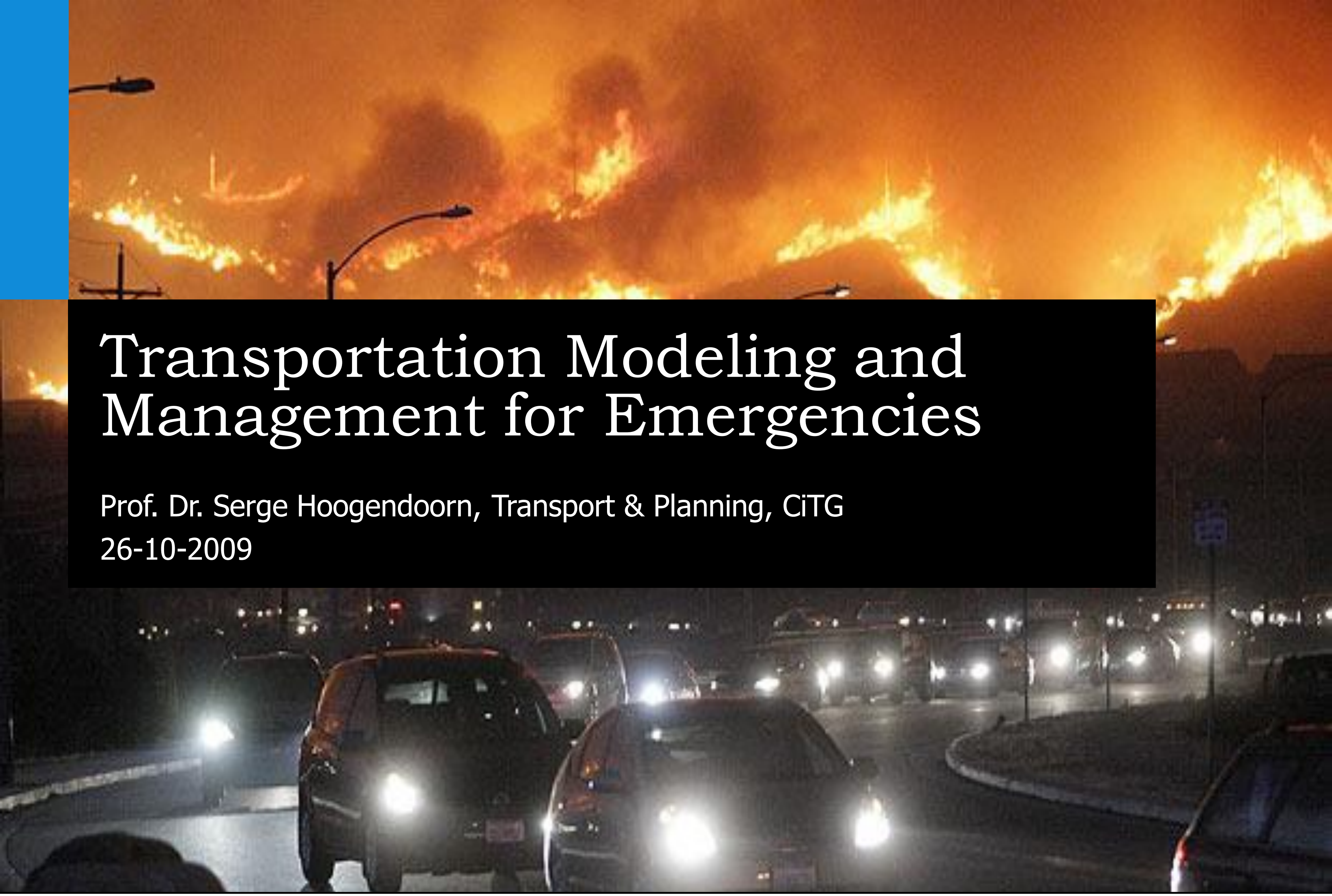


Transportation Modeling and Management for Emergencies

Prof. Dr. Serge Hoogendoorn, Transport & Planning, CiTG

26-10-2009

Main conclusions

Exceptional Traffic Network Operations

- Exceptional events (large incidents, heavy weather conditions, disasters, terrorist strikes) cause large changes in **driving and travel behavior**, and in infrastructure availability
- Including behavioral changes is **essential to correctly predict network operations** in case of exceptional events
- Models for normal conditions are generally not suitable
- Behavior in case of exceptional events follows **repeatable and hence predictable patterns**
- Dedicated models can be designed and applied to predict and manage network flow operations yielding large improvements
- Ability to deal with extreme events will also provide new ways to manage daily congestion: “Si vis pacem, para bellum”

1.

Introduction

Exceptional events
What are we talking about?

- Exceptional event:
  - High impact transportation system (demand and/or supply)
  - Small probability of occurring

- Examples of exceptional events:
  - Large accidents
  - Bad weather conditions (blizzards, snowstorms, black ice)
  - Disasters (natural or man-made)
  - Terrorist strikes

Taxonomy of events

Relating event and responses

- Event dimensions:
  - Spatial and temporal scope and scale
  - Speed and predictability
  - Probability of occurring and preparedness (training)
  - Man-made or natural
  - Impact on infrastructure

- Behavioral response dimensions
  - Traveler choice dimensions affected
  - Driving behavior impacts
  - Psychological impacts

Exceptional events

Why look at exceptional events at all?

- Transportation is Nation's lifeline, also in exceptional situations!
- In particular in case of 'exceptional events' functioning of transportation often turns out to be problematic

- Example: 25 November 2005 (heavy winter storm)
  - Electricity network collapsed, corrupting train network
  - Emergency power units could not reach destinations because they were stuck in traffic, as were de-icing trucks that had to clear roads
  - Result: the busiest Dutch evening rush hour ever!

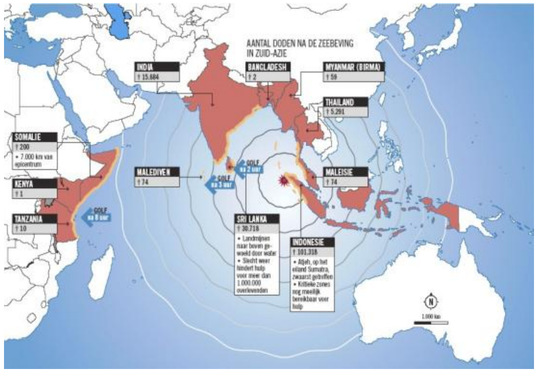
- Ability to deal with extreme events will also provide new ways to manage daily congestion: "Si vis pacem, para bellum"

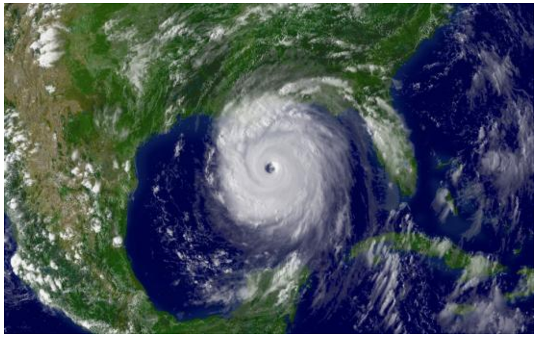
Need for evacuation

Recent disasters

Some recent disasters:

- 2004, Tsunami hits (is)lands Indian Ocean
- 2005, hurricanes hits South-East states in the US
- 2007, 2009, bushfires in Greece
- 2008, heavy snowfall in the South of China





Need for evacuation
Flooding and evacuation

- 1st of january 1995:
  - Heavy rainfall in Germany, Belgium, and France causing high water levels for rivers Rijn, Maas and Waal, 250.000 people evacuated
- 23rd of august 2005:
  - Heavy rainfall causing flooding, and landslides
  - Floods halted rail services through the Alps towards Italy; major roads were closed and villages cut off
  - Electricity was cut off and water contaminated due to inundation
  - About 1000 people were evacuated

Perspectives on evacuation?

To evacuate or not to evacuate, that's the question

- Is evacuation reasonable option for dense areas e.g. Randstad (7,5 million / 8300 km^2) or Shanghai (19 million / 6300 km^2)?
- No conclusive answer: model studies point in different directions…
  - Study of Jonkman / Asselman shows limitations of evacuation, yielding strong focus on (costly) prevention
  - Recent study of TNO suggests possibilities to evacuate within short period of time (say, 48 hours)
- Both studies are limited due to limited validity of models used:
  - Assumptions regarding properties of underlying transportation process and traveler / driving behavior
  - Degradation of infrastructure / infrastructure use is neglected
  - Solution directions are neglected (public transit, flow reversal)

State of the art review (upcoming)

Regular and dedicated models

- Older studies use traffic/transport models for normal situations
- Many recent studies use simulation models design for regular traffic operations (in particular Paramics, Vissim, and Corsim, OREMS), sometimes with changed model parameters

- Recognition of need to modify travel demand, route choice, etc., has led to development of dedicated models
- Dedicated models mostly developed in 80's and 90's (NETVAC, DYNEV, MASSVAC, TEDSS), mostly specific for a kind of disaster

- However, even for dedicated models, underlying behavioral assumptions and modeling paradigms are unsuitable

Traditional theory and models

Why 'traditional' models do NOT apply!

- Travelers are not familiar with situation and hence have no valid expectations regarding prevailing traffic conditions
- Travel objectives are very different from normal conditions
- Travel and driving behavior will be different due to stress, emotion, driving task attention loss, weather conditions, etc., causing large changes in lane capacity

- Infrastructure may be affected substantially (flooded tunnels) or used differently (lane reversal)

- Traffic demands will be very high and traffic conditions are highly uncertain, further adding to the uncertainty of travel conditions

Demand-Supply perspective

Relation to exceptional events?

- Large changes in demand and/or supply are expected
- Changes in <u>supply</u> are caused by:
  - Changes in driving behavior due to stress, emotion, mood, attention, prevailing weather conditions, etc.
  - Reduction in infrastructure availability
- Changes in <u>demand</u> are caused by:
  - Number of people that want to travel / evacuate is likely to be large
  - Travelers are not familiar with the situation
  - Make decisions based on information, guidance and instructions instead of experience

- Imbalance in supply / demand may yield extreme flow conditions

Intermezzo

Network Fundamental Diagrams

Network Fundamental Diagram

Network load and performance degradation

- Recall the NFD of Daganzo / Geroliminis?

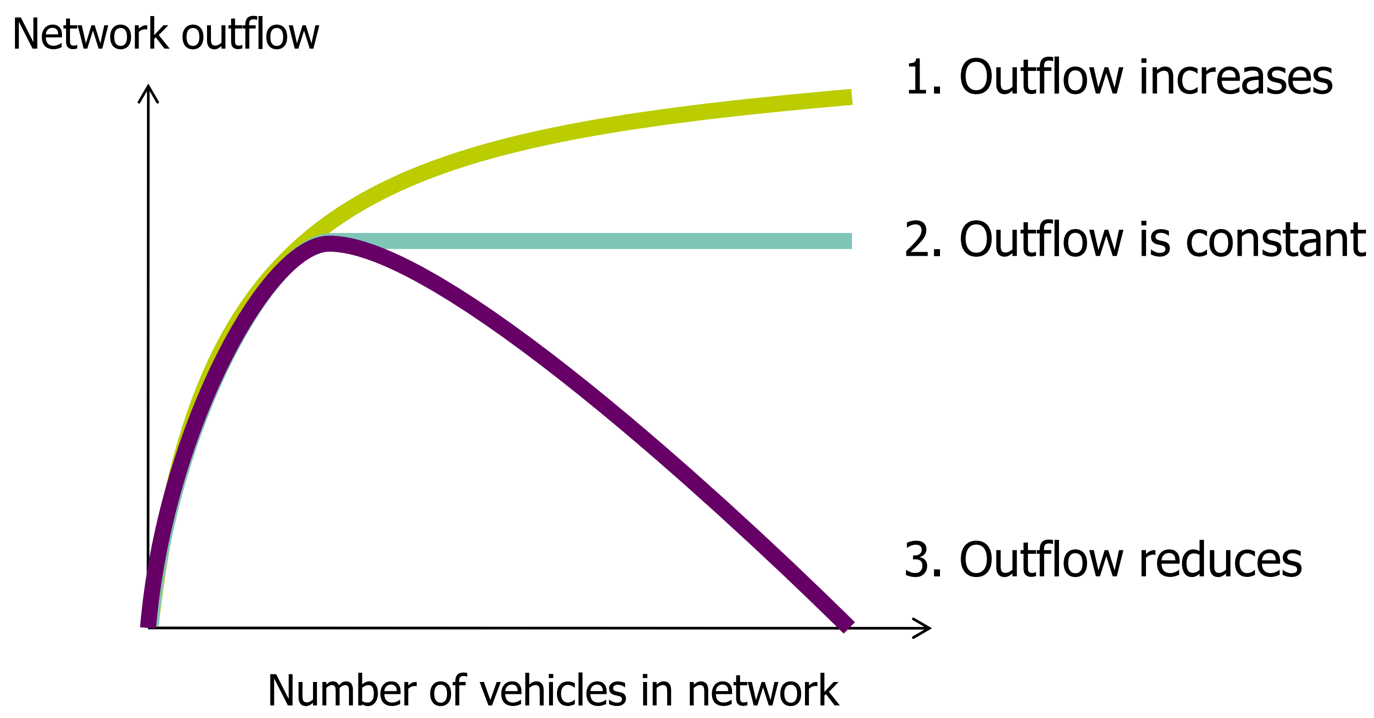
- Consider average relation between number of vehicles in network (accumulation) and performance (number of vehicles flowing out of the network)
- How does average production (outflow) relate to accumulation of vehicles?

- What would you expect based on analogy with other networks?
  - Think of a water pipe system where you increase water pressure
  - What happens?

Network Fundamental Diagram

Coarse model of network dynamics

- Fundamental relation between network outflow (rate at which trips end) and accumulation



Network Fundamental Diagram

Coarse model of network dynamics

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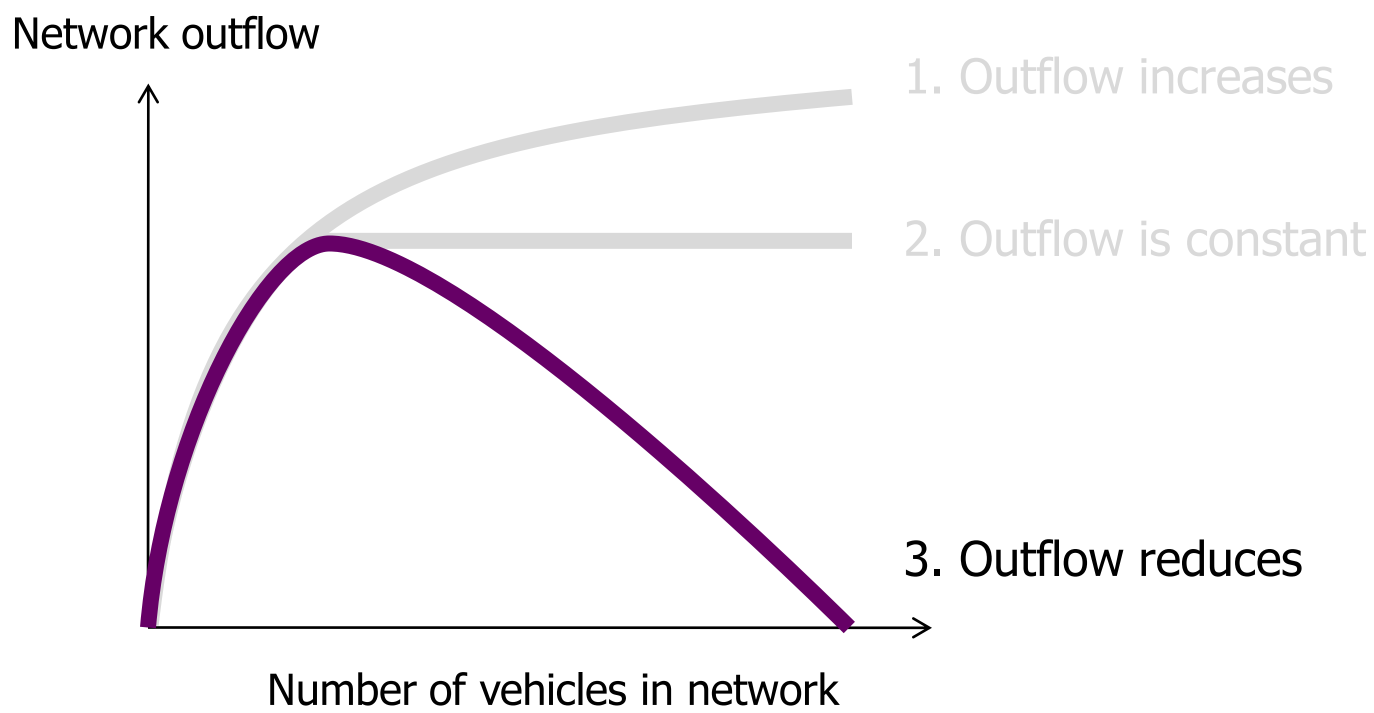
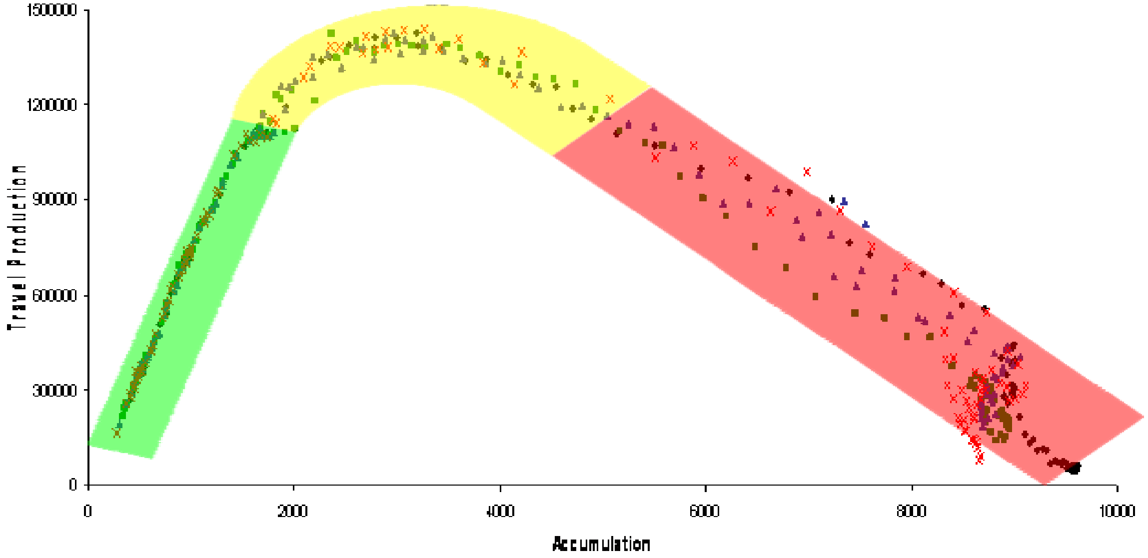


Network Fundamental Diagram

Demand and performance degradation

- Different examples (simulation and real data) confirm shape of NFD being mainly dependent on network topology



Network Fundamental Diagram

Relevance for Exceptional Events

- Network Fundamental Diagram shows coarse performance degradation due to network overloading
- Performance degradation is of particular interest for exceptional events (e.g. evacuation)
- Two direct applications:
  - Provides indications on how to load the network (e.g. evacuation instructions)
  - Benchmarking tool: model needs to capture shape, while many models do not!

2.

Driving Behavior Adaptation and Capacity Implications

Driving behavior

Capacity reduction

- Conditions during an exceptional event may have strong impact on driving behavior:
  - Bad weather (heavy rain and wind -5% to -15% cap. reduction)
  - Road conditions (partial flooding of roads, debris)
  - Visibility (e.g. smoke, fog) changing perceptual queues
  - State-of-mind of driver (hurry, ‘panic’)
  - Level of attention to driving task (distraction due to incidents, presence of police / emergency services)
  - No experience with deployed measures (flow reversal, etc.)
- Some examples…

Evacuation characteristics

Pedestrian flow operations

- So-called ‘faster-is-slower’ effect
- NOMAD / Social-Forces: pedestrians are compressible ‘particles’ exerting friction on each other when touching
- Friction increases with compression
- In case of evacuation pressure and friction between pedestrians, and pedestrians and infrastructure increases due to
  - Increased desire to get out
  - Higher demand of pedestrians aiming to get out of the facility
- See research of Helbing and Molnar
- Similar results have been found with vehicular traffic increased anxiety to merge onto main road

Evacuation characteristics

Polonaise!

- Recent research at TU Delft showed minor impact of stress on bottleneck capacity
- Organizing pedestrian flow at door turned out have high impact
- Polonaise increase door capacity with 30%

Evacuation characteristics

Polonaise!

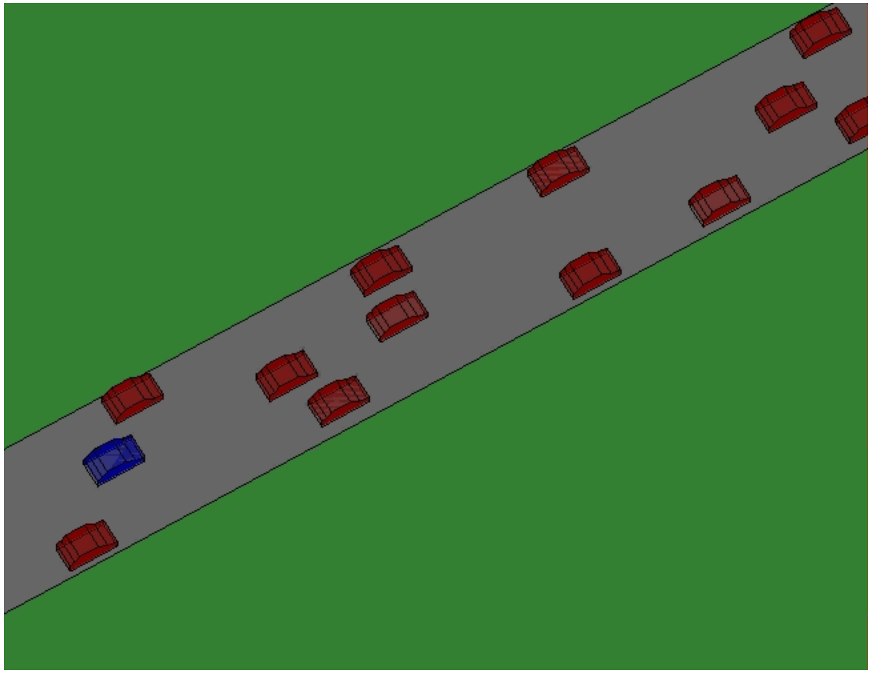
- Recent research at TU Delft showed minor impact of stress on bottleneck capacity
- Organizing pedestrian flow at door turned out have high impact
- Polonaise increase door capacity with 30%

Studying car-following behavior

Vehicle trajectory identification

- Since 2003, TU Delft has been working on automated ways to identify vehicle trajectory data from aerial observations

- TU Delft has developed dedicated statistical techniques to estimate parameters for car-following models *for individual drivers* based on these data
- Approach allows for cross-comparing of car-following models (benchmarking)



Estimation of car-following models

Parameter identification

- Example: consider linear Helly model:

- Model describes acceleration of follower as a function of:
  - Relative speed to leading vehicle
  - Difference between desired gap s^* and actual gap

  explicitly considered delay T_r

- Minimize difference between observed and predicted trajectory

Estimation of car-following models

Parameter identification

- Difference is expressed in terms of the log-likelihood:

  where σ is the standard deviation of error between observed and predicted speeds

- Resulting problem is to find the parameters that maximize the likelihood of observing the trajectories

Estimation of car-following models

Parameter identification

- Approach allows for statistical analysis of estimation results:
  - Estimation of parameters for individual drivers!
  - Estimation of parameter covariances
  - Comparison of models via likelihood ratio test
- Generalization of approach:
  - Inclusion of prior information of model estimates
  - Joint estimation of multiple drivers
  - Inclusion of alternative data sources

- Many new insights into individual driving behaviour and impacts on traffic flow (e.g. multi-vehicle anticipation, driver heterogeneity, synchronized flow scatter, etc.)

Driving behavior near incidents

Changes in driver attention

- Example stabilized movie from incident site
- Extensive analysis have been performed on macroscopic and microscopic trajectory data
- Some example results…

Main findings incident study

Changes in driver attention

- Estimation of car-following model on empirical trajectory data
- Changes in driver attention, supported by:
  - Distribution of headways in an active bottleneck around the incident is different compared to an active bottleneck in normal traffic and the mean is larger (substantial increase to 3.2 s vs. 1.9 s normally)
  - Car-following behaviour differs from normal traffic
  - Reaction time distribution of drivers is different
  - Accident sight reduces driving speed substantially (about 6.2 m/s)

- Capacity at accident site is substantially lower than capacity under normal conditions for the same roadway geometry (30~50% reduction for available lanes)

Driver simulator studies

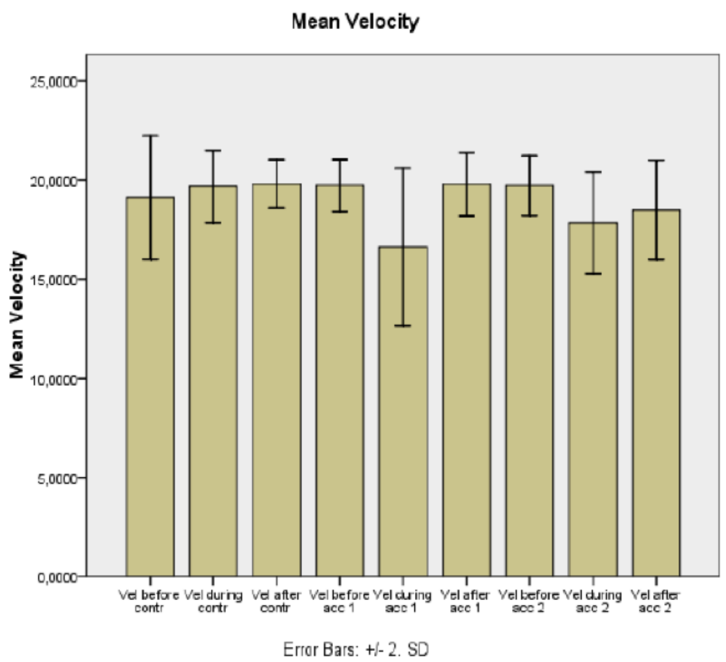
What causes behavioral changes?

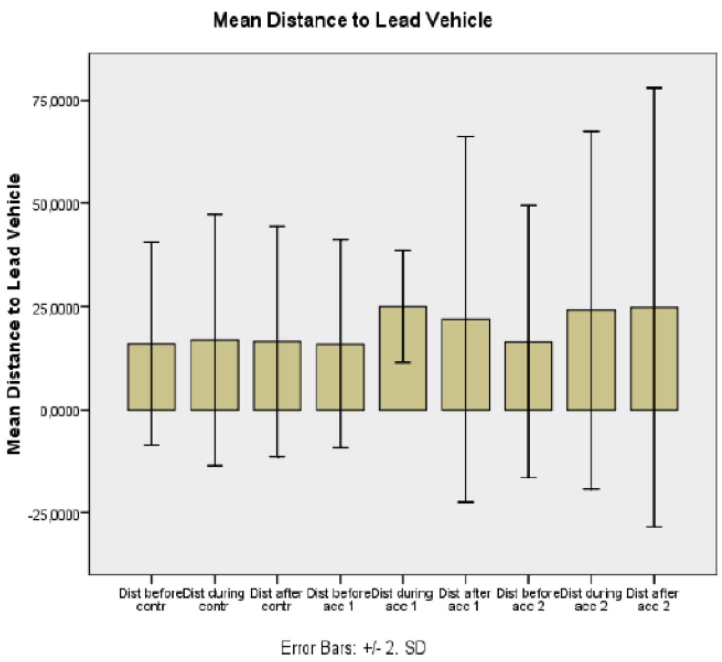
- Simulator experiment with accident
- Test subjects were equipped with all kinds of measurement equipment (heart rate, skin conductivity, etc.)

Driver simulator studies

Changes in driver behavior

- Changes in distance to leader / reduction of speed near incidents

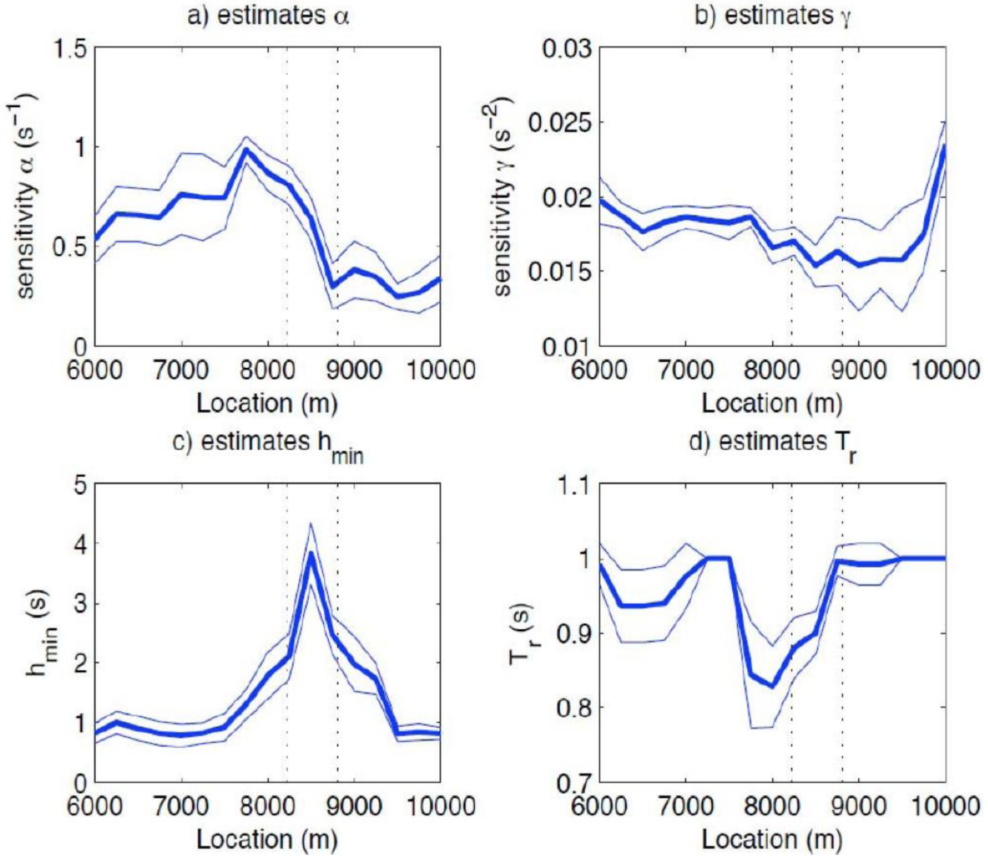




Driver simulator studies

Fitting car-following models

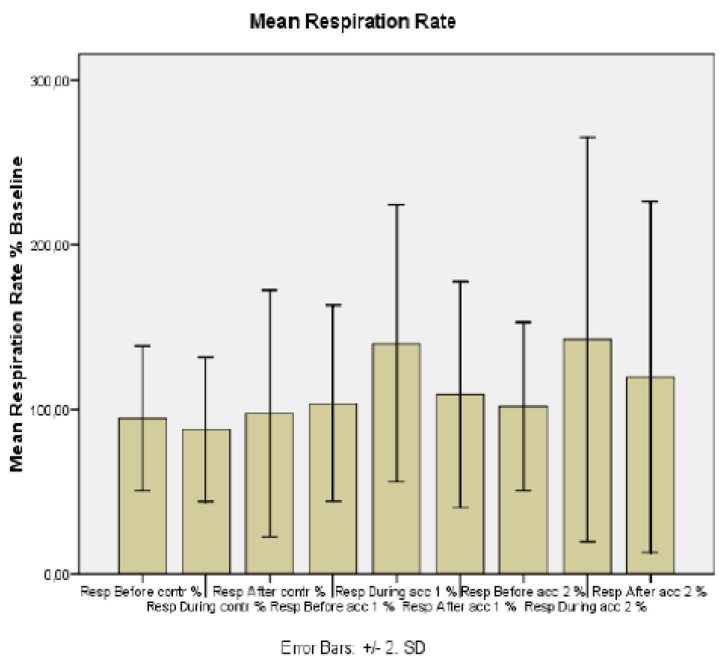
- Maximum-likelihood estimation approach applied for moving time window data
- Clear changes parameters are found near incident location
- Also indications of differences between drivers

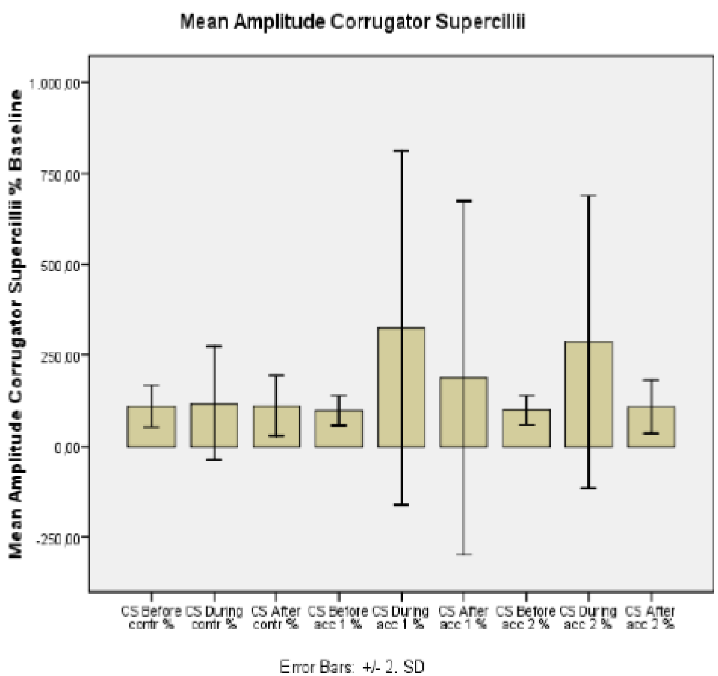


Driver Simulator Study

Psychological Impacts

- Changes in driver physiology
- Facial expression / respiration





3.

Travel Behavior Changes and Dynamic Network Modeling

Transport & Traffic Theory

Changes in case of exceptional events

- Differences normal / exceptional conditions:
  - Travelers unfamiliar with situation (no experience); need to rely on information on hazard / traffic conditions
  - State of mind of travelers may be different
  - Infrastructure may be compromised (e.g. less lanes available, tunnels flooded, etc.)
  - Infrastructure availability may change over time
  - Infrastructure use may change (use of roadway in both directions)
- Decision making style is different from decision making under normal conditions

Different hazard situations

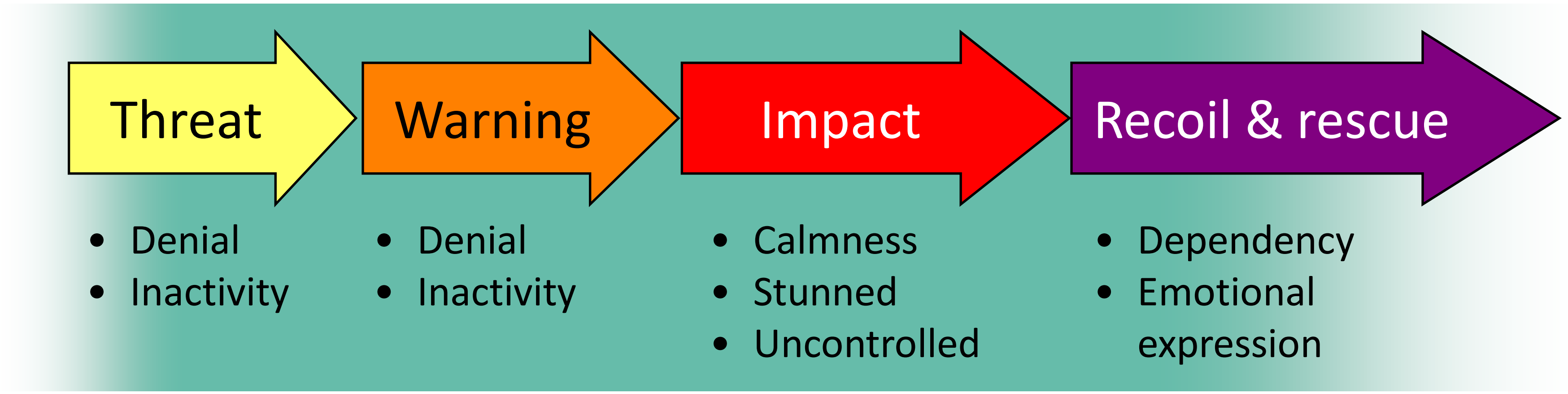
Commonalities in behavior?

- Comparing behavioral responses in case of exceptional events (i.e. hazards, disasters) reveal patterns in human response behavior
- Behavior is generic for different types of hazard situations (plane crash, tunnel evacuation,…)
- Typical behavior is observed for different phases of the disaster
- Essential to incorporate in travel modeling

Evacuee behavior

How to improve travel behavior models?

- Improving travel choice models by embedding (survival) psychology in modeling
- Example: dynamic model framework of John Leach showing different phases in human behavior



Evacuee behavior

Pop quiz!

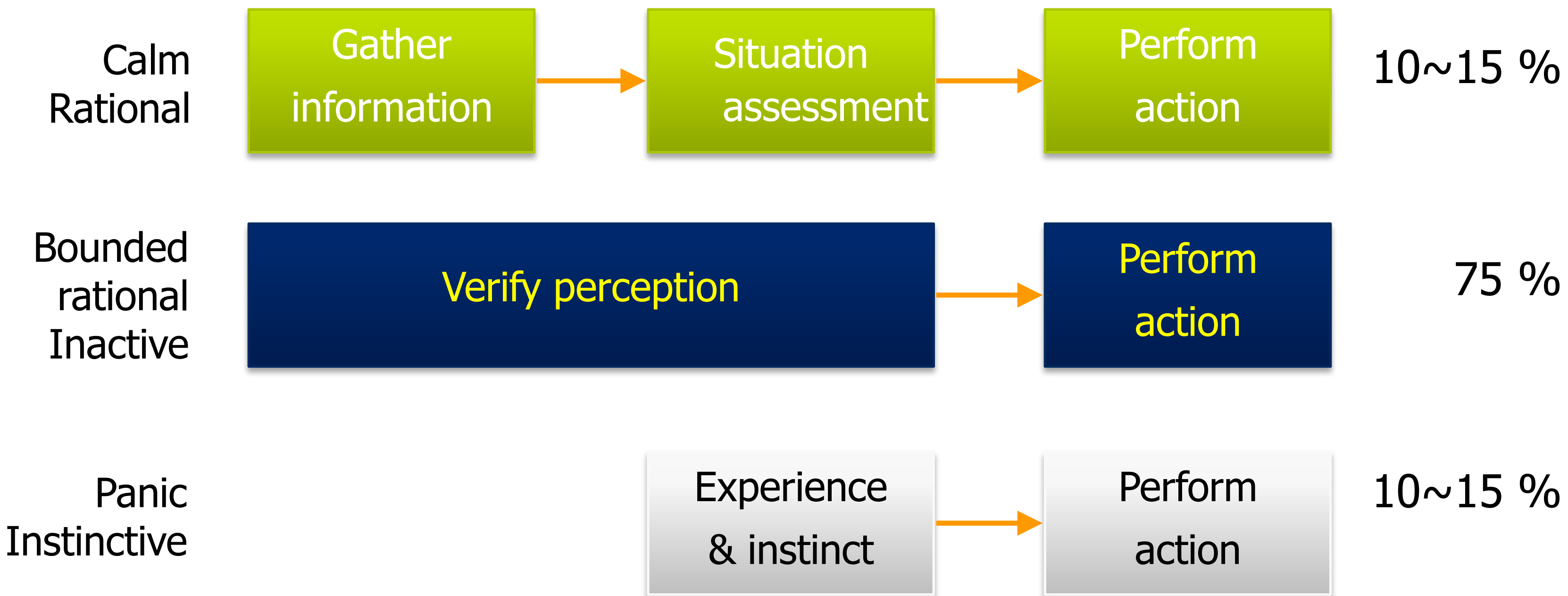
- Distinction of different phases when calamity unfolds characterized by different behavioral patterns

- In general, during the hazard, 3 groups of reaction types can be identified, with different behavioral patterns:
  - People remaining calm and rational despite of emergency
  - People of react in semi-automatic manner (bounded rationality)
  - People who breakdown mentally and act in an uncontrolled and often inappropriate way

Evacuee behavior

Pop quiz!

- As the disaster unfolds, 3 reaction types can be identified, with different behavioral patterns



EVAQ
Model characteristics

- Incorporate this knowledge in traffic network model, yields...
- EVAQ is a model for Dynamic Traffic Assignment that allows to predict traffic patterns on a network, distinguishing voluntary, advised or mandatory evacuations

- Evacuees are *not familiar* with the (future) traffic situation, but may possibly receive (limited) traffic information
- Evacuees may adapt their depature time, destination and evacuation route to the evacuation plan. They may *fully comply*, but this is not necessary (advised or mandatory)
- Speeds and capacities are dependent on the road conditions and weather conditions and on DTM measures

EVAQ model overview

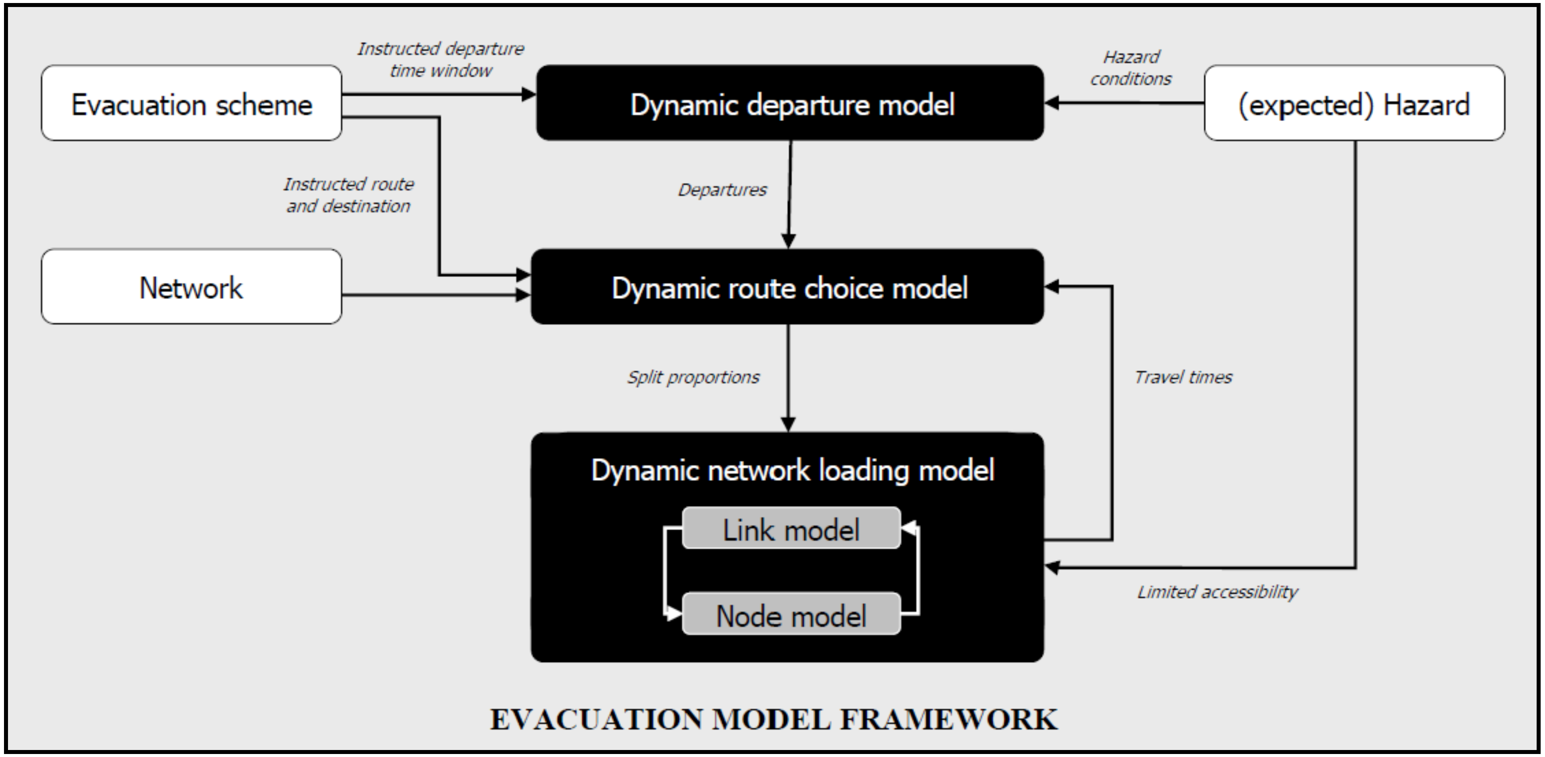
Model components overview

- Dynamic departure time choice model:
  - Determines dynamic demand as a function of perceived circumstances and instructions
- Dynamic route choice model (hybrid pre-trip and en-route route choice model):
  - Determines stochastic assignment of traffic over available routes based on expected route costs
- Dynamic assignment model:
  - Simulation of traffic flow operations taking into account availability of infrastructure and impact of hazard

- All this includes (varying) compliance to evacuation plan

EVAQ model overview

Model components overview

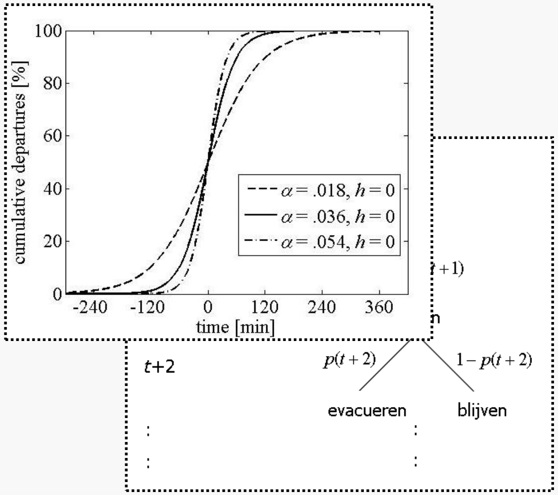


Framework traffic model

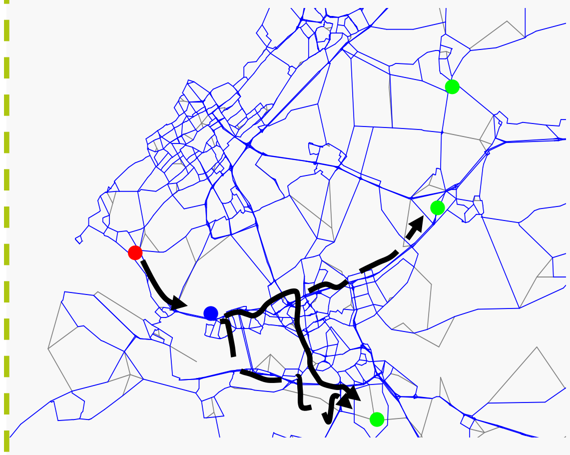
Modeling traveler behavior in EVAQ

Skip to case-study

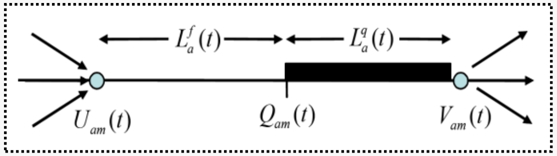
Traffic demand



Traffic assignment



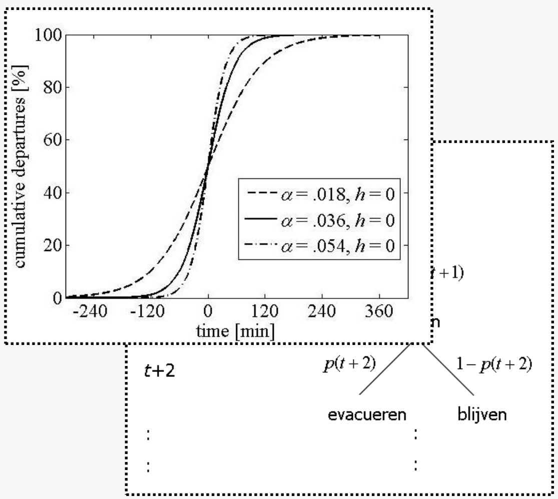
Traffic operations



Framework traffic model

Modelling traveler behavior

Traffic demand



Traffic assignment

Traffic operations

Modeling traffic demand

Two methods…

Response curve (often used because simple)

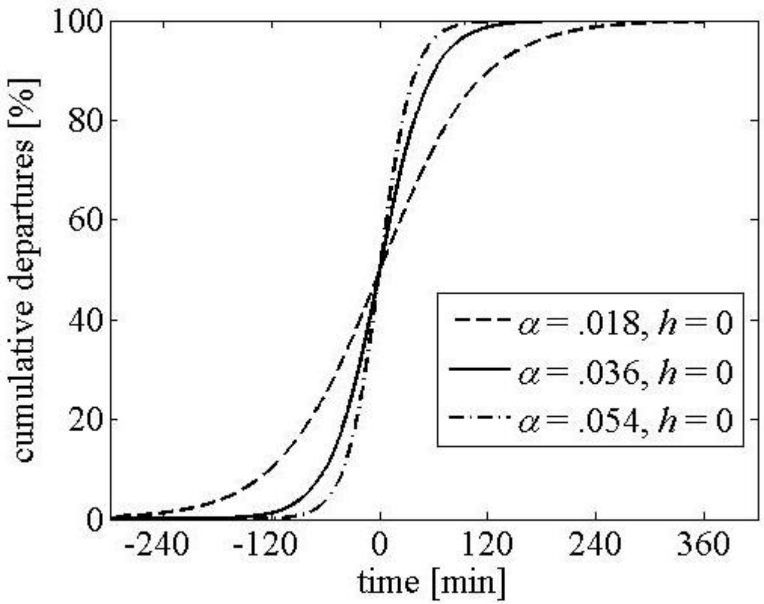
- Behavioral assumption:
  - People know changing conditions and expect them to smoothly worsen. At the start of the evacuation, people choose to evacuate (or not) and subsequently the departure time is chosen indepently

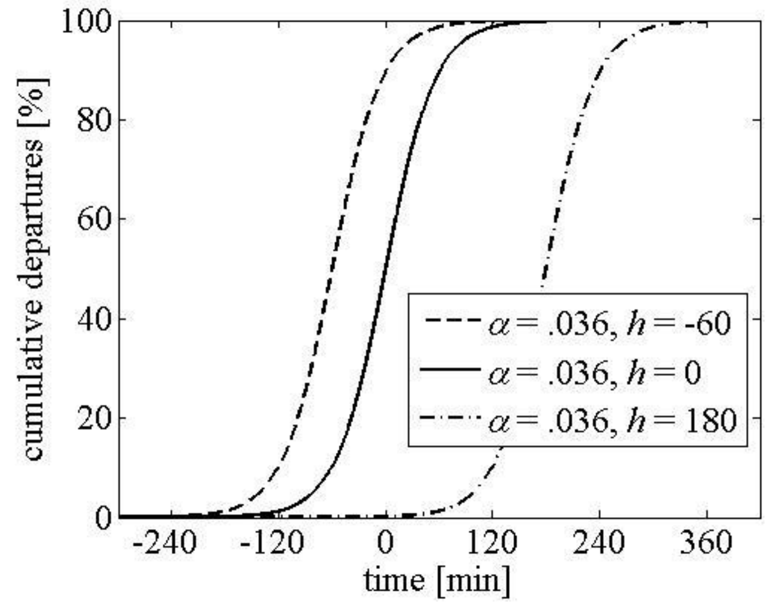
Sequential probability function (seldom used but more realistic)

- Behavioral assumption:
  - People do not know the changing future situation for certain. During evacuation, they choose repeatedly to evacuate or postpone the evacuation to a later moment

Modeling transport demand

Response curve



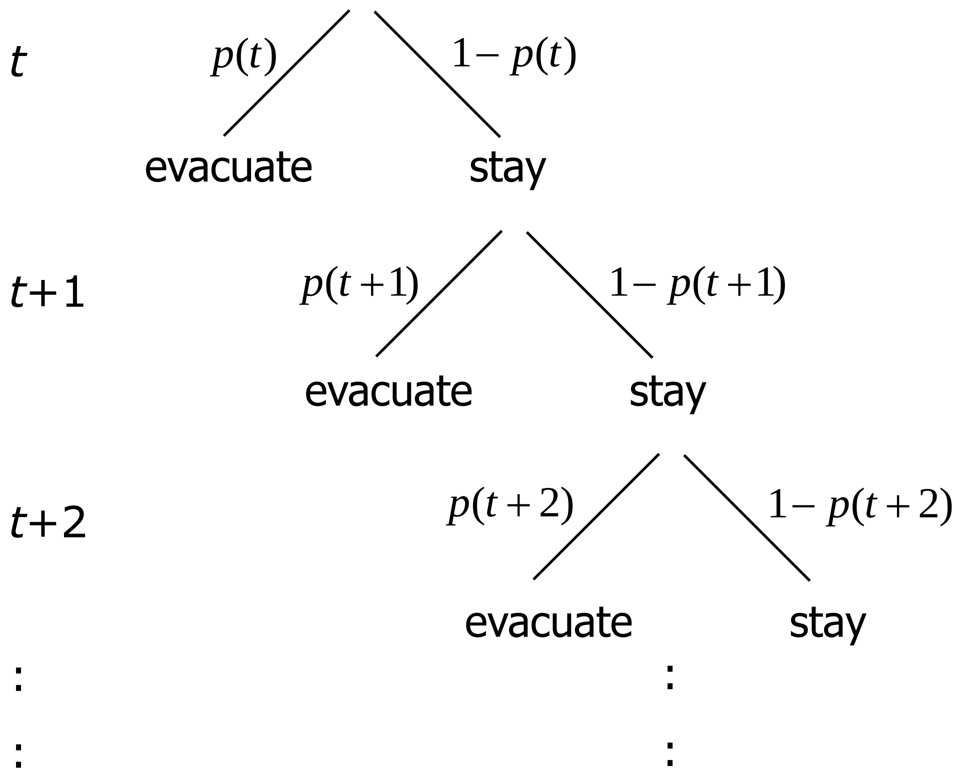


Mostly sigmoid curves are applied. However, behavioral assumptions are unrealistic

$$P\;\;t\;\;=\;1+\exp\left[-\alpha\;\;t-h\;\;\right]^{-1}$$

Modeling transport demand

Sequential probability function



The probability p is a function of the characteristic of the disaster, the household, instructions to evacuate, etc.

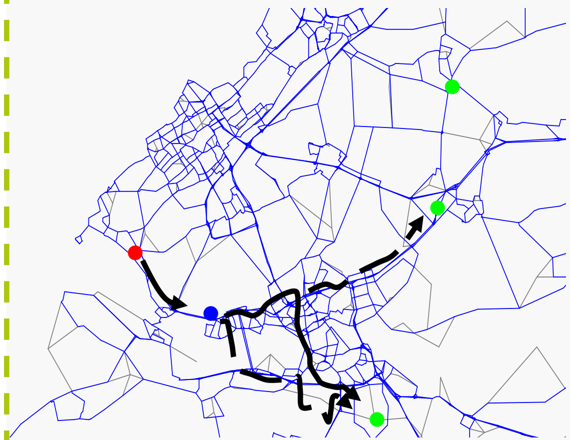
Probability functions are estimated for bushfire-evacuation (Stopher et al. 2004) and hurrican evacuation (Fu and Wilmot, 2004, 2006) by means of surveys

Modeling traffic assignment

Destination choice and evacuation route

Vervoersvraag

Traffic assignment



Verkeersafwikkeling

Pre-trip route choice

Behavioral assumption and modeling

Behavioral assumption

Travelers are assumed to choose their route from origin to destination at the time of departure, anticipating future changes in network conditions (user-equilibrium) or complying to instructions (mandatory evacuation)

Modeling (route-flow based)

Routes are generated and *route flows* are modeled from origin to destination. Travelers cannot change their pre-trip chosen route during the trip

En-route route choice

Behavioral assumption and modeling

Behavioral assumption

Travelers use information about current traffic conditions and change their route continuously during their trip accordingly, thereby reacting on unexpected network conditions

Modeling (split proportions at decision points)

Travelers update their route continuously at each intersection (decision point). Their routes are suboptimal since the prevailing travel times are used instead of actual travel times and no user-equilibrium results

Pre-trip and *en-route* route choice

So what is the deal?

- In reality, choice behavior is mixed (both pre-trip and en-route)
- A traveler will make a *pre-trip* route choice (based on expected traffic conditions, and instructions)...
  ...and divert from that route if they consider to be better off (based on information on the hazard or traffic information)
- In particular for exceptional events, including both types of choices is important since unexpected changes in the network conditions are expected

Hybrid route-choice modeling

Combining pre-trip and en-route choices

In hybrid route choice model

- Pre-trip route flows are updated during simulation, that is en-route choice behavior is enabled (mixed route-flow / split-proportion based approach)

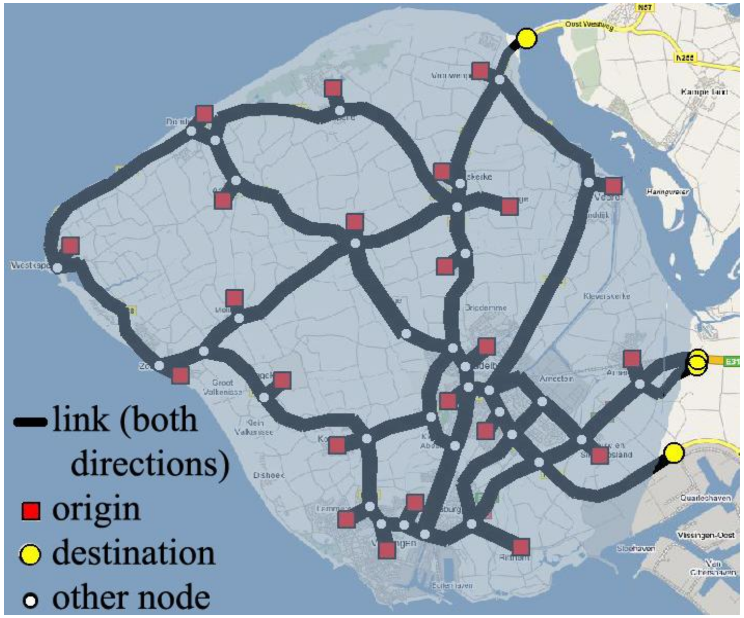
- An additional parameter is introduced in the route choice model to capture the traveler intertia to change their initial route

- This parameter determines their route choice behavior, which is either pre-trip, en-route or somewhere in between

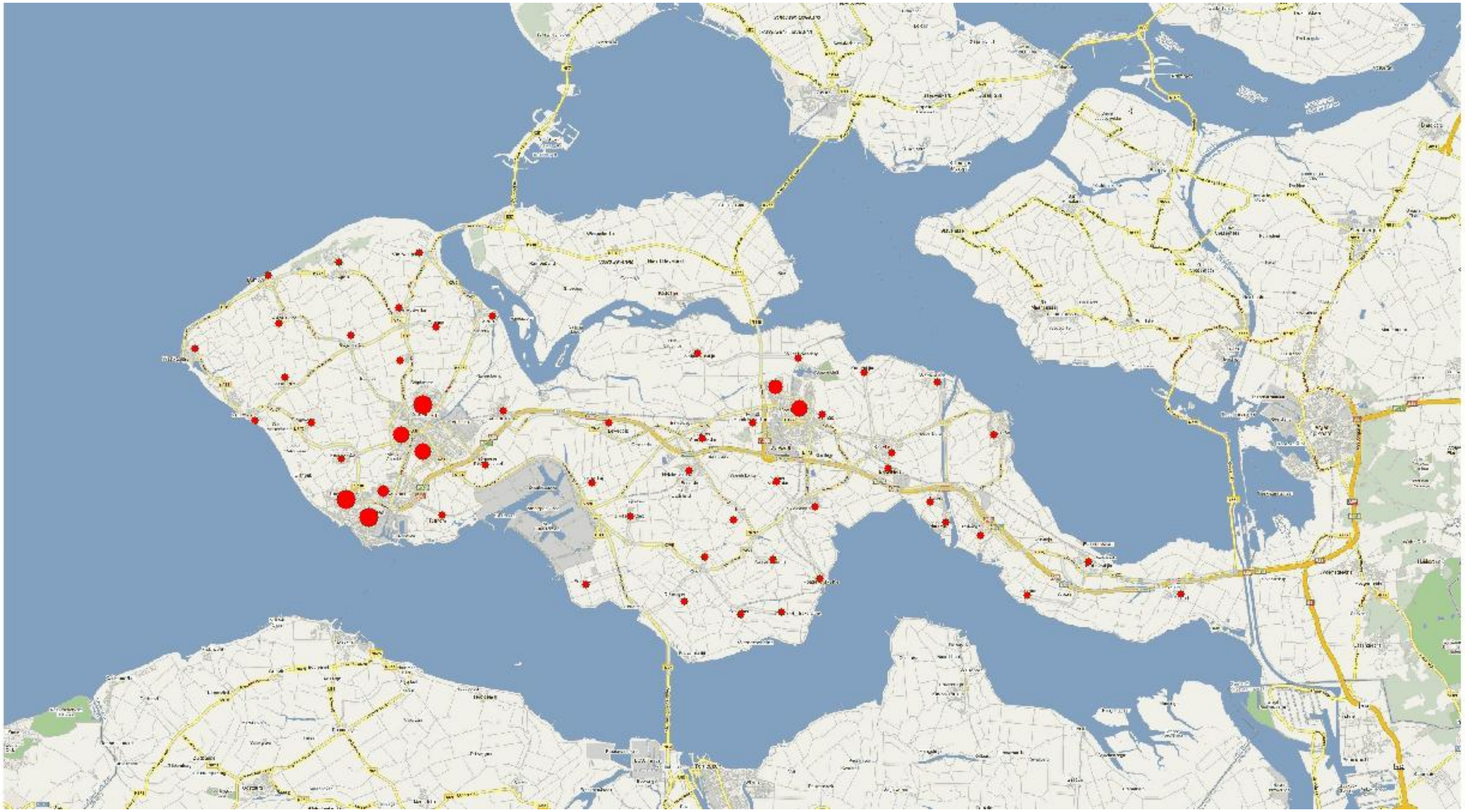
Case study

You name it, we flood it!

- 120,000 residents
- 216 square kilometers



Evacuation Walcheren



EVAQ model improvements

Recent improvements to EVAQ

- Average network dynamics do not show sufficient performance degeneration in case of network overload

- Several improvements have been implemented
- Limitation of maximum link inflow
- Improved queuing behavior and spillback
- Capacity drop
- Improvement of the node model
  - Inclusions of controlled intersections
  - Inclusion of unsignalized intersections
  - Inclusions of roundabouts
- Dedicated models for other discontinuities (e.g. weaving sections)

4.

Emergency management: Example application to evacuation planning

Case Rotterdam-Rijnmond

Skip to optimization

Data evacuation area

Municipalities:

- Albrandswaard, Barendrecht, Capelle aan den IJssel, Hoogvliet, Krimpen aan den IJssel, Nieuwerkerk aan den IJssel, Ridderkerk, Rotterdam, Schiedam, Vlaardingen
- Households: ca. 370,000 (2004)

Get away roads:

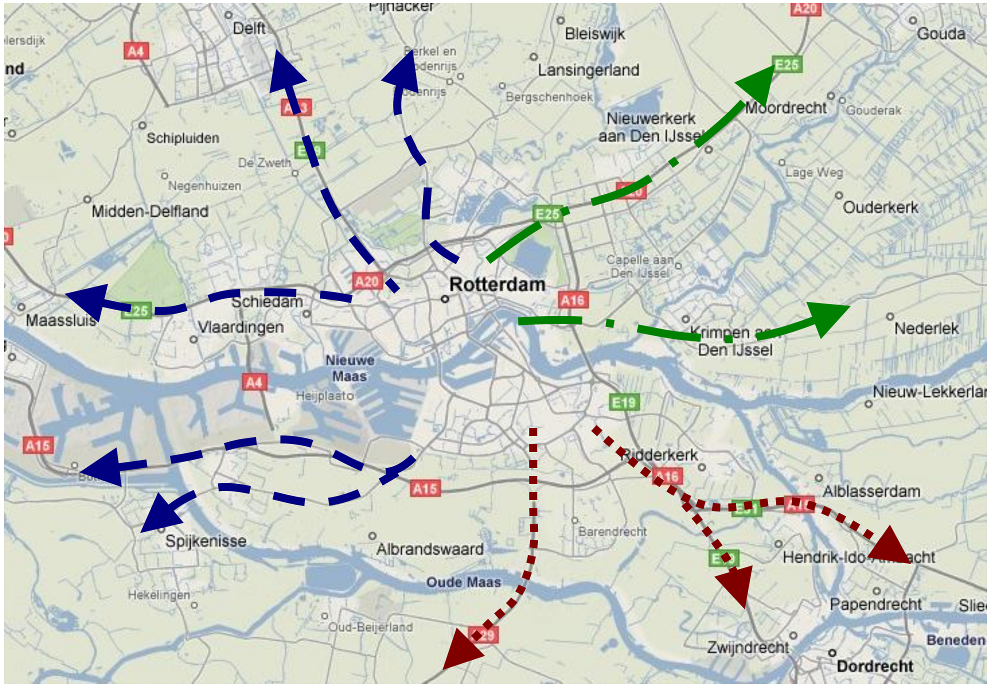
- North: A13 (Delft), N470 (Pijnacker)
- East: A20 (Gouda), N210 (Nieuwegein)
- South: A15/A16 (Dordrecht), A29 (Willemstad)
- West: A15 (Brielle), A20 (Westland), N492 (Spijkenisse)

Case Rotterdam-Rijnmond

Scenarios

Considered scenarios

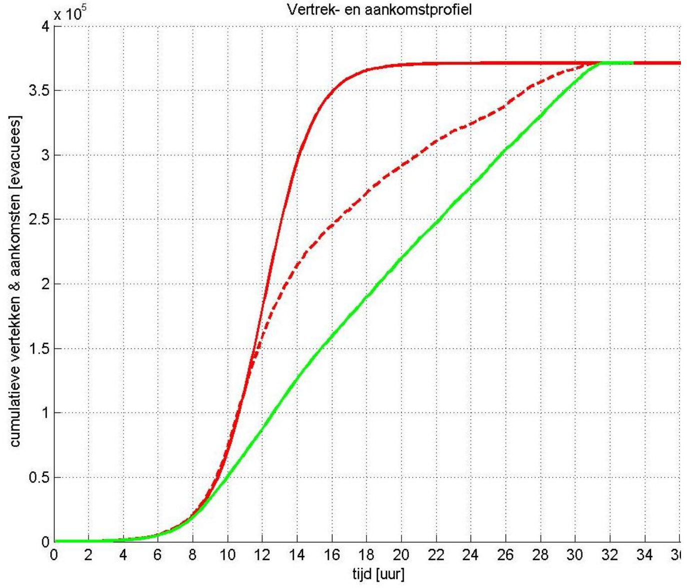
- Destinations
  - A15/A16 & A29 South
  - A20 & N210 East
  - All directions
- Traffic information
  - Extensive - limited
- Evacuation plan
  - Depature times, routes, destinations
- Compliance evac plan
  - High – low

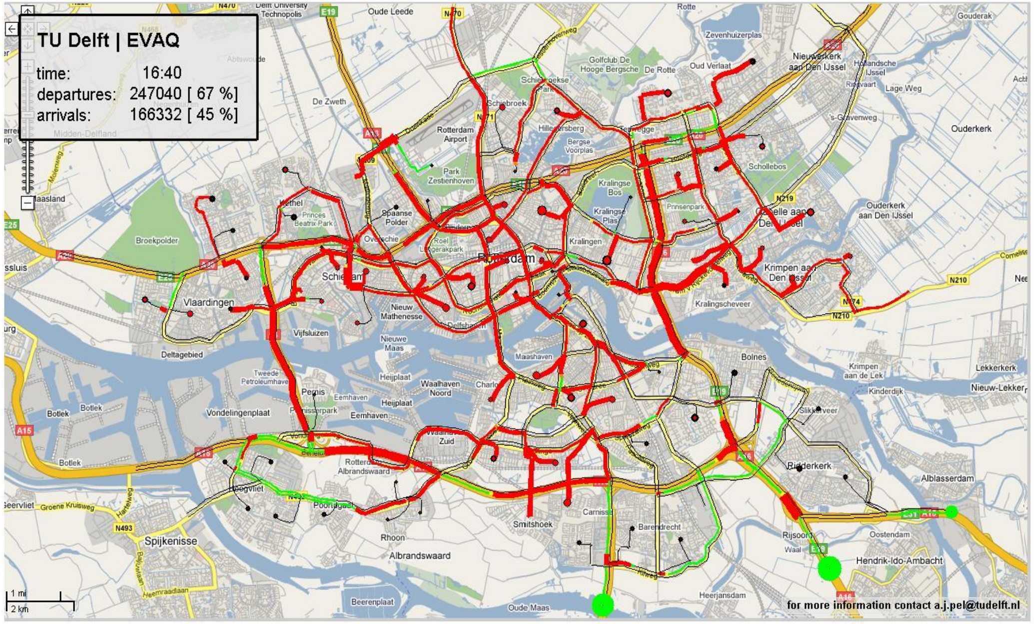


Case Rotterdam-Rijnmond

Modeling results EVAQ

- Instructed Southward, litte traffic information, high compliance

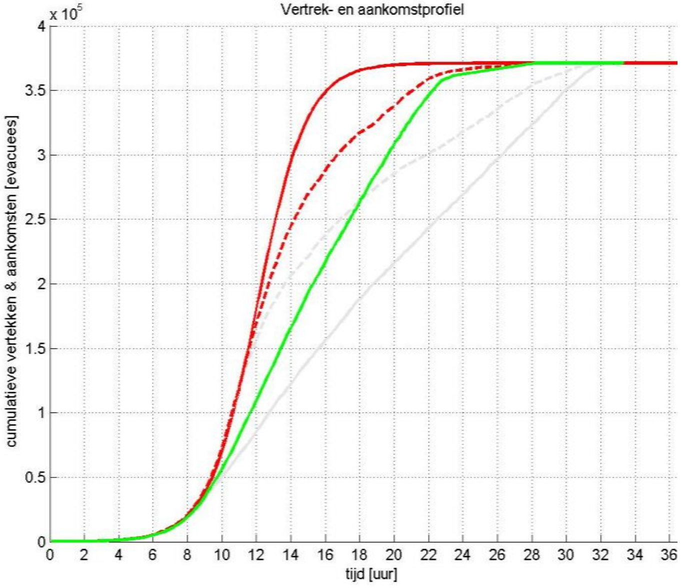


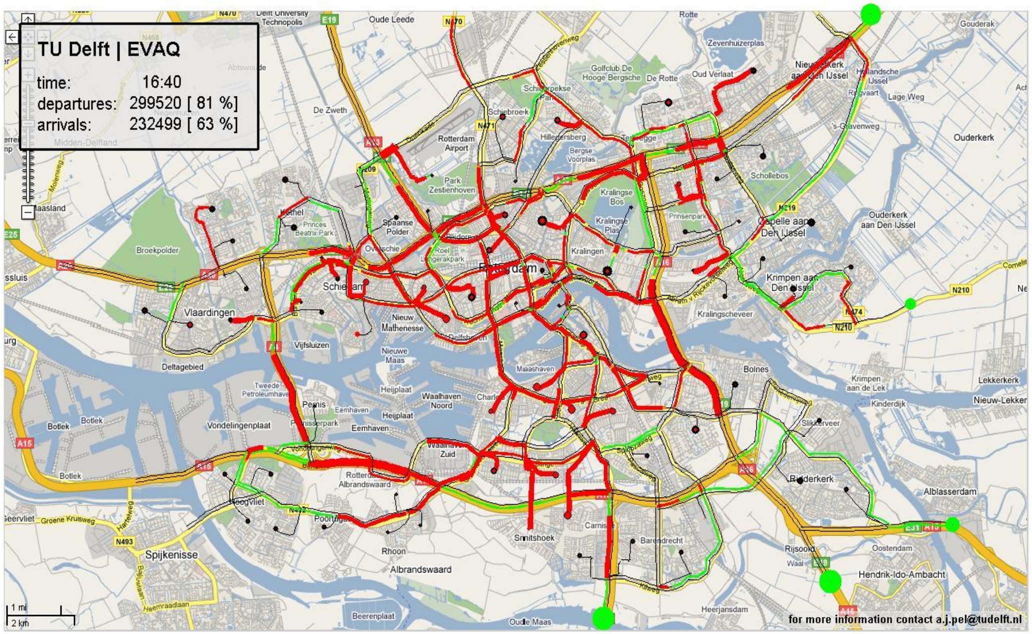


Case Rotterdam-Rijnmond

Modelresultaten EVAQ

- Instructed South-East, moderate information, low compliance





Evacuation plan design

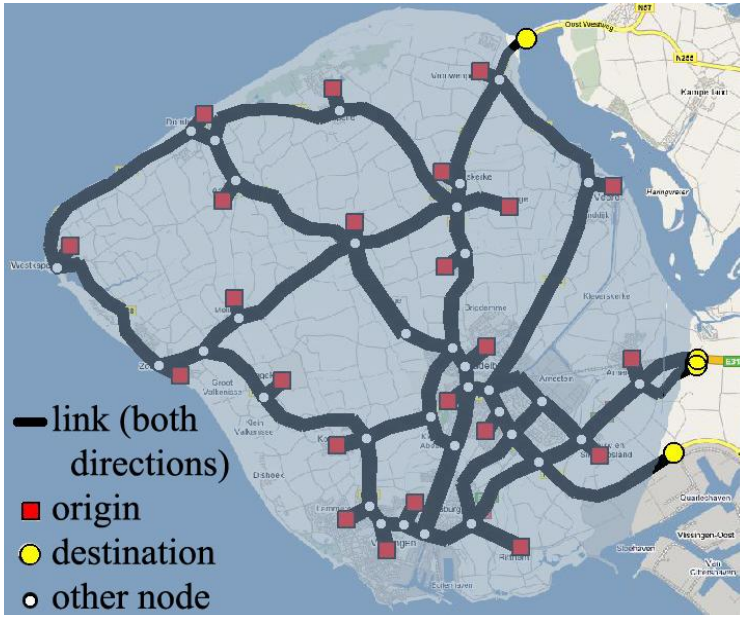
How can we improve evacuation plans?

- Flood strikes from West to East in six hours
- 120.000 residents need to be evacuated

- Evacuation instructions entail:
  - Departure time (!!!)
  - Safe haven (or safe destination)
  - Route to destination

  for specific groups of evacuees (e.g. per area code)

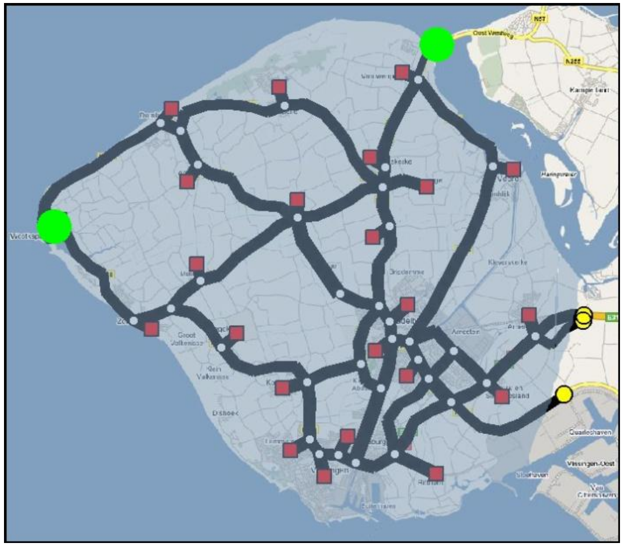
- Spatio-temporal dynamics of hazard is known

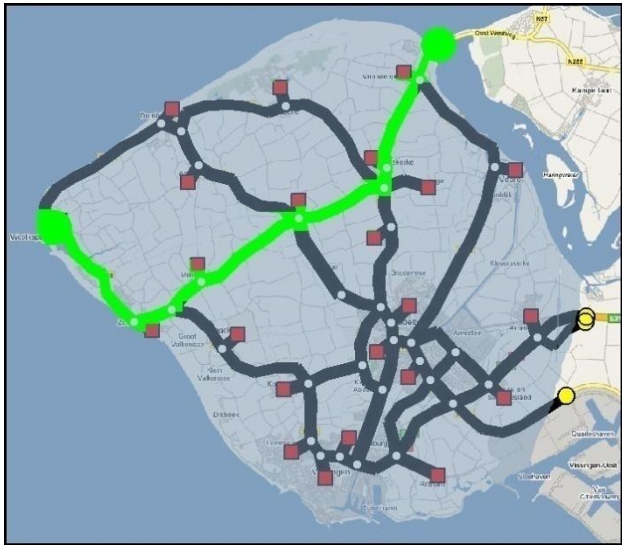


Standard evacuation schemes

Flooding of Walcheren

- For each origin, use closest destination
- Choose shortest route to safe destination (under free conditions)
- Choose departure times such that congestion is avoided





Optimization objectives

Objective applied in this research

- Maximizing function of the number of arrived evacuees in each time period:

number of arrived evacuees in time period t

evacuation scheme

- Evacuate as many people as quickly as possible
- Robust against time at which calamity unfolds
- Use of evacuation simulation model EVAQ to compute J(E) as function of E

Optimization method

Flooding of Walcheren

- The problem is NP-hard: approximation optimal evacuation scheme
- Ant Colony Optimization (Dorigo, 1996)
- In each iteration all ants in a colony create an evacuation scheme based on
  - Problem specific information (departure times and routes)
  - The iteration best evacuation schemes

Example results

Strategy comparison

- Compared to voluntary evacuation, simple evacuation rules yield significant improvement
- Optimization of evacuation plan yields very significant improvement compared to other scenarios

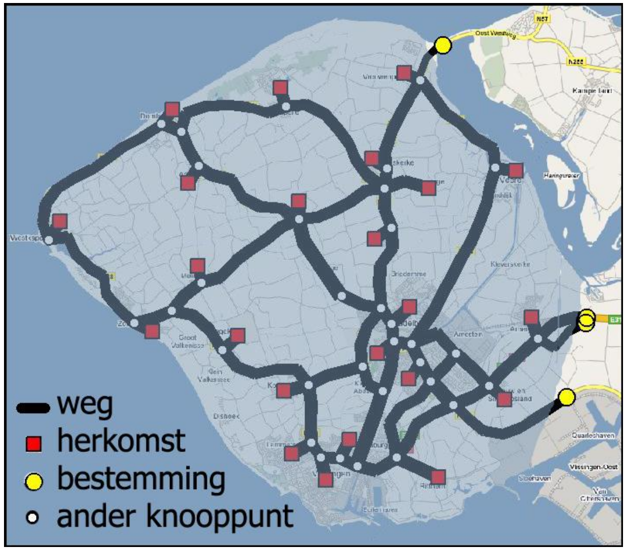
Possible explanation

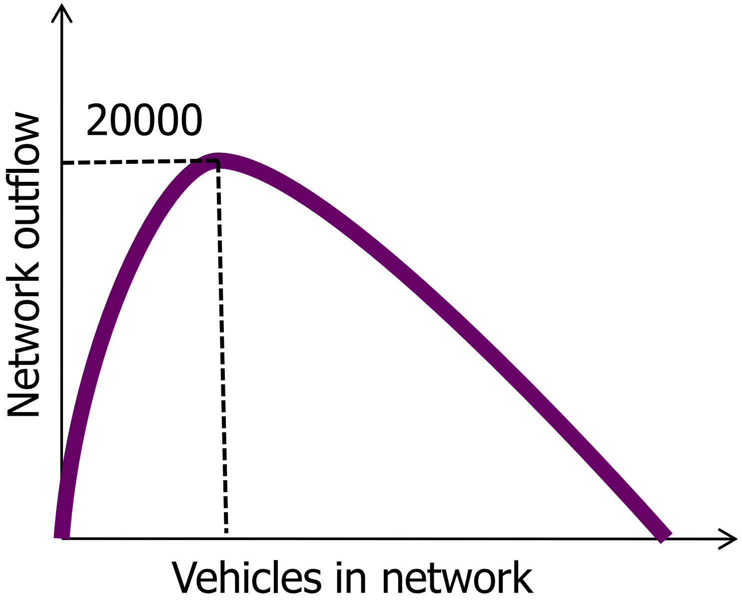
Macro Fundamental Diagram

- Optimal evacuation plan should ensure synchronization of demand and supply

- Accumulation is less than critical accumulation, so that performance degradation does not occur

- Furthermore, no under-utilization should occur

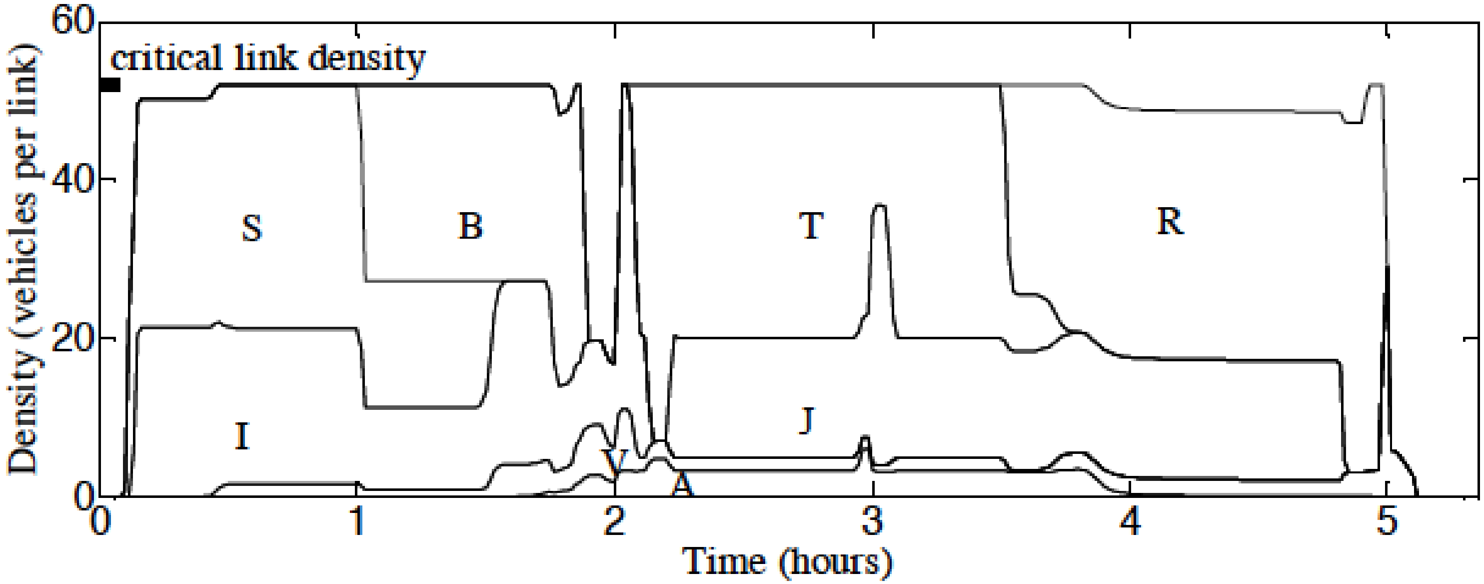




Analysis optimal evacuation schemes

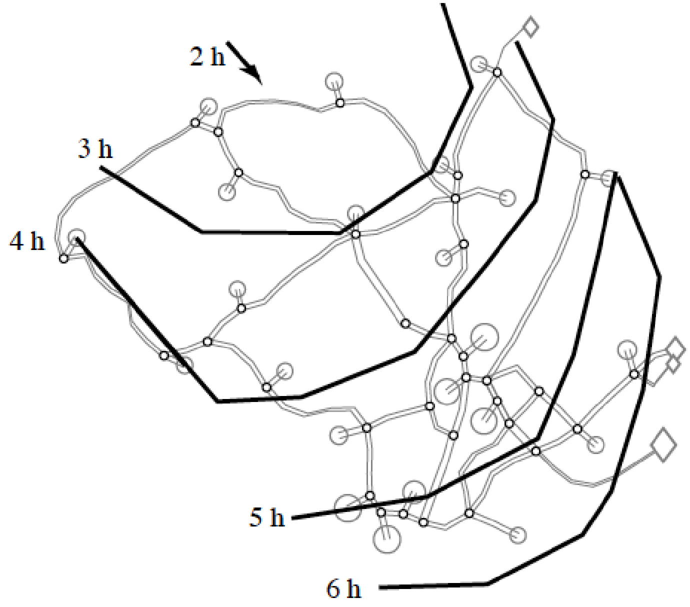
Non trivial solutions

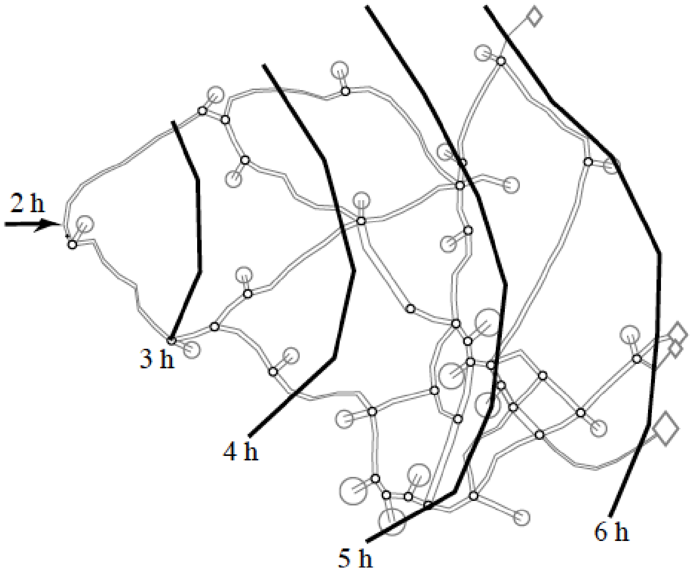
- Analysis of optimal solutions shows that optimization scheme ensures maintaining link density below critical density
- Use of network capacity about 88% (average I/C)



Impact of uncertainty
Robust evacuation plans

- Different disaster scenarios
- Turns ot that normal scnenario is quite robust
- Small improvements by explicitly considering uncertainty





5.

Closing remarks

Future work

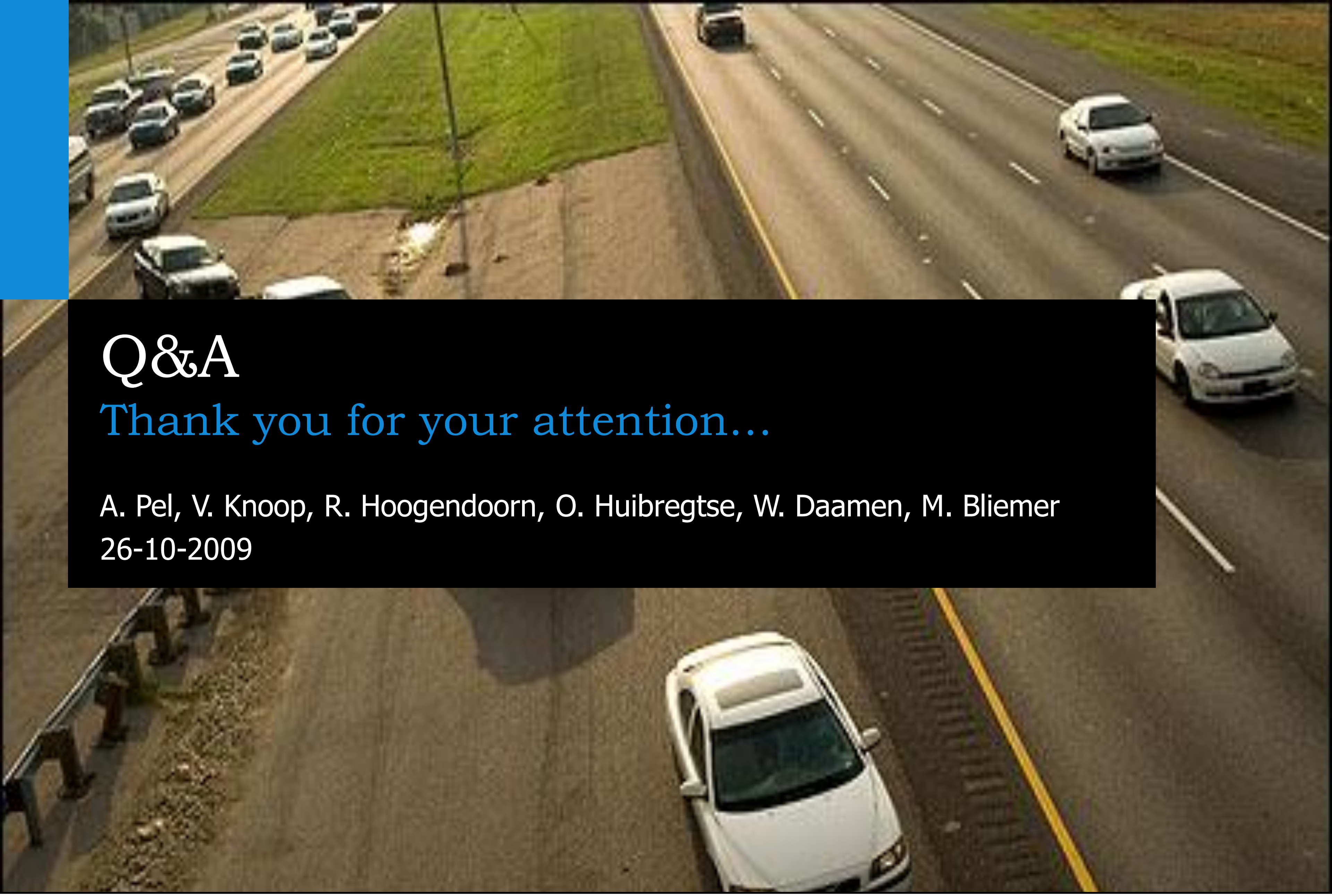
Exceptional Transportation Network Operations

- Presented work part of 5 year research project (6 Phd, 1 Postdoc) funded by the National Science Foundations
- Fields on research:
  - Driving and travel behavior in exceptional events (2 Phd)
  - Multi-scale / multi-modal transportation systems including public transit (2 Phd)
  - Mobility and traffic management strategies and operations (2 Phd)
  - Data collection (1 Post-doc, vacant!)

Main conclusions

Exceptional Traffic Network Operations

- Exceptional events (large incidents, heavy weather conditions, disasters, terrorist strikes) cause large changes in **driving and travel behavior**, and in infrastructure availability
- Including behavioral changes is **essential to correctly predict network operations** in case of exceptional events
- Models for normal conditions are generally not suitable
- Behavior in case of exceptional events follows **repeatable and hence predictable patterns**
- Dedicated models can be designed and applied to predict and manage network flow operations yielding large improvements
- Ability to deal with extreme events will also provide new ways to manage daily congestion: "Si vis pacem, para bellum"



Q&A

Thank you for your attention…

A. Pel, V. Knoop, R. Hoogendoorn, O. Huibregtse, W. Daamen, M. Bliemer

26-10-2009