Markovian velocity model, while Kamphuis developed the online version of the problem. Algorithms for obtaining the departure time were designed by Levering. Kamphuis and Levering jointly designed and analyzed the numerical experiments, which were implemented by Levering. All authors contributed equally in the writing and editing process of the paper.

Chapter 4 is based on [143], and is joint work of N. Levering, M. Boon and M. Mandjes. Boon and Mandjes proposed the project, after which all three authors contributed equally to defining the proposed methodology. With guidance from Boon and Mandjes, Levering performed the in-depth data analysis and implemented the numerical experiments. The writing of the paper was a joint effort.

Chapter 5 is based on [120], a collaboration between R. Kamphuis, N. Levering, and M. Mandjes. The initial idea to building a routing framework using online velocity measurements came from Kamphuis and Levering, whose idea it was to work with a stochastic fundamental diagram. The construction of the estimation framework for current and future traffic densities was carried out by Kamphuis, after which Levering devised the (online) algorithm for obtaining the optimal route. Levering and Kamphuis jointly designed and analyzed the numerical experiments, which were implemented by Levering. All authors contributed equally in the writing and editing process of the paper.

Chapter 6 is based on [145], and is joint work of N. Levering and R. Núñez Queija, the latter proposing the initial ideas for this paper. Levering had the lead in the project itself, including the construction of the mathematical framework, the design and implementation of the numerical experiments, and the writing process. Núñez Queija provided feedback during all stages of the project.

Chapter 7 is based on [114], and is joint work of R. Jacobovic, N. Levering and O. Boxma. Jacobovic came up with the main theorem of the paper. The mathematical analysis and writing tasks were mainly shared by Jacobovic and Levering. Boxma suggested the addition of a heavy-tailed analysis, which was then mainly carried out by Jacobovic and Levering. Moreover, Boxma provided important feedback on the original manuscript, and was heavily involved in the editorial process.

Chapter 8 is based on [113], and is joint work of R. Jacobovic and N. Levering. The authors contributed equally to the (writing of the) paper. Specifically, Levering came up with the results of the continuous optimization, and specified the combinatorial optimizer for the case $r = 0$. Jacobovic performed an extensive literature survey, and enhanced and proved the combinatorial results for the case $r > 0$.

Summary

Modeling and control of congestion phenomena

As congestion plays a more prominent role in today's world than ever, this thesis is devoted to the development and study of models that capture the dynamics of systems that may experience congestion, and the construction of control measures that aim to mitigate congestion phenomena. An important aspect of this thesis is that the fluctuating dynamics of such systems are taken into account. That is, it is acknowledged that certain processes governing these systems may be time-dependent and/or stochastic in nature. Examples include rates of incoming calls in mobile phone networks and the occurrence of incidents in road networks.

This thesis is divided into two parts. Part I centers around highway networks, and presents stochastic road traffic models and corresponding control problems in the areas of routing, departure-time advice, and input rate control. Part II does not focus on a single application area, but studies a specific regulation measure for the single-server queue, a classical model for congestion. Below, contributions of both parts are described in more detail.

In the road traffic context of Part I, Chapter 2 studies optimal routing for a vehicle aiming to minimize the travel time between its origin and a chosen destination, assuming the vehicle may adapt the chosen route while driving. An important contribution is the introduction of the Markovian velocity model (MVM). This stochastic model uses an environmental background process to track both recurrent events (i.e., near-periodic events such as rush hours) and non-recurrent events (i.e., semi-random events such as incidents) affecting vehicle speeds in a road network. Importantly, the underlying mechanism is rich enough to allow for correlation between the speeds on different segments in the network (present due to, e.g., spillback and rubbernecking after incidents), and can be made operational with relatively low complexity. The latter property is illustrated by the data-study performed in Chapter 4, which demonstrates how traffic data can be used to obtain a description of both the recurrent traffic patterns and the randomness of incidents, using the results to operationalize the MVM.

Chapter 2 shows that, in the MVM framework, the optimal routing policy following from dynamic programming procedures is computationally intractable for networks of realistic size. Therefore, the highly efficient EDSGER* algorithm is introduced, and it is shown that this dynamically-used shortest path algorithm yields close-to-optimal results. In the same MVM framework, Chapter 3 considers the problem of determining the latest time of departure for which a certain user-specified on-time arrival probability can be guaranteed.

The chapter contains efficient numerical methods that output the optimal departure time for a given path or origin-destination pair. As the conditions in the road network may change between the time of request and the advised departure time, an algorithm for the online version of this procedure, in which the traveler receives departure time updates while still at the origin, is presented as well.

Chapter 5 again considers the problem of finding the route with minimum expected travel time in a highway network, but in a setting in which the traffic manager only has (i) real-time vectors of velocity measurements on the different network links and (ii) historic routing probabilities. Focusing on recurrent congestion, the relation between traffic densities and vehicle velocities is explicitly modeled by a stochastic fundamental diagram (SFD). A maximum likelihood procedure estimates current link densities, and expected future density estimates are inferred by the implementation of a scheme that mimics the average dynamics of the SFD. Similar to Chapter 2, an efficient dynamically-used shortest path algorithm is proposed, whose time-dependent link weights are now functions of the time-stamped density estimates.

The last problem studied in Part I, the topic of Chapter 6, concerns input rate control. As congestive settings are often a result of high traffic demands, the aim is to avoid any violation of link capacities. First, to account for the inherent randomness of the available capacity of a road, a stochastic flow model is introduced, which describes the impact of traffic input streams on the available road capacities. Second, exploiting similarities with the control of telecommunication networks, a traffic rate control policy that is based on the concept of effective bandwidths is developed.

Part II considers the M/G/1 queue, with the objective to study externalities, i.e., the total additional waiting time a joining customer imposes on the other customers in the system. The interest in externalities arises from its application as a pricing mechanism for social-planners aiming to maximize the long-run average welfare. Chapter 7 studies the joint distribution of the externalities when the underlying service distribution is either LCFS-PR or FCFS. It presents a decomposition of the externalities under the above-mentioned service disciplines, and uses this decomposition to derive (steady-state) moments and several asymptotic results.

Motivated by a classical mean-variance analysis in Chapter 7, the final chapter (Chapter 8) considers the minimization of the externalities in the M/G/1 LCFS-PR queue under a different set of constraints. Specifically, the analysis concerns a system manager that observes the service requirements of both the newly arriving customer and the customer in service upon their arrival. Of the waiting customers, however, the manager only has access to their number and their total remaining service demand. Under these constraints, the minimal variance that can be attained for some families of parameterizations is identified, and a conjecture for the general case is posed.

Samenvatting

Het modelleren en reguleren van congestie

Aangezien congestie een steeds grotere invloed heeft op het functioneren van systemen die gedeeld worden door meerdere gebruikers, is dit proefschrift gewijd aan de ontwikkeling en studie van modellen die de dynamiek van deze systemen beschrijven en maatregelen die ertoe dienen de congestie in deze systemen te verminderen. Belangrijk is dat hierbij rekening wordt gehouden met het feit dat de processen die invloed hebben op deze systemen tijdsafhankelijk en/of stochastisch van aard kunnen zijn. Voorbeelden zijn onder meer de frequentie van inkomende oproepen in telefoonnetwerken en het optreden van incidenten in wegennetwerken.

Dit proefschrift bestaat uit twee delen. Deel I, welk draait om snelwegnetwerken, presenteert stochastische modellen voor wegverkeer en behandelt bijbehorende problemen op het gebied van routering, vertrektijdadvies en het managen van instromend verkeer. Deel II richt zich niet op één toepassingsgebied, maar bestudeert een specifieke maatregel voor een klassiek congestiemodel: de wachtrij met één server. Hieronder worden de bijdragen van beide delen in meer detail beschreven.

In de wegverkeerscontext van Deel I bestudeert Hoofdstuk 2 de optimale routering voor een voertuig dat ernaar streeft de verwachte reistijd tussen vertrekpunt en bestemming te minimaliseren, in het geval het voertuig de gekozen route onderweg mag aanpassen. Een belangrijke bijdrage is de introductie van het Markoviaanse snelheidsmodel (MVM). Dit stochastische model gebruikt een achtergrondproces om zowel recurrente gebeurtenissen (zoals spitsuren) als eenmalige gebeurtenissen (zoals incidenten) die de snelheden van de voertuigen op een wegennet beïnvloeden te beschrijven. Het onderliggende mechanisme is flexibel genoeg om de correlatie tussen de snelheden op verschillende segmenten in het netwerk te modelleren, nodig omdat files zich over verschillende segmenten kunnen verspreiden, of omdat er bij een incident kijkersfiles kunnen ontstaan. Belangrijk is ook dat het model met relatief lage complexiteit operationeel kan worden gemaakt, wat wordt geïllustreerd door de datastudie uitgevoerd in Hoofdstuk 4. Dit hoofdstuk laat zien hoe verkeersdata kan worden ingezet om zowel de verkeerspatronen als de stochasticiteit van incidenten te beschrijven, en operationaliseert met behulp van deze resultaten het MVM.

In Hoofdstuk 2 wordt aangetoond dat het, voor netwerken van realistische omvang, computationeel te zwaar is om de dynamische programmeerprocedure uit te voeren waaruit de optimale routering in het MVM-raamwerk volgt. Daarom wordt het zeer efficiënte EDSGER*-algoritme gepresenteerd, en wordt gedemonstreerd dat dit dynamisch gebruikte kortstepad-algoritme vrijwel altijd optimale resultaten geeft. In hetzelfde MVM-raamwerk wordt in Hoofdstuk 3 gekeken naar het laatste vertrektijdstip waarop een vooraf-gespecificeerde

kans kan worden gegarandeerd dat de gebruiker vóór een gegeven tijd op de bestemming aankomt. Het hoofdstuk bevat efficiënte numerieke methoden die dit optimale vertrektijdstip bepalen, zowel voor een gegeven pad als een gegeven bestemming, en zowel onder de aanname dat de gebruiker geen updates over het vertrektijdstip kan ontvangen, als onder de aanname dat de reiziger updates mag ontvangen terwijl deze nog bij de oorsprong is.

Hoofdstuk 5 probeert opnieuw de route met minimale verwachte reistijd in een snelwegennet te bepalen, maar nu in het geval de verkeersmanager slechts beschikt over (i) huidige snelheidsmetingen op verschillende segmenten en (ii) historische routeringskansen. Om de congestie die ontstaat door een hoog verkeersaanbod te beschrijven wordt de relatie tussen verkeersdichtheden en voertuigsnelheden gemodelleerd door een stochastisch fundamenteel diagram (SFD). Met maximum likelihood-schatters voor de huidige dichtheden worden benaderingen voor de verwachte toekomstige dichtheden afgeleid uit de implementatie van een systeem dat de gemiddelde dynamiek van de SFD nabootst. Net als in Hoofdstuk 2 wordt een efficiënt en dynamisch gebruikt kortstepad-algoritme voorgesteld, waarin de tijdsafhankelijke gewichten van de wegen nu functies zijn van de toekomstige dichtheidsschattingen.

Het laatste probleem dat wordt bestudeerd in Deel I, tevens het onderwerp van Hoofdstuk 6, betreft het managen van de instroom van het netwerk. Aangezien congestie vaak het gevolg is van een te grote verkeersvraag, is het doel is om eventuele overschrijdingen van de wegcapaciteit te voorkomen. In de eerste plaats wordt, om rekening te houden met fluctuaties in de beschikbare capaciteit van een weg, een stochastisch model geïntroduceerd dat de impact van verkeersstromen op de beschikbare wegcapaciteit beschrijft. Daarna worden de overeenkomsten tussen wegverkeer en communicatieverkeer geëxploiteerd, en wordt een instroombeleid gepresenteerd dat gebaseerd is op het concept van effectieve bandbreedtes.

Deel II concentreert zich op de M/G/1-wachtrij en bestudeert de totale extra wachttijd die een toetredende klant aan de andere klanten in het systeem oplegt. Deze zogenaamde externaliteiten zijn interessant vanwege de toepassing als prijsmechanisme voor managers die gericht zijn op het maximaliseren van de langetermijnwelvaart. Hoofdstuk 7 analyseert de gezamenlijke verdeling van de externaliteiten wanneer de onderliggende bediening LCFS-PR of FCFS is. Het presenteert een uiteenzetting van de externaliteiten onder de bovengenoemde bedieningsvormen, en gebruikt deze uiteenzetting om (stationaire) momenten en verschillende asymptotieken af te leiden.

Gemotiveerd door een klassieke gemiddelde-variantieanalyse in Hoofdstuk 7, bestudeert Hoofdstuk 8 de minimalisering van de externaliteiten in de M/G/1 LCFS-PR-wachtrij onder een andere reeks aannames. Concreet gaat het bij deze analyse om een systeemmanager die de bedieningsduren van de extra aankomende klant en de klant in bediening tijdens deze aankomst kent. Echter, van de wachtende klanten heeft de manager alleen informatie over hun aantal en hun totale resterende bedieningsduur. Onder deze aannames wordt de minimale variantie die voor sommige parametrische families kan worden bereikt bepaald, en wordt een vermoeden voor andere parametrische families opgesteld.