A Bachelor Thesis

IMPACT ANALYSIS OF A TRANSPORT NETWORK DISRUPTION IN ZWOLLE

Bachelor Civil Engineering

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PREFACE

Dear reader,

I am pleased to present the thesis in front of you titled: “Impact Analysis of a Transport Network Disruption in Zwolle,” which is the result of my research at Rijkswaterstaat.

I want to take this opportunity to express my gratitude to my company supervisor, W. Traag, for allowing me to conduct this research at his company. Furthermore, I want to thank the employees at the company for their warm welcome and helpful assistance.

Additionally, I want to thank the staff from the university who assisted me in all parts of the research. Special thanks goes out to Dr. A. Tirachini, who was my primary supervisor from the University of Twente. His advice and feedback were incredibly helpful from the beginning to the end of conducting this research.

Enjoy reading,

S. Endendijk
Enschede, July 2024

ABSTRACT

The Zwartewaterbrug is a vital part of the A28 highway in Zwolle. Built in 1939, this bridge has reached the end of its life, with experts predicting that its structural integrity will fail around 2034. Replacement is therefore necessary, with a recommended start date in 2030. This construction work will result in a partial or complete closure of the A28, causing significant disruptions in traffic flow and affecting commuters and freight operators. This study evaluates the impact of the closure on Zwolle's transport network and the wider regional system, and explores three potential alternatives to mitigate traffic disruption: a full single-lane closure, a temporary lane shift , and a temporary bridge. These alternatives were assessed based on multiple criteria, including traffic flow, travel times, regional impact, ease of implementation, safety, and cost.

A full single-lane closure offers benefits such as increased safety for construction workers due to the absence of traffic and potentially lower costs as it requires minimal traffic management infrastructure. However, it has the disadvantage of still causing significant congestion in one direction on alternative routes, increasing travel times and causing frustration among road users, as well as an increased risk of traffic incidents due to higher congestion. The temporary lane shift improves traffic flow by optimizing the use of existing road capacity, reduces congestion, and leads to shorter travel times. It has a positive regional impact with better traffic distribution and moderate costs due to temporary infrastructure adjustments. The temporary bridge offers substantial improvements in traffic flow and a significant reduction in congestion and travel times. However, it is the most difficult to implement due to the need for extensive construction work and has high costs associated with building and maintaining this temporary bridge.

Based on the Multi-Criteria Decision Analysis, the temporary lane shift was identified as the most suitable solution, balancing cost, ease of implementation, and improvements in traffic flow and safety. While the temporary bridge scored highest on individual criteria like traffic flow and travel times, its high cost and implementation complexity made it less feasible. These findings emphasize the importance of a well-rounded approach to traffic management, considering both the immediate and long-term impact of each alternative on traffic conditions and regional mobility. The findings will provide recommendations for policymakers, urban planners, and transport authorities to ensure a smooth transition during the replacement and improve urban mobility and resilience in Zwolle.

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1 INTRODUCTION

The Zwartewaterbrug plays a crucial role in the transport network of the city of Zwolle, the Netherlands. This bridge, built in 1939, spans the Zwarte Water and forms an integral part of the A28 highway, an important artery for both local and regional traffic. Over the years, the bridge has shown significant wear and tear, needing urgent attention and planning for its replacement.

In 2019, experts concluded that the bridge will not be able to maintain its structural integrity beyond the next 15 years, implying that a complete replacement is necessary by 2034 at the latest. Experts have advised that reconstruction work should start no later than 2030 to minimize the risk of unexpected failures and manage the transition more efficiently.

The necessary construction on the A28 highway to replace the bridge poses a significant challenge to Zwolle's transport network. This construction work is likely to lead to partial or complete closures, causing significant disruptions in traffic flow. Commuters and freight operators will experience major disruption, depending on variables such as the duration of the closures and the effectiveness of the alternative routes offered during this period.

Addressing these challenges requires a comprehensive and strategic approach. Short-term traffic management strategies should be combined with long-term infrastructure planning to minimize the effect of disruptions. Stakeholder engagement and clear communication will be crucial to ensure that residents, businesses and other affected parties are informed and involved in the decision-making process throughout the construction period.

This study aims to assess the impact of the closure of the Zwartewaterbrug on Zwolle's transport system, examine the wider effects on the regional network and propose possible solutions to mitigate these issues. The study will provide valuable insights and evidence-based recommendations for policymakers, urban planners and transport authorities, with the ultimate aim of improving urban mobility and resilience in Zwolle.

1.1 RESEARCH OBJECTIVE

The objective of this research is to evaluate the impact of the closure of the Zwartewaterbrug in Zwolle on the city's transport system and to identify potential solutions to mitigate any resulting issues. The study will specifically seek to understand how the closure of this vital bridge will impact traffic flow, travel patterns and accessibility. Additionally, the study will investigate broader effects on nearby areas and the regional transportation network.

The research will also identify the key factors contributing to these challenges, such as infrastructure limitations and traffic management issues. Building on this understanding, the study will propose and evaluate various strategies to address these challenges. These will include short-term measures such as traffic management adjustments and long-term solutions such as infrastructure upgrades and policy changes.

The objective of this research is to provide evidence-based recommendations that will assist decision-makers, including policymakers, urban planners and transportation authorities, in making informed decisions. The ultimate goal is to enhance urban mobility.

1.2 RESEARCH QUESTIONS

Two main questions arise from the research objective. These two questions concern the closure of the Zwartewaterbrug in Zwolle.

Main question 1:

To what extend does the closure of the Zwartewaterbrug affect traffic patterns and accessibility in the city of Zwolle?

Sub questions:

How will traffic flow change as a result of the closure of the Zwartewaterbrug?

Which areas in Zwolle will be affected by the traffic disruptions?

Main question 2:

What measures can effectively reduce the impact of the closure of the Zwartewaterbrug?

Sub questions:

What temporary infrastructure modifications can improve traffic flow during the reconstruction of the bridge?

What role can traffic management strategies play in minimizing the impact on the local and regional transport network?

2 STUDY AREA

An overview of the study area is shown in Figure 1. The figure highlights a part of Zwolle through which the A28 highway passes. The A28 is one of the main highways in the Netherlands and serves as a link between Zwolle and the rest of the Netherlands. Zwolle acts as the central hub within the study area. It is a major city with significant economic, social, and cultural importance in the region. As such, it experiences high traffic flow, particularly along key transportation routes leading to and from the city centre. The study area extends beyond Zwolle to include nearby municipalities that rely on the infrastructure network.

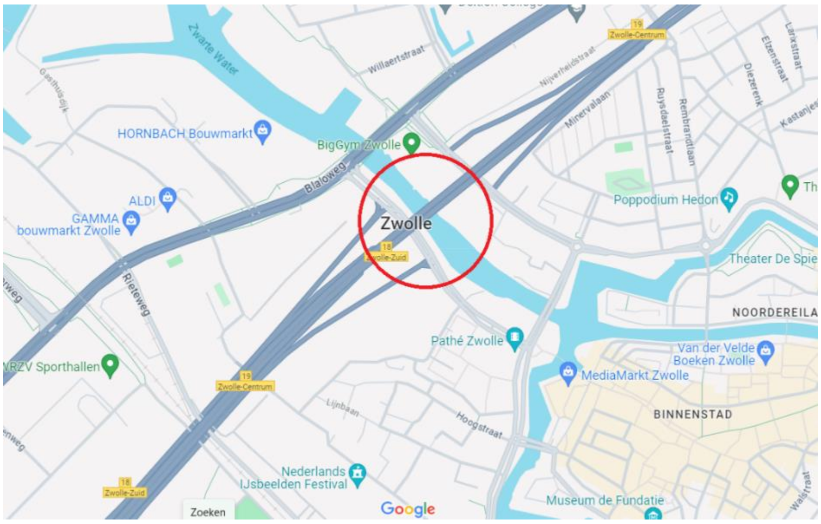

Figure 1: Zwartewaterbrug within Zwolle

The primary focus of the study is on the transportation corridors directly impacted by the closure of the Zwartewaterbrug. This includes major roads, highways and arterial roads that connect Zwolle to surrounding towns and regions. Figure 2 shows Zwolle and its nearby towns, providing an overview of this impacted area. In the next section, the Zwartewaterbrug is described in more detail, including its structural significance and the reason for its closure.

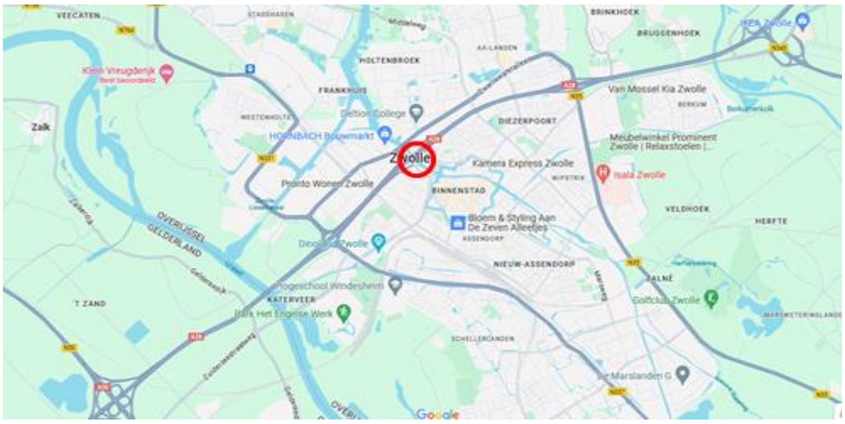

Figure 2: Zwolle and its surrounding towns

2.1 ZWARTEWATERBRUG

Figure 3: Side view Beatrixbrug

The Zwartewaterbrug serves as a plate bridge that spans the Zwarte Water and the Katerdijk. The bridge is supported by eight columns, four of which are positioned in the water and the remaining four are on land. The bridge has a total length of 120 meters and a maximum clearance width of 15 meters between the columns. The passage width is 12 meters, with a clearance height of 8.4 meters. Figure 4 shows that the bridge has two times four lanes, divided per direction into two regular lanes, one left exit and one merge lane. Additionally, there is an emergency lane of approximately 1.5 meters wide (Hellewaard, 2023a).

Figure 4: Overhead view of the Zwartewaterbrug

Table 1 displays the traffic flows on the Zwartewaterbrug during the morning peak, evening peak, and a 24-hour period. The numbers represent single vehicles. These traffic flows were obtained using INWEVA, a model from Rijkswaterstaat that covers approximately 4.000 road sections. One of these sections is the one that includes the Zwartewaterbrug. In the table, the column labelled ‘A28 Li’ represents the traffic flow from the norths towards south, while the ‘A28 Re’ column represents the flow in the opposite direction (GeoWeb 5.5, z.d.).

Table 1: Intensities Beatrixbrug

	A28 Li	**A28 Re**
Vehicles 24 hours	49.800	48.600
Passenger vehicles 24 hours	40.137	39.036
Medium-heavy freight 24 hours	3.857	3.722
Heavy freight 24 hours	5.805	5.841
Freight percentage 24 hours	19%	20%
Vehicles morning peak (7-9)	7.787	6.188
Passenger vehicles morning peak (7-9)	6.580	5.028
Medium-heavy freight morning peak (7-9)	528	490
Heavy freight morning peak (7-9)	679	670
Freight percentage morning peak (7-9)	15%	19%
Vehicles evening peak (16-18)	7.480	8.883
Passenger vehicles evening peak (16-18)	6.486	7.698
Medium-heavy freight evening peak (16-18)	427	516
Heavy freight evening peak (16-18)	567	669
Freight percentage evening peak (16-18)	13%	13%

2.1.1 Construction history

The Zwartewaterbrug was built in 1939 as part of the ring road of Zwolle, which was not yet part of the A28 at that time. The bridge was commissioned in 1941 when the ring road was officially opened. Originally, the bridge had a width of 12 meters for motorized traffic and bicycle/footpaths of 2 and 3 meters wide on both sides, resulting in a total width of 17 meters.

The first modifications were made in 1966, when the slopes and the existing bridge were widened by 8.8 meters, creating a total width of 34 meter, which is also the current width of the bridge. In 1970, the bridge became part of the A28. In 1976, modifications were made to the central reservation.

From 1976 to 2004, no further modifications were made to the bridge. In 2004, additional lanes were constructed within the existing space on the bridge, almost completely eliminated the emergency lanes. Additionally, the bridge was reinforced with carbon bond reinforcement on both top and bottom.

In 2007, the steel roller bearings at the abutments were replaced by rubber ones. New concrete piles were poured between the old bearings, on which the pads were placed. The asphalt, waterproofing membrane and joints were replaced in 2018 (Hellewaard, 2023a).

2.2 CROSSOVERS ZWARTE WATER RIVER

Only three bridges span this part of the Zwarte Water river, as indicated in Figure 5, with the Zwartewaterbrug being the only one that is not movable. The first bridge is the Holtenbroekerbrug, which is movable and opens on average 3.1 times a day for approximately 3 minutes each time (Is De Holtenbroekerbrug Open?, z.d.) This bridge is part of a local road and features two lanes in each direction, making it smaller than the Beatrixbrug.

The final option is the Hofvlietbrug, which has only one lane for each direction and is also movable like the Holtenbroekerbrug. On average, this bridge is open 2.5 times per day for about 4 minutes (Is De Hofvlietbrug Open?, 2023).

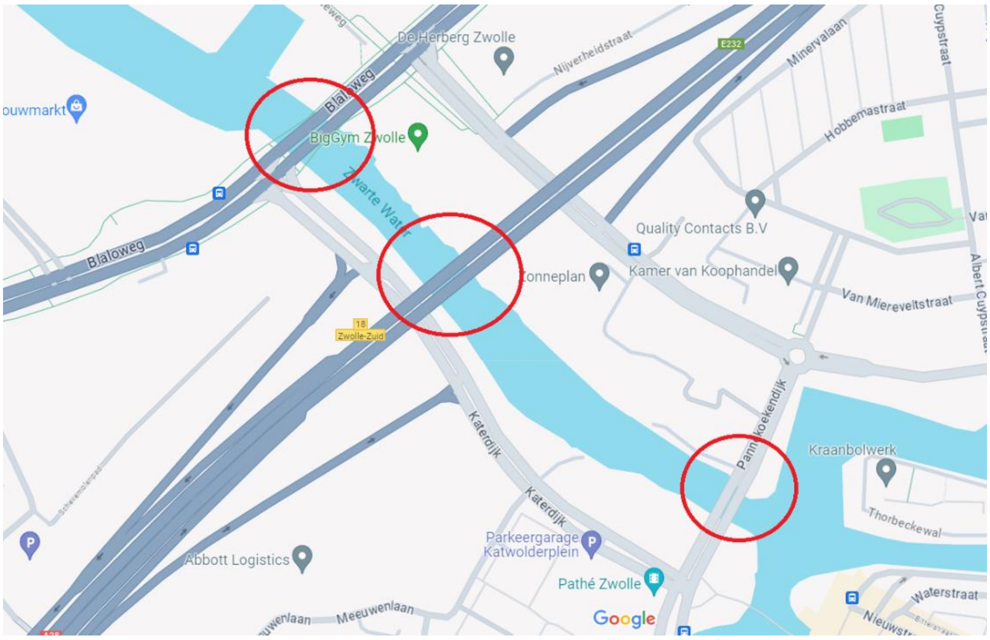

Figure 5: Crossovers Zwarte Water

3 STAKEHOLDER ANALYSIS

The replacement of the Zwartewaterbrug is a complex project involving numerous stakeholders with different interests and levels of influence. The successful completion of this project depends on understanding and addressing the concerns of these stakeholders, ensuring coordinated efforts and maintaining transparent communication throughout the process. This section provides an in-depth analysis of the key stakeholders involved, their roles and the impact of the project on them. The following figure provides an overview of the stakeholders, categorising them according to their interests and power within the scope of the project.

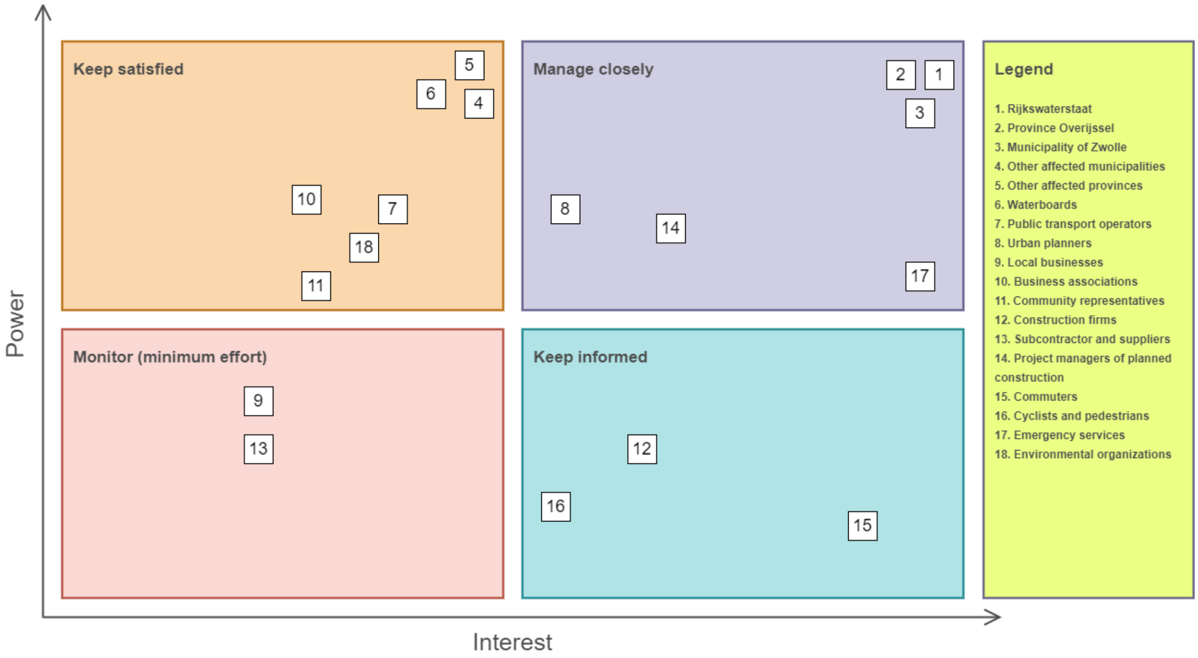

Figure 6: Stakeholder analysis (source: own elaboration)

- Governmental organizations
    - Rijkswaterstaat

Rijkswaterstaat is the primary stakeholder commissioning the assignment. Rijkswaterstaat is the executive part of the Dutch Ministry of Infrastructure and Water Management and plays a crucial role in the management of the infrastructure in the Netherlands. It is responsible for the implementation of measures that are aimed at keeping the Netherlands safe from natural elements, improving accessibility across the country, and providing pleasant living conditions for residents. Rijkswaterstaat also manages the national highways, waterways, and other water bodies with their vision of working together on a safe, liveable, and accessible Netherlands. Therefore, Rijkswaterstaat is seen as the most important stakeholder within this project.

- Province Overijssel

The province of Overijssel plays a vital role in the replacement of the Zwartewaterbrug, ensuring the project's success at multiple levels. As the regional authority, Overijssel is responsible for regional transportation planning and integrates the bridge replacement into broader strategies, enhancing connectivity while minimizing disruptions. The province contributes essential funding, facilitating timely completion. Overall, the involvement of Overijssel ensures that the Zwartewaterbrug replacement is technically sound, legally compliant, economically beneficial, and environmentally sustainable.

  - Municipality of Zwolle

The municipality of Zwolle is deeply involved in the project, overseeing its impact on the local community and ensuring alignment with the city’s development goals. They coordinate with various stakeholders to integrate the bridge replacement into urban planning frameworks, managing traffic, and minimizing disruptions. Engaging residents through public consultations and informational meetings, the municipality addresses community concerns and gathers feedback to inform decision-making. They manage traffic during construction, developing alternative routes, and ensuring accessibility to essential services. They assess and mitigate the economic and social impacts on local businesses and residents. Ultimately, the municipality’s involvement aims to enhance the city’s infrastructure while maintaining the quality of life for residents.

  - Municipalities of other affected regions

The municipality of Zwolle will not be the sole entity affected by the closure of the Zwartewaterbrug. It is necessary for vehicles that typically use the A28 to utilize alternative routes. This will result in an increase in traffic on other, smaller roads that may not be able to accommodate the additional volume. It is recommended that municipalities in which these roads pass through be afforded the opportunity to contribute to the proposed bridge replacement project, thus recognising them as a stakeholder. Exactly which municipalities these will be can only be assessed after the first simulations have been done in this assignment. This will show where most of the traffic will go after the closure.

  - Provinces from other affected regions

For these stakeholders, the same holds true as for the municipalities. It may be possible that the affected regions lay in other provinces than Overijssel, these should be considered.

  - Waterboards

Waterboards play a role in the replacement of the Zwartewaterbrug due to their responsibilities in water management and environmental protection. They are involved in ensuring that the construction does not negatively impact water levels, flow, and flood defences, given that the bridge spans the Zwarte Water. Their expertise is essential for assessing potential environmental impacts and ensuring compliance with regulations related to water quality and ecosystem health.

- Public Transport Operators (NS, Arriva, Blauwnet)

Public transport operators will ensure continuous mobility for residents and commuters during the construction period. They are responsible for adjusting routes and schedules to accommodate changes in traffic flow. This involves rescheduling busses and rail services to minimize the effects of the disruption. Their involvement is crucial for communicating changes to passengers, providing timely updates and offering alternative travel options. Public transport operators collaborate closely with local authorities and construction planners to develop effective transit solutions, ensuring public transport remains a reliable option despite the disruptions.

- Urban Planners

The goal for urban planners is to maintain the broad urban development and sustainability goals. Assessing the bridge’s impact on the city’s overall transportation network, land use, and urban environment. This involves analysing traffic patterns, identifying potential bottlenecks, and designing alternative routes to minimize disruption.

They collaborate closely with other stakeholders, such as local governments, transportation authorities and construction firms to integrate the bridge replacement into the city’s long-term development plans. Their involvement is essential for ensuring that the new bridge enhances connectivity, supports economic activities and meets the needs of the growing population.

- Businesses
    - Local businesses

Local businesses rely on the bridge for the transportation of goods, services, and customer access. Any closure or alternation in traffic flow can affect their supply chains, delivery schedules and customer access, and increase transport costs. Engagement with local businesses ensures that their needs and feedback are incorporated into the planning process, helping design measures that support business continuity.

    - Business associations

Business associations represent the concerns of the local businesses and work with project planners to develop strategies that minimize negative impacts. This might include proposing alternative routes, temporary logistical solutions and clear communication plans to inform customers and suppliers about changes. By collaborating with local authorities and construction firms, business associations help ensure that the economic vitality of the area is maintained throughout the bridge replacement project.

- Residents
    - Community representatives

Residents are crucial stakeholders that participate in the planning and implementation phases. Their involvement includes providing feedback during public consultations, voicing concerns and suggesting improvements based on daily experiences and needs. This feedback helps planners design solutions that minimize disruptions and enhance community benefits. They also participate in informational meetings and stay informed through regular updates from local authorities and planners. By staying engaged, residents help ensure that their needs and priorities are considered, promoting a more transparent and responsive project planning process. Residents can form or join community groups to represent their interests collectively, facilitating more effective communication with decision-makers.

- Construction contractors
    - Construction firms

Construction firms are directly involved in the actual rebuilding of the Zwartewaterbrug. Their role includes managing the entire construction process, from planning and procurement to execution and quality control. They coordinate with various stakeholders to ensure the project stays on schedule and within budget. Construction firms are also responsible for implementing safety protocols and minimizing disruptions to traffic and local communities during the construction period.

    - Subcontractors and suppliers

Subcontractors and suppliers are crucial for providing the specialized labour, materials and equipment needed for the replacement of the bridge. Subcontractors may oversee specific tasks, while suppliers ensure the timely delivery of construction materials. Effective collaboration between subcontractors, suppliers and the main construction firm is essential for maintaining workflow efficiency and meeting project deadlines.

    - Project managers from planned construction projects

Planned construction refers to other infrastructure projects scheduled to occur simultaneously with the Zwartewaterbrug replacement, in relatively close proximity. These concurrent projects can impact alternative routes and overall traffic flow in the region. It is crucial to coordinate with these projects to manage potential conflicts and cumulative impacts in the transportation network. Effective planning and communication with other project managers help in devising comprehensive traffic management strategies, ensuring that alternative routes remain viable and disruptions are minimized.

- Transportation users
    - Commuters

Commuters are significantly impacted by the construction, as changes in traffic flow and accessibility can affect their daily travel routines. They rely on efficient transportation routes to commute to work, school or other destinations. Disruptions caused by bridge closures or construction related detours can lead to increased travel times and inconvenience. Commuters may need to find alternative routes or modes of transportation to reach their destinations, requiring adaptation and flexibility during the construction period. Timely communication of traffic updates and alternative routes is crucial to help commuters plan their journeys effectively and minimize disruption in their daily lives.

    - Cyclists and pedestrians

Cyclists and pedestrians also feel the impact of the closure, as changes in traffic patterns and construction activities can affect safety and accessibility. Dedicated bike lanes and pedestrian pathways may be temporarily rerouted or altered during the construction period, requiring cyclists and pedestrians to navigate new routes. Safety measures must be implemented to ensure that cyclists and pedestrians can travel safely amidst construction-related hazards and increased traffic.

- Emergency services

Emergency services, including police, fire and medical services are involved in the project primarily to ensure public safety. Their involvement includes adapting response routes to accommodate changes in traffic flow and accessibility caused by construction-related detours. They must coordinate closely with construction authorities to stay informed about construction schedules, road closures and potential hazards. Additionally, emergency services must maintain emergency access to all areas surrounding the construction site, implementing contingency plans if necessary.

- Environmental organisations

Environmental organizations are involved to ensure that environmental impacts are assessed, mitigated and monitored throughout the construction process. They contribute their expertise in environmental conservation and sustainability to assess potential ecological impacts on water bodies, wildlife habitats and air quality. Environmental organizations participate in environmental impact assessments to identify potential risks and propose mitigation measures to minimize harm to ecosystems and biodiversity. They also advocate for sustainable construction practices and the integration of green infrastructure elements to enhance environmental resilience.

4 THEORETICAL FRAMEWORK

In this section, a comprehensive theoretical framework is established to understand the various aspects of traffic delays, disruption measures and travel behaviour during road closures. This framework serves as a foundation for analysing the impacts of the closure of the Zwartewaterbrug.

4.1 TRAFFIC DELAYS

Traffic delays are a common occurrence in transportation systems worldwide, often causing frustration and inefficiency for commuters. These delays are caused by various factors, each contributing to the overall congestion on roads and highways. Understanding the underlying cause of traffic delays is crucial for developing effective strategies to resolve them (Brasuell, 2023, Cartrack, n.d.).

Volume of vehicles: One of the primary reasons for traffic delays is simply the sheer volume of vehicles on the road. As populations continue to grow and economic activities expand, the number of vehicles on the road increases. This will lead to congestion, especially during peak hours.

Road capacity: The capacity of roadways to accommodate vehicles is limited, leading to congestion when demand is close to or exceeds capacity. Bottlenecks, such as narrow lanes, intersections and merges can be the reason for restrictions of traffic flow levels.

Incidents and accidents: Traffic delays often result from incidents and accidents, such as vehicle collisions, breakdowns or emergencies. These unexpected events can disrupt the flow of traffic, causing traffic jams.

Traffic signal timing: Inefficient traffic signal timing can contribute to delays at intersections. Poorly synchronized signals can lead to unnecessary stops and starts, increasing travel times and congestion.

Weather conditions: Heavy weather conditions, such as heavy rain, snow or fog can significantly impact traffic flow. Reduced visibility and slippery road can lead to accidents and slower travel speeds.

Specials events and holidays: Large-scale events, festivals or holidays often attract a large number of visitors to specific areas. Road near event venues or popular tourist destinations may experiences significant delays during such events.

Construction and road work: Construction projects and road maintenance can disrupt traffic flow by reducing the number of available lanes or closing entire sections of roadways. Detours and lane closures can lead to congestion and longer travel times.

Driver behaviour: Lastly, driver behaviour plays a crucial role in traffic delays. Factors such as aggressive driving, speeding, improper lane changes and distracted driving contribute to congestion and an increase in the likelihood of accidents.

Traffic delays is the overarching theme of this research, which aims to develop and evaluate strategies for improving urban traffic flow and reducing congestion, during the bridge construction phase. Traffic delays are not only caused by construction work, but also by unplanned factors. The analysis of traffic delays provides the groundwork for the subsequent chapters where alternative strategies are proposed.

4.2 TRAFFIC DISRUPTION MEASURES

During large-scale construction projects, effective traffic management is essential to minimize disruptions and maintain safety. Measures can reduce traffic disruptions by decreasing regular traffic intensity and increasing road capacity. This section focusses on these measures to manage traffic.

According to Crow (2014), measures can reduce the traffic disruption on three aspects:

- Reducing the intensity of construction traffic;
- Reducing the intensity of already present regular traffic;
- Increasing the transport capacity.

The traffic flow of construction vehicles is crucial in the analysis of a road closure as it affects safety and traffic flow. Additionally, efficient logistics of materials and equipment is needed. Proper planning minimizes the impact on the environment, including noise and dust. However, in an early project phase like this, construction traffic is not yet fully analysed because the initial focus in on design and general traffic management. Detailed construction plans are often still variable and a full analysis may be premature. A full analysis of construction traffic is therefore carried out at a later stage, when more detailed and up-to-date information is available, allowing planners to allocate their resource more effectively and respond better to specific circumstances. Therefore, at the current stage only the measures for the already present traffic and for increasing road capacity will be explained.

Deployment of traffic regulators

The deployment of traffic regulators making unsafe or unclear situations safer and smoother. This is particularly useful when signs are inadequate or at high traffic volumes. For long-term adjustments, temporary traffic lights can be a cheaper alternative. Only certified traffic controllers should be used, usually hired by the construction project contractor. For them it is important to keep contact with the road authority, especially as it often cooperates with traffic controllers who know the local situation. The preparation time for them is short and the costs for this alternative are mainly the (hourly) costs of the traffic controllers (CROW, 2014).

Establish diversion routes (incl. signage plan)

During a closure, diversion routes are necessary. Through signage and, if available, DRIPS (Dynamic Route and Information Panels), traffic is diverted around the construction project. Responsibility for the implementation may lie with the contractor or the road authority, depending on the agreements that are made. Close cooperation between the contractor and the road authority is crucial, as is informing emergency services of the diversion routes. The effort varies depending on the size of the diversion routes, from a few streets to several kilometres and increases with the complexity of the route. The costs for smaller diversions are mainly related to signage, while for larger diversions, organisational and communication costs weigh more heavily (CROW, 2014).

Carpooling

By encouraging carpooling, the number of vehicles on the road can be reduced, reducing the expected traffic disruption during construction projects. The primary goal is to decrease the intensity of regular traffic, by reaching and encouraging commuters to carpool, using existing carpooling initiatives and platforms (CROW, 2014).

Efficient use of space (fewer lane closed)

This measure focuses on projects that are (partly) on the roadway, such as construction projects where part of the road is regularly used for supporting activities such as loading, unloading and storage. The primary aim is to maintain the available road capacity as much as possible to reduce traffic flow disruptions. The effort is high, as there is less space available for the work, which impacts the entire execution of the project (CROW, 2014).

Create separate infrastructure

If there is sufficient space, consideration can be given to building separate (temporary) infrastructure for regular traffic. This is particularly beneficial in longer-term construction projects. To save costs and/or space, temporary roads can be constructed with a narrower profile. The primary goal is to increase road capacity. Given the additional costs, the client will usually play a leading role, while realisation lies with a contractor. In consultation with the road authority and other public space managers, the incorporation of the temporary structure is determined. Preparation time varies from medium to long: for smaller projects, it can be ready within a year, while larger projects require more than a year of preparation. The largest cost item is the realization of the infrastructure, besides costs for (permit) procedures and (preliminary) research (CROW, 2014).

Stimulate public transport

Encouraging public transport during large-scale construction projects is essential to decrease traffic intensity and improve traffic flow. Encouraging commuters to use public transport will relieve pressure on road, reducing congestion and delays. This contributes to a more sustainable environment by reducing emissions. Moreover, less traffic reduces traffic managements costs and increases road safety around the construction area (CROW, 2014).

4.3 ROUTE CHOICE BEHAVIOUR

The Wardrop principle, named after John Glen Wardrop, is a concept in traffic and transport management that describes how car drivers distribute across a road network. The principle consists of two fundamental principles that describe traffic patterns in a transport network (Krylatov et al., 2019).

1. **User Equilibrium**: This principle states that in an equilibrium situation, no driver can reduce their travel time by choosing an alternative route. This principle describes a state in which no traveller can reduce their travel time by switching roues. In essence, it represents a situation where travellers have no incentive to change routes because all the routes have the same travel time.
2. **System Optimum**: This principle states that the total travel time in the network as a whole is minimized. The overall travel time for all travellers in the network is minimized, leading to the most efficient allocation of traffic flow. However, because the system optimum is typically different from the user equilibrium, it is not reachable without incentives from decision makers, for instance, in the form of pricing incentives.

These principles are crucial for understanding and analysing traffic flow patterns in road networks, helping transportation planners and engineers make informed decisions to improve traffic efficiency and reduce congestion.

4.4 TRAVEL BEHAVIOUR DURING CLOSURES

This section explores the impact of road closures on travel behaviour based on previous studies and interviews. Understanding how commuters react to disruptions provides valuable insights for managing traffic.

4.4.1 Previous studies and interviews

Road closures are inevitable during major infrastructure projects and maintenance works. They have significant impact on people's daily traffic and travel behaviour. To understand and manage this impact, several studies have been conducted that provide insights into how road closures affect commuters. These studies, such as the renovation of the Roertunnel on the A73 and renovation of the Heinenoordtunnel and Haringvlietbrug, provide valuable data and conclusions on the adaptability and behavioural changes of commuters. These case studies are analysed in Midden Limburg Bereikbaar & MuConsult (2024) and Hofmans et al., (2024), and a summary of results and findings follows.

Commuters react to road closures by adjusting their behaviour to minimize inconvenience, often by choosing alternative routes. For example, the evaluation of the A73 construction works showed that eight out of ten users surveyed chose an alternative route. Additionally, alternative means of transport such as e-bikes and public transport discounts are offered, although little use is made of these options. People tend to prefer using their own bikes or regular public transport. Companies were encouraged to allow employees to work from home or take days off during the closures. This proved effective in reducing the number of cars on the road.

The level of satisfaction and perceived inconvenience varied among the users, with a large proportion of users being satisfied with the timeliness and clarity of information about the closures. During the work on the A73, almost all respondents were satisfied with how they were informed. However, the degree of inconvenience experienced varies. On average, one in ten interviewees experienced a lot of inconvenience during the work on the A73. Additionally, during the closures of the Heinenoordtunnel and Haringvlietbrug, many road users experienced more inconvenience than expected.

Some users reacted negatively or even aggressively to the closures and traffic measures. For instance, aggressive behaviour was observed during the Heinenoordtunnel and Haringvlietbrug closures. Road users moved barriers, drove over cycle paths and farmland, and even committed theft on traffic system components. The closure of shortcuts led to increased pressure on unaffected roads, causing frustration among users.

Communication campaigns were effective in informing and influencing road users' behaviour. Smart travel information campaigns reached a large audience by showing tailored advertisements on social media, navigation apps and websites. This led to a lot of interaction and awareness among the users. As a result, road users felt well informed about the closures and possible alternatives, contributing to a certain level of understanding and acceptance of the inconvenience.

Commuters' reactions to road closures vary widely, including both adjustments in travel behaviour and negative reactions. Effective communication and the provision of alternatives, such as clear signage and public transport options, play a crucial role in managing these reactions and minimizing inconvenience. Timely and clear information helps road users adapt better to the changes, reducing overall frustration.

An example of financial incentive is the 'Ervaar het OV' campaign in Gelderland, the Netherlands. The aim of this campaign was to let residents experience what public transport (OV) can do for them and encourage them to start using public transport. The campaign started in 2007 in Gelderland. A platform was set up in which the province and transport operators worked together, enabling a coordinated approach despite the different operators. Actions in this campaign included handing out free day passes and €3 tickets with including discounts at some shops. This campaign proved successful, with high interest, especially for the shopping option. About 70% of the 18,000 applicants said they would use public transport more often in the future. The campaign showed that a public transport ticket does not necessarily have to be free; it has to be attractive (CROW et al., 2024).

In the Swedish town of Lund communication campaigns were conducted to promote alternative transportation to achieve a more sustainable environment, public transport trial ticket was distributed and a mobility centre was set up. These actions focussed on promoting cycling, public transport, car sharing, fuel-efficient driving and clean vehicles. The results of these initiatives were impressive: 26% of residents started travelling in a more sustainable way and 10 % started cycling more often. A key success factor in Lund were the 'kitchen table talks' Mobility advisors visited 19.000 households and gave personal information on alternatives to the car. 35% of the households visited said they were influenced in some way by these talks. These initiatives underline the importance of personalization. Direct contact and conversations with residents about their specific circumstances and how to use more sustainable means of transport proved successful (CROW et al., 2024).

Finally, in an interview with Joris Kessels, who has been with Rijkswaterstaat for 14 year, the last 10 of which as consultant and project leader in the field of smart mobility and behavioural change, additional insights were provided regarding behavioural changes during road closures. He emphasized that commuters react differently to closures depending on the extent of the inconvenience and the available alternatives. Effective information provision helps reduce the disruption. Measures such as clear signage and timely updates can achieve a traffic reduction of 30-40%. Behavioural changes, such as reducing travel or changing modes of transportation, have a greater impact than merely choosing alternative routes. Structural behavioural changes, such as shifts towards cycling and public transport, are essential for long-term solutions.

4.4.2 Information availability

As discussed earlier, providing reliable information is crucial for passengers during transport disruptions. In the case of public transport, effectively distributing information can significantly improve passenger experience by reducing waiting times and enabling better decision-making. Information can be shared through various channels, such as mobile devices, real-time displays and social media.

The availability of information influences passengers' decisions, such as choosing alternative routes or cancelling trips. Leng & Corman (2020) provide a framework for classifying information availability is introduced: who, when, where and what.

Three scenarios are examined: no information, timely information and advance information. Under 'no information', passengers receive information only when they encounter the disruption, leading to higher delays and lower satisfaction. With 'timely information', passengers receive information at the start of the disruption, resulting in moderate delays and satisfaction levels. 'Prior information' provides full knowledge before the disruption starts, resulting in the highest satisfaction and the lowest delays (Leng & Corman, 2020).

Although this study focussed on public transport, important lessons can be drawn from is for our own disruption. Timely and accurate information provision proves crucial for managing passenger satisfaction and minimizing the impact of disruptions. It helps drives make better decisions and improve theirs travel experience.

4.4.3 Modal shift

A literature review on the travel behaviour of commuters following a transport network disruption provides valuable insights and lessons. A table with a complete overview of the studies and results can be found in the appendix.

Firstly, there is a wide range of changes in transportation modes. The rates of modal shift vary considerably between different studies and situations. For example, the closure of a bridge in Los Angeles (Zhu et al., 2008) resulted in a modal switch of 5.8%, while the reconstruction of a highway in Sacramento (Yun et al., 2011) led to a of 21.3% modal shift. This suggests that the context and circumstances of the disruption play a major role in how people adjust their mode of transport.

Additionally, the type of disruption significantly impacts the degree of modal shift. Public transport disruptions, such as in Amsterdam (Yap & Cats, 2022), resulted in a modal shift of 33%, which is significantly higher than many cases of road transport disruption. This suggests that public transport disruptions force people to seek alternative means of transport, especially in urban areas where public transport plays an important role in daily transportation.

Another crucial aspect is the difference between planned and unplanned disruptions. Planned disruptions, such as the highway reconstruction in Sacramento (Yun et al., 2011) with a modal switch rate of 21.3%, give people time to prepare and find alternatives, leading to a higher rate of switch. Unplanned disruptions, on the other hand, may require unexpected adjustments, often resulting in lower rates of modal switch. The duration of the disruption also plays a crucial role. Long-term disruptions generally lead to higher rates of modal switch. For example, the prolonged closure of a metro line in Athens (Lin et al., 2013) resulted in a switch of 13%, while shorter disruptions such as a one-day disruption in Krakow (Drabicki et al., 2021) produces a switch of 26% to 33%. This indicated that longer disruptions force people to consider and use alternative transport modes for longer periods of time.

Furthermore, urban areas with well-developed alternative transport options show higher rates of modal switch. In Amsterdam (Yap & Cats, 2022) modal shift was 33% during a public transport disruption, suggesting that the availability of alternative transport options plays a crucial role in how people adjust their travel behaviour.

All-in-all, we can learn that it is important to consider the availability of alternative transport modes during transport disruptions, whether planned or unplanned, and that the rate of people that switch modes might be marginal or significant depending on the conditions. Policymakers should invest in robust and versatile transport networks that offer multiple options for people is case of disruptions, to help minimizing the negative effects of disruptions in daily lives.

5 METHODOLOGY

This chapter outlines the methods used to address the research questions and objectives. Two transport models from Rijkswaterstaat are explained, as these model simulate and predict traffic flows, and are useful for the analysis of disruptions. The Growth Factor Module is discussed, incorporating future traffic projections. Finally, a Multi-Criteria Decision Analysis framework is described, which also is an useful tool to guide the evaluation and prioritization of infrastructure alternatives.

5.1 NATIONAL MODELS RIJKSWATERSTAAT

Rijkswaterstaat uses two different models for forecasting the traffic network in the Netherlands, called ‘het Landelijk Model Systeem en Vervoer’ (LMS) and ‘het Nederlands Regionaal Model’ (NRM). These tools have been in use by Rijkswaterstaat since 1986. They are used for forecasting several modes of transport, including car drivers, car passengers, train, bus, trolley, metro, cyclists and pedestrians can be modelled and analysed. LMS and NRM can estimate the future traffic flows, both on the road network as on the train system, with the road network being the primary focus (Hofman, 2017).

Mobility in the Netherlands is increasing every year, with more people travelling for work, leisure or study. In addition to passenger transport, freight transport will also increase the pressure on the roads, leading to a higher risk of congestion. Using LMS and NRM, one or more possible policy measures can be identified. The forecast can be used to estimate the impact of various measures (Hofman, 2017).

LMS and NRM distinguish different trip purposes, namely:

- Commuting
- Business from home
- Business not from home
- Shopping
- Social-recreational and other from home
- Social-recreational and other not from home
- Education
- Land-based mobility of air travellers
- Primary education for children
- Other travel for children
- Shopping for children

5.1.1 Workings of LMS and NRM

The present section is mostly based on Hofman (2017). The LMS and NRM models are crucial for forecasting Dutch transport, and an explanation of both models follow. LMS is a model that simulates the entire region of the Netherlands, focussing on the main transport network. In contrast, NRM divides the country into zones, creating a more detailed transport network. In this research, the NRM model will mainly be used. Each model, the country area is divided into numerous zones, each with its own characteristics and implemented in the base year. This distinction is necessary because a transport model like this has to calculate spatial transport flows. The models use a logit mode choice model, meaning that the probability of choosing a particular mode for a trip is based on several factors. Figure 7 shows a schematic step-by-step plan of how the two models work, with a more detailed explanation below.

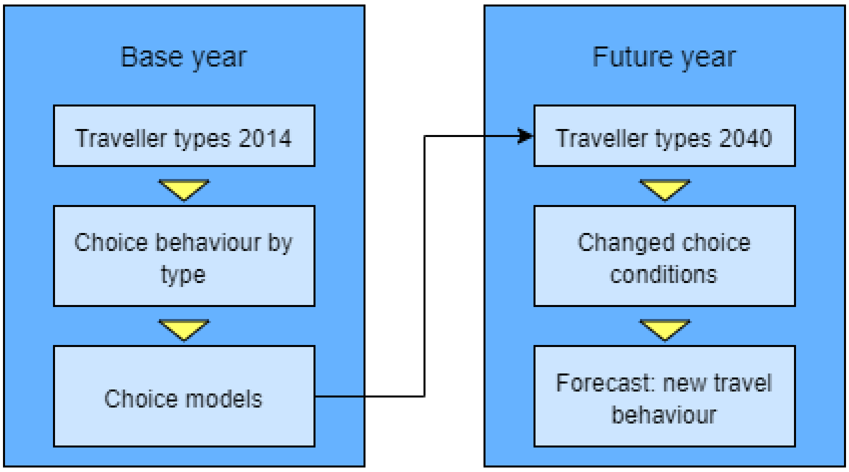

Figure 7: Schematic step-by-step plan RWS models (figure is translated from Hofman(2017))

Step 1 – Choice behaviour by type of user

The first step involves understanding the choice behaviour by type of user. The model assumes that individuals or households make transport choices based on maximizing benefits. Each person will make a logical trade-off based on cost, time and various other factors. This information is gathered from previous research on how people would react to a change in events, such as what mode or route someone would use if a closure affected their usual pattern.

Step 2 – Traveller types in 2014

In the second step, traveller types based on the choices that are made in step 1 are determined. These are characterized by factors such as age, gender, income and car ownership. These combined factors create diverse traveller profiles, which help predict travel behaviour in the future. The model also accounts for the growth of certain age groups; for example, the 60+ age group could be larger in the coming years than it is currently.

Step 3 – Choice models

In the third step, the choice model establishes the relationship between the determined factors. LMS and NRM use seven different choice models, with the choice of model depending on the specific objective of the analysis.

Step 4 – Traveller types in the future

Before applying the choice models, the size and composition of the future travel population for each zone are determined. The models use input on demographic and socioeconomic data and spatial trends to predict the traveller types that will be in the desired year.

Step 5 – Changed choice conditions

In this step, the conditions from previous steps are updated to reflect new policy decisions that provide additional options and influence choice behaviour. For example, in the current situation, there is no rail network present, but in the future scenario there is. This change will affect future decision making.

Step 6 – Forecast: new travel behaviour

In the final step, LMS and NRM calculate changes in decision making in both the short and long term. In the short term, changes on a stretch of road may load people to travel at a different time or take an alternative route. In the long term, there could be more significant changes, such as using different modes of transport or even relocating to another city. The model combines various data types to visualize the overall impact on the region, including the effects on public transportation and the road network.

5.1.2 Inputs and outputs LMS and NRM

Model administrators determine the required outputs and the corresponding inputs. Input data are rigorously checked to prevent errors. The models take time to generate outputs, with an LMS run taking up to 12 hours.

Inputs

1. Information on the traffic system in the base year and forecast year.
    a. Road network
    b. Public transport system
    c. Parking costs
2. Demographic and socioeconomic data, for each zone in the base year and forecast year.
    a. Number of inhabitants by gender and age
    b. Number of households
    c. Employment by sector and total
    d. Size of labour force by gender
    e. Number of places for students for primary education
    f. Number of places for students for secondary education
    g. Number of places for students for college/university
    h. Car ownership
    i. Driver's license ownership
    j. Number of male part-timers
    k. Number of female part-timers
    l. Average income
3. Description of passenger mobility in the base year
4. Description of freight traffic in the base year and the forecast year

Outputs

1. Projections of passenger mobility in the Netherlands in the forecast year.
2. Differentiated by the mentioned modes of transport and motives and in the case of car and train transport if divided by morning rush hour, evening rush hour and rest of the day for an average weekday.
3. Forecast of the load on the road network in the forecast year.
4. After further processing by ProRail track section loads and allocations of passengers to trains.

5.1.3 Validation

The quality of the RWS models is assessed in several different manners.

- Comparison of the amount of traffic on the road according to the model and according to measurements with information from CBS.
- Examine whether the model reproduces the important traffic jams with information from CBS.
- Examine whether the distance distribution of the traffic is consistent with information from CBS.
- The sensitivities of the model are assessed against scientific insights about the magnitude of these sensitivities.
- Comparing the predictions with the reality.

5.1.4 Limitations

Each model is a simplification of reality and has therefore its limitations.

- It is a static model; it only shows the final situation. In reality, people do not adjust their behaviour at ones, but gradually.
- Natural behaviour, behaviour that is not based on maximum utility, is not included in the model.
- The model assumes that people compare all available alternatives with each other. In practice this is not the case, a traveller often takes the first choice that is acceptable.
- Accuracy of intensities and travel times on the road network is not everywhere guaranteed. Especially on places where congestions play an important role.

5.2 GROWTH FACTOR MODULE

As mentioned in 5.1.1, characteristics of road users in the year 2040 need to be estimated. This is achieved using the growth factor module (GM). The growth factor module is used to determine the growth in travel behaviour in the future year compared to the base year. To utilize the module, the population module, reachability module and foreign transport module must be executed first. These three modules will be explained briefly below, followed by a detailed explanation of the growth factor module.

5.2.1 Other modules

The population module focusses on demographic data and trends. It models population growth and changes, such as birth and death rates, migration and ageing. The output of this module helps predict future demand for transport and infrastructure, considering changes in population density, urbanisation and the distribution of households across the country.

Rijkswaterstaat's accessibility module analyses the accessibility of locations within an uncongested network. This module includes network conversions and determines the quality of accessibility based on different modes of transport, such as cars, bicycles and walking.

The foreign transport module identifies traffic related to foreign origins and destinations. This includes airport traffic (car and train journeys to airports) and outbound traffic (international car traffic). Airport traffic is modelled for two types of travellers: access travellers departing from the Netherlands and egress travellers, who come to the Netherlands for business and other reasons. International traffic refers to traffic whose origin and destination are not in the same country, focusing on trips using the Netherlands as a transit country (Rijkswaterstaat, 2023).

5.2.2 Growth factor

The growth factor module can be divided into four sections:

- Determining the primary transport demand.
- Determining the transport demand for secondary destinations.
- Determining the growth of travel behaviour in the future year compared to the base year.
- A congestion-sensitive allocation.

Determining the primary transport demand within the GM is a crucial step in understanding the basic travel behaviour of individuals in a study area. This process utilizes of various models and methodologies precisely designed for different travel motives and personality profiles. Several models are used to determine this transport demand, including the frequency model and the mode-day-destination choice model.

The frequency model focusses on the travel frequencies of individuals, determining the average number of trips they make in a day for each person within the sample. It works in two steps: first, calculates the probability of a person making one or more trips and then determines whether an additional trip of the same type is made. This approach is known as the stop/repeat-model. The sub-models within the frequency models are specified as logit models, where explanatory variables are based on five person and household characteristics.

1. Car availability;
2. Gender, driver's license ownership and occupation
3. Age;
4. Level of education;
5. Household's annual spendable income.

The result of the frequency model is the total number of trips per origin zone, categorized by motive and personality profile. This output is than used in the mode-day-destination model that is explained below.

The mode-day-destination choice model is a choice model used in traffic analysis to describe how a decision unit, such as a person, makes a choice among different alternatives, such as transport modes (car, train, bus, etc.). These alternatives differ in characteristics like travel cost and the decision unit can also vary, for example, in income. In this model, all combinations of transport modes, destinations and parts of the days in which travel takes place are compared side by side and the probability of choosing each combination is determined simultaneously.

Secondary transport demand concerns trips to secondary destinations that are not directly residential, such as commercial and recreational trips. The process for determining this secondary transport demand involves two main steps: again, the frequency model and the destination choice model.

The frequency model calculates the probability of a person visiting a secondary destination during a primary trip. This probability depends on several factors: the motive of the primary trip, the motive for visiting the secondary destination, the employment rate, the direction of travel and the travel time of the primary trip. Given the probability of visiting the secondary destination, the destination choice model calculates which specific zone is chosen as a secondary destination. The probability of choosing a particular zone is influenced by factors such as the motive of the primary trip, the motive for visiting the secondary destination, the absolute detour time, the relative detour time, the distance to the residential zone and the attractiveness of the destination.

In the growth factor model, growth factors are determined and forecast matrices are constructed using the programme PIVOT. The purpose of PIVOT is to calculate a forecast value for a given period for each origin-destination relationship. This is achieved by determining a growth factor between the base and the forecast year and applying it to the base matrix value. This forecast value is calculated using the following formula:

$$Forecast = \left(\frac{forecast^{syntetic}}{baseyear^{syntetic}}\right) \times baseyear$$

Equation 1: Forecast value

Here, the $forecast^{syntetic}$ and the $baseyear^{syntetic}$ are the synthetic values calculated by the model for the forecast year and the base year, respectively.

The PIVOT programme works for both domestic and foreign traffic. For foreign traffic, growth is based on the Foreign module explained above, which determines the spatial distribution of traffic. However, the volume of foreign traffic requires a correction based on a user-specified exogenous growth rate.

The initial growth of foreign traffic is calculated using the foreign module for both the base year and the forecast year. The adjustment for foreign traffic is performed as follows:

$$Growth_{endo} = \frac{\sum_O \sum_D forecast^{syntetic}}{\sum_O \sum_D baseyear^{syntetic}}$$

Equation 2: Growth calculated by PIVOT

After that, PIVOT calculates an adjustment factor to ensure that the calculated growth in foreign traffic for the relevant user group and period matches the exogenous growth.

$$Corrfac_{foreign} = \frac{Growth_{exo}}{Growth_{endo}}$$

Equation 3: Correction factor for foreign traffic

Where:

$Growth_{exo}$ = The exogenous growth reported in the GM

$Growth_{endo}$= The growth calculated by PIVOT

Using this correction factor, it can be applied to the base matrix for the relevant user group and period.

The allocation model, known as the QBLOK, uses a congestion-sensitive allocation method to distribute traffic across the network based on road section capacity, transport size and route choice behaviour. This model follows the Wardrop principle, meaning that all routes used between an origin and a destination are as long as, or shorter than, all non-used routes in term of generalized travel time. QBLOK is thus an equilibrium allocation model.

An important feature of QBLOK is how travel times on links are calculated. When determining journey times on a link, QBLOK takes the limited inflows from previous links into account. The inflow on a considered link is limited to the combined outflow from previous links, which may have been reduced by congestion. This differs from most other static equilibrium allocations that do not take this constraint into account. Additionally, QBLOK explicitly considers blocking back. Traffic held up in a traffic jam is not ‘vertically stacked’ as in many other models but place upstream. This means that traffic upstream, beyond an exit or other highway link, is also held up, even if it is not directly part of the congestion. This is more realistic than models in which traffic remains unhindered if it is not directly involved in the congestion.

QBLOK uses a heuristic approach to balance transport demand and network capacity. It employs a predetermined number of iterations and a weight distribution per iteration, depending on the iteration number. This speeds up the computation, but the equilibrium point is not always accurately approximated. The shortest paths are determined based on generalized travel times, a combination of travel times and additional costs such as toll and costs per kilometre, weighted by the preference of different user groups. The corresponding shortest paths are determined for each user group. To stabilize the iteration process and ensure convergence, the feedback of congestion effects is mitigated by mixing the newly calculated synthetic matrices (ODnew) with the matrices from the previous iteration (OD-1) according to the following. The iteration scheme ensures that the iteration process remains stable and convergent, making the results reliable (Rijkswaterstaat, 2023).

$$OD_i = (1 - \alpha) \times OD_{i-1} + \alpha \times OD_{new}$$

Equation 4: Keep the iteration process convergent

Table 2: Iteration scheme

Iteration	**α**
1	1
2	1
3	0.5
4	0.5
5	0.5
6	0.5

5.2.3 Network output QGIS

Originally, the NRM runs on CUBE. However, due to licensing problems, it was not possible to do the analysis in CUBE for this study. For this reason, shapefiles were exported to the program QGIS. The network output refers to the results and data generated by the traffic model NRM. Different types of network output help to analyse and improve traffic situations. The following is a detailed explanation of the different types of network output, including any formulas used (Rijkswaterstaat, 2021).

Traffic intensities

Traffic intensities show the amount of traffic on a specific link or route. This can be measured on a 24-hour basis or during peak hours. The 24-hour intensities show the amount of traffic (passages) per 24-hour period, helping to assess the logic and plausibility of traffic flows. This involves measuring the number of passing vehicles in different vehicle categories.

- ET_L1: Total number of passenger cars and vans in length class L1, typically up to around 6 meters in length.
- ET_L2: Total number of trucks and vans in length class L2, between 6 to 12 meters in length.
- ET_L3: Total number of freight vehicles in length class L3, longer than 12 meters.
- ET_L23: total freight traffic including vans in class L2.
- ET_123: Sum of all vehicles in all length classes.

Rush hour intensities assess traffic performance during peak hours by representing the number of passing vehicles per hour. This includes morning rush hour (OS_), evening rush hour (AS_) and residual day (RD_).

Saturation (I/C ratio)

The I/C ratio depicts capacity utilisation. This ratio shows how full the road is during a specific part of the day or rush hour. The I/C value is calculated as the ratio between the amount of traffic (_QBB) and the dynamic capacity (_FLCPW) of the link. The formula for this is:

$$I/C = \frac{Intensity\ (QBB)}{Dynamic\ capacity\ (FLCPW)}$$

Equation 5: Intensity/capacity ratio

An I/C value below 0.8 indicates sufficient residual capacity and sufficient traffic flow without structural congestion, often coloured green on traffic maps. An I/C value between 0.8 and 0.9 indicates limited residual capacity, with risk of congestion during peak hours, usually indicated in yellow. An I/C value between 0.9 and 1.0 means little or no residual capacity, leading to regular congestion and structural congestion, often coloured red. Situations where demand exceeds capacity (I/C value is greater than 1.0) indicate severe congestion and traffic jams, where congestion can expand upstream and cause backlash.

Driving speed

Travel speeds represent the average speed on a link, calculated from the link length and total travel time. The formula is:

$$Speed\left(\frac{km}{h}\right)=\frac{Link\ length\ (m)}{Total\ travel\ time(\mathrm{sec})/3600}$$

Equation 6: Average travel speed on a link

Waiting times

Waiting times identify congestion locations and severity by displaying the waiting time per vehicle. The average waiting time per vehicle (_WCST) is measured in seconds.

Congestion locations

Congestion locations identify where congestion occurs on the network in the model allocation. This is done by marking links with stationary vehicles, often using attributes such as _NBB (stationary vehicles) and _WCST (waiting time per vehicle.

Loss times (macro)

Loss times, expressed as vehicles loss hours (VVU), identify sections of the road with extensive time losses and compare the effects of different measures on total travel time losses. VVU is calculated as the sum of loss time for all passing vehicles.

$$VVU100=\sum\left(\frac{Delayed\ travel\ time\ (sec)}{3600}\right)$$

Equation 7: Vehicles loss hours

The reference speed is 100 km/h for passenger cars and 80 km/h for freight traffic.

Cause of congestion

The cause of congestion can be determined by identifying bottlenecks and network faults. The variable _NEK indicates which link is the cause of congestion, measured by the number of vehicles that cannot be processed in an hour.

Travel times over routes

Journey times and journey time factors show travel times by period for a selection of trajectories. The average travel time (_TCST) is measured in seconds. The NOMO travel time factor represents the realised rush hour speed compared to the travel time at 100 km/h.

5.3 MCDA

Multi-Criteria Decision Analysis (MCDA) is a methodology used in research and decision making to evaluate and compare different alternatives based on multiple criteria. The aim of MCDA is to support complex decisions by providing a structured and transparent approach to weighing various factors that influence the final choice. MCDA is particularly useful for decisions where multiple, often conflicting, criteria need to be considered. It is frequently applied in areas such as environmental management, health, transport and energy, where decisions involve multiple dimensions and stakeholders (Esmail & Geneletti, 2018).

The MCDA process begins with defining the problem and objectives, involving the identification of the decision problem and the objectives to be achieved. Next, the different alternatives or options available for the decision are identified. Relevant criteria for evaluating the alternatives are then selected, which may be quantitative or qualitative. The criteria are weighted according to their relative importance. Each alternative is scored on each criterion and the scores are aggregated to give an overall score for each alternative. The results are analysed and a choice is made based on the aggregated scores (Esmail & Geneletti, 2018).

6 RESULTS

This chapter presents the results of the study, focusing on the analysis and evaluation of the impact of the closure of the Zwartewaterbrug on the transport network of Zwolle. The results provide a comprehensive overview of traffic intensities, congestion levels and effectiveness of proposed mitigation measures. These insights are critical for informing policymakers, urban planners and transport authorities about the potential consequences of the closure and the best strategies to minimize the disruptions.

6.1 RESULTS Q1

This section presents the results for the first main research question. The goal is to understand the impact of the closure on traffic flow and accessibility in Zwolle. By analysing differences in 24-hour traffic intensities and I/C ratios before and after the closure, changes can be determined in traffic volume and potential bottlenecks.

The 24-hour intensity provides an overview of the total traffic volume during a day. By analysing the differences in intensities before and after the closure, it is possible to determine how much traffic increases or decreases on different road segments. This is crucial to understand how the traffic network responds to the closure of the Zwartewaterbrug. An important limitation of using 24-hour intensities is that an increase in traffic volume on a highway has less impact than a similar increase on a small country road. Highways can manage higher traffic volumes, while smaller roads become congested faster with a relatively smaller increase in traffic. This difference in capacity can lead to a distorted picture when looking only at 24-hour intensities.

To compensate for this limitation, the I/C ratios are also analysed. The I/C ratio represents the ratio of traffic intensity to the capacity of the road, showing immediately where congestion occurs. An I/C ratio of 0.9 or higher indicates that a road has reached its maximum capacity, indicating potential bottlenecks and congestion.

By analysing both the differences in 24-hour intensities and I/C ratios, a more complete picture of the traffic impact of the closure emerges. This combined approach makes it possible to identify both overall changes in traffic volumes and specific locations of congestion. The goal is to understand where bottlenecks are located in the transport system.

6.1.1 Intensities and I/C ratio complete closure

Figure 8 shows traffic intensities during the complete closure of the Zwartewaterbrug, which means that part of the A28 highway can no longer be used. This forces commuters to find alternative routes, leading to significant increase in traffic certain road in the city. In this analysis only the route choice is taken into account, not modal choice. The map shows traffic flows using three different colours, each indicating a certain increase in the number of cars per 24 hours:

Yellow lines: These roads see an increase of 2.000 to 4.000 cars per day. These are usually secondary roads and smaller diversion routes. Yellow lines are visible on the map in different part of the city and for example northwest and east of the city centre.

Orange lines: These roads experience an increase of 4.000 to 10.000 cars per day. These roads function as important secondary routes that capture more traffic than the yellow routes. The map shows orange lines along key traffic corridors running through the city, such as parts of the route towards Marslanden and parts east of the city centre.

Red lines: These roads see the largest increase in traffic, ranging from 10.000 to 32.000 cars per day. These roads function as the primary alternative routes for traffic that would normally use the Zwartewaterbrug. The map shows red lines along the main thoroughfares through the city, such as roads parallel to the A28.

The closure forces commuters who normally use the A28 to seek new routes, significantly increases traffic on secondary roads and other main roads around Zwolle. This can lead to traffic congestion and longer journey times on these routes.

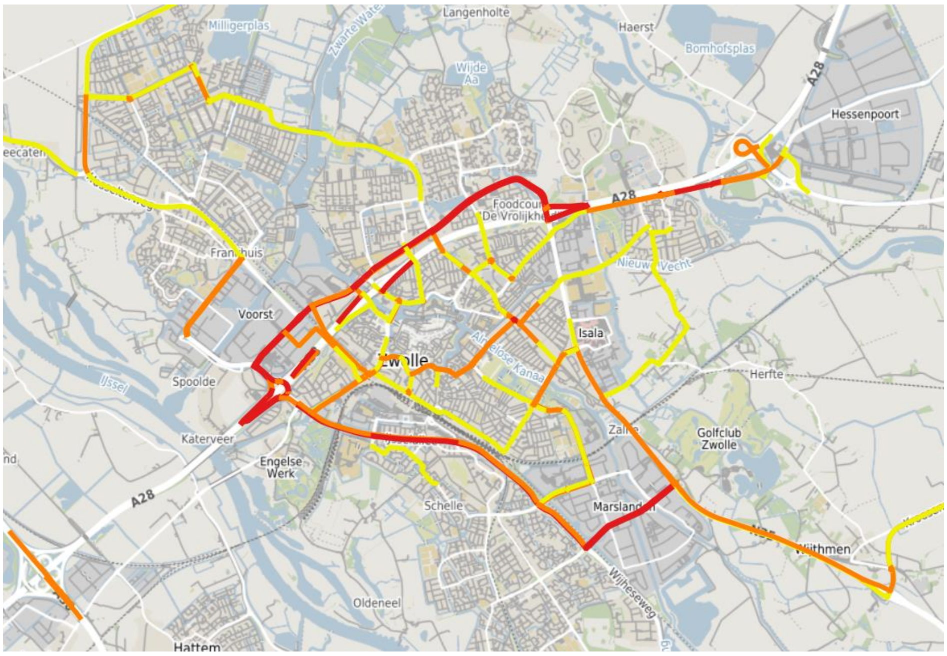

Figure 8: Difference in 24-hour intensities on a complete closure

Figure 9 clearly shows that due to the closure, commuters no longer travel on the A28, as many vehicles are now using other highways and regional roads. For example, traffic that normally uses the A28 now uses the A7 from Groningen, then heads towards the A6 and use the N50. These alternative routes show a significant increase in traffic. The yellow, orange and red stripes on the map illustrate this increase the same way as on Figure 8. These alternative routes can get congested and have longer journey times.

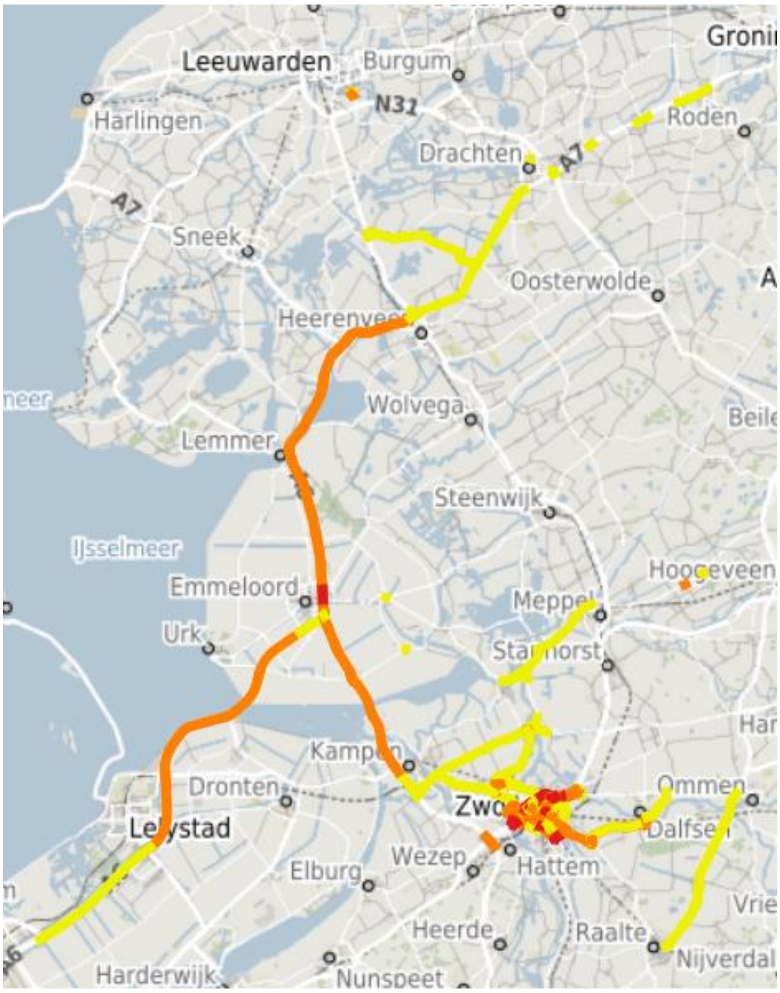

Figure 9: Overview 24-hour intensities during a complete closure

The map in Figure 10 illustrates the impact of the closure of the Zwartewaterbrug by means of traffic intensities. The red lines on the map indicate roads where the I/C ratio is between 0.9 and 1.0, meaning that these roads have reached or even exceeded their maximum capacity. This indicates severe congestion and potential bottlenecks. The yellow lines indicate an I/C ratio between 0.8 and 0.9, meaning that these roads are approaching their maximum capacity and are experiencing significant delays and congestion, but remain just below the threshold of complete congestion.

Analysing where congestion occurs shows that the southern ring road near the A28 is heavily congested. These roads operate at maximum capacity, as a significant proportion of traffic now used this route. Additionally, several inner-city roads, such as those around the city centre and towards the south (e.g. towards Marslanden), are also heavily congested.

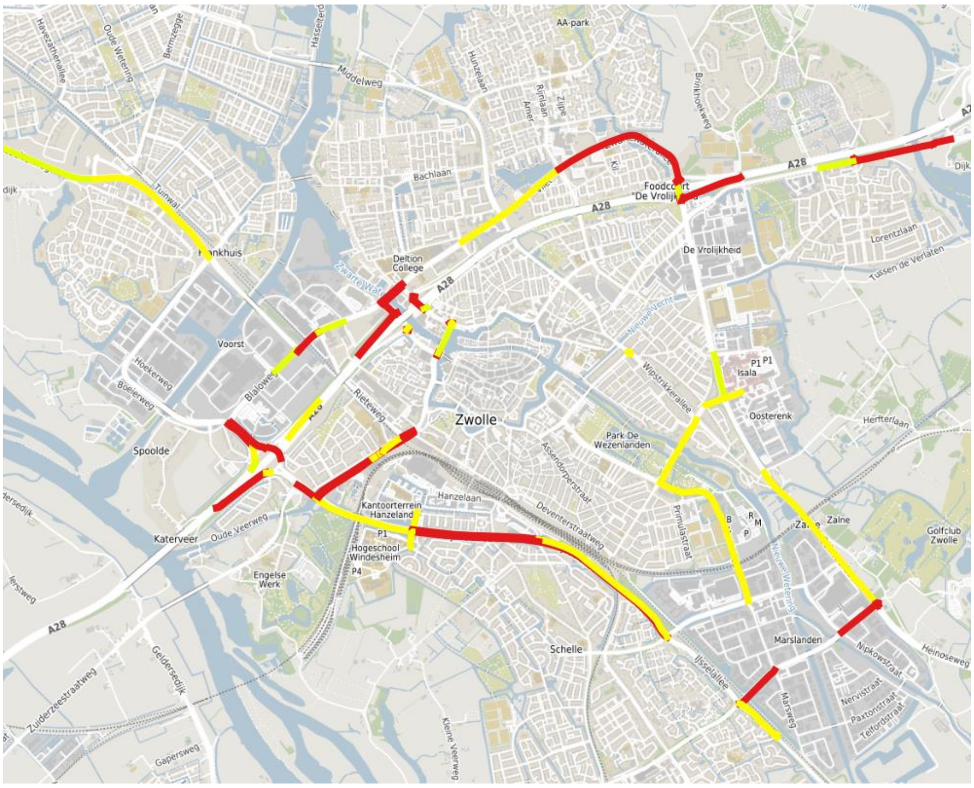

Figure 10: I/C ratios during a complete closure

The map on Figure 11 shows the wider regional impact of the closure. As mentioned earlier, commuters will use the A7, A6 and the N50 to reach Zwolle. This figure also shows that this increase will lead to congestion. The map makes it clear that the closure has a significant impact on traffic flows not only locally but also regionally. Vehicles are now choosing alternative routes leasing to increased traffic volumes and congestion. This insight helped identify the most critical areas in the regional transport network that need extra attention and possible interventions to improve traffic flow.

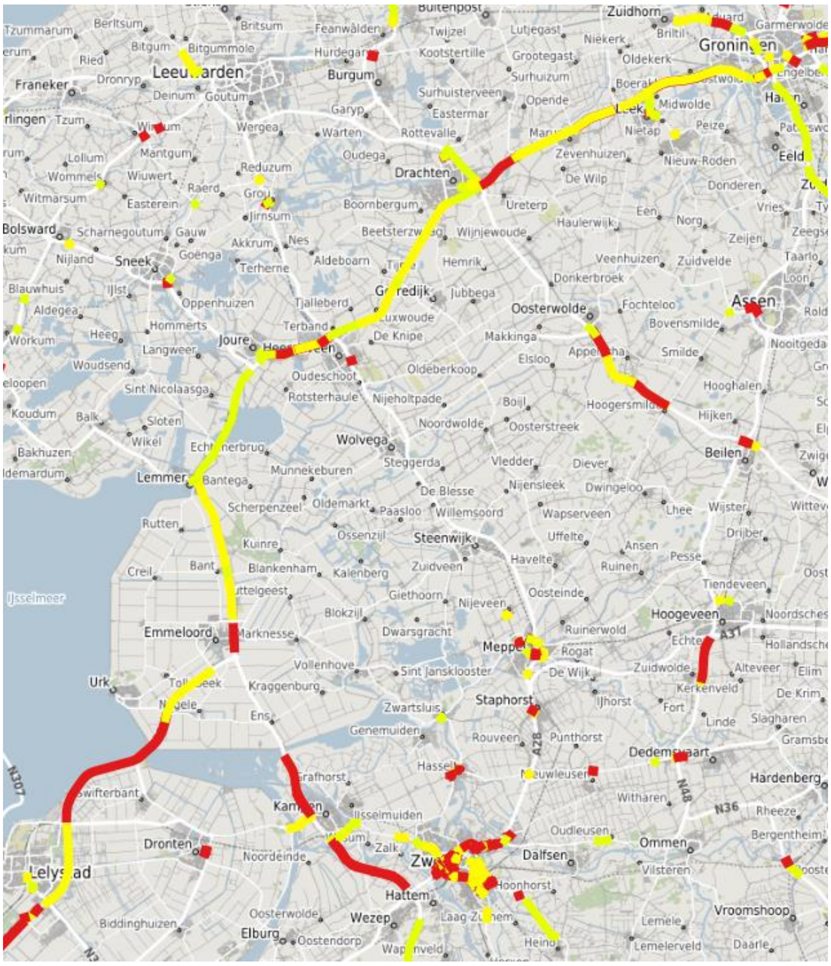

Figure 11: Regional overview of the I/C ratios during complete closure

The closure has a significant impact on the region's traffic network, involving several municipalities and provinces. As indicated in the stakeholder analysis, more municipalities and provinces are involved in this closure than just Zwolle and Overijssel. This highlights the wider regional impact of the closure and the need for cooperation between different governmental organizations.

In the province of Overijssel, the municipalities of Zwolle, Meppel, Steenwijk and Raalte are heavily involved in the diversions. Zwolle acts as the central hub, while Meppel, Steenwijk and Raalte handle the traffic flows entering and leaving the city. In addition, the province of Flevoland plays a crucial role, with Lelystad and Emmeloord as important municipalities involved in the diversion routes. Traffic normally travelling via the Zwartewaterbrug now uses routes through these municipalities, leading to increased traffic congestion. In Friesland, Heerenveen, Drachten and Lemmer are the main municipalities accommodating the increased traffic flows.

6.2 RESULTS Q2

In this section, the findings related to the second main research question are presented. This analysis focuses on evaluation the effectiveness of various traffic management alternatives implemented during the closure. The results include detailed comparisons of traffic intensities, I/C ratios, and the impact of different mitigation measures on travel behaviour.

6.2.1 Alternatives

This section discusses three main alternatives for managing traffic flow during roadworks: full single lane closure, temporary lane shifting and the deployment of a temporary bridge. Each alternative offers unique advantages and disadvantages depending on the specific circumstances and needs of the project. A detailed explanation of each alternative is given below.

Full single lane closure

A full single-lane closure involves the complete closure of one direction of the road. This means that all traffic that would normally travel in this direction must be diverted to alternative routes. This measure is usually taken for maintenance work, reconstruction or in response to unexpected events such as an accident or natural phenomena that render part of the road unusable.

There are several advantages to a full single lane closure. First, it increases safety by allowing workers to operate without constant traffic around them, reducing the risk of accidents. In addition, it can be more efficient to completely close one lane instead of diverting traffic around the works, which can shorten the time needed for construction. Moreover, a full closure can sometimes be cheaper because it requires less traffic management.

However, there are also disadvantages to a full single lane closure. It can lead to severe traffic congestion on alternative routes, especially if these routes are not well prepared for the increased traffic load. Drivers may have to travel significantly longer distances or schedule extra time for their journeys.

Temporary lane shift

The 3-0 system is a specific configuration for work lanes on motorways, used during roadworks to ensure the availability of road capacity in both traffic directions. A clear visualization of this system is depicted in Figure 12 and Figure 13. In this, carriageway A gets two lanes, with the left lane being 3.00 meters wide and the right lane 3.25 meters wide. The maximum speed in this direction is 90km/h, resulting in a capacity of 3,400 vehicles per hour. In contrast, direction B has one lane with a width of 3.25 meters and the same speed limit of 90 km/h, with an eventual capacity of 1,500 vehicles per hour (Rijkswaterstaat, 2015).

This system is used when work is taking place on one side of the road and the available space needs to be reallocated to ensure smooth traffic flow. By adjusting the available lanes to the intensity of traffic in both directions, the 3-0 system allows flexibility. The width of the lanes is chosen so that traffic can pass safely, even with the presence of workers and equipment near the carriageway.

However, several disadvantages of the 3-0 system compared to a full single lane closure should be considered. Firstly, the narrower lanes may not comfortably accommodate larger vehicles such as trucks, potentially leading to an increased risk of accidents. Additionally, the reduced lane width can cause driver discomfort and increase the likelihood of collisions. Secondly, maintaining a maximum speed of 90 km/h can be challenging, as drivers might not adhere to speed limits in narrower lanes, again increasing the risk of accidents. Enforcing these speed limits requires additional traffic management measures, which can be resource-intensive. Lastly, implementing the 3-0 system requires careful planning and constant monitoring. Traffic sign, barriers, and other control measures need to be in place and properly maintained, adding complexity and cost to the roadwork project.

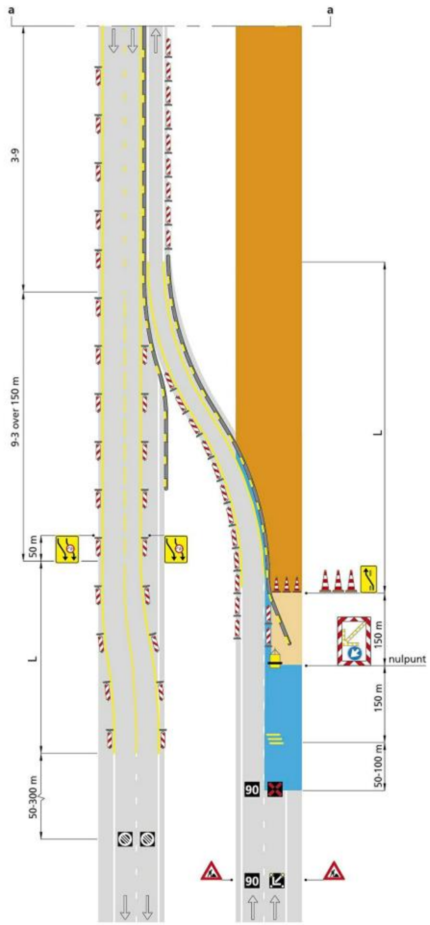

Figure 12: Example 3-0 system onramp (source: CROW, 2020)

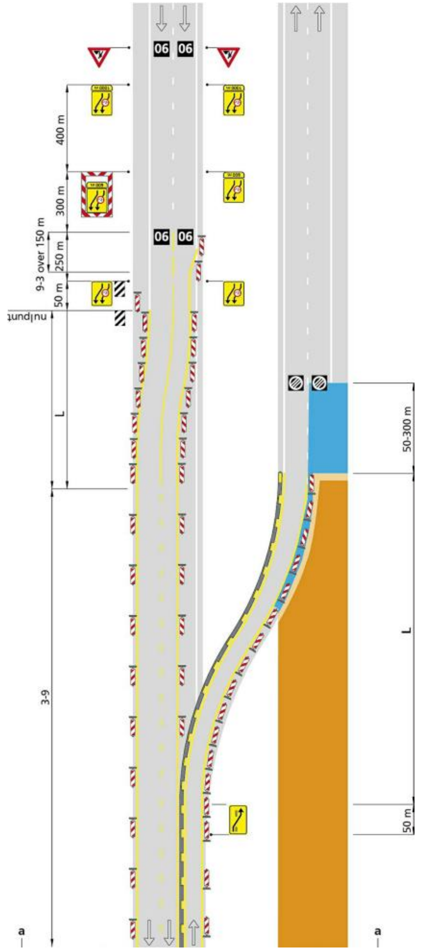

Figure 13: Example 3-0 system offramp (source: CROW, 2020)

Temporary alternative bridge

An effective alternative to reduce congestion during the replacement of the Zwartewaterbrug is to deploy a temporary bridge. By deploying a temporary bridge, traffic flow can be maintained and traffic congestion and delays are significantly reduced. This temporary infrastructure solution provides a fast, flexible and reliable way to minimize the impact on traffic while work on the permanent bridge is carried out. An example of such a temporary solution is the Acrow bridge, known for its modular design, quick installation and high load-bearing capacity.

Acrow bridges offer several advantages that make them particularly suitable for temporary solutions, such as when replacing a bridge on a motorway. These bridges have a modular design, which means they can be easily adapted to different lengths and load requirements. This makes them highly flexible and suitable for various applications, from short spans to large-scale bridge development projects.

The bridges are designed for quick and easy assembly, which is crucial for temporary solutions where speed and efficiency are essential. The modular components can be installed quickly, significantly reducing project lead times. Moreover, Acrow bridges are made of durable, high-quality steel components, ensuring high strength and reliability. This makes the bridges suitable for carrying heavy traffic loads, including trucks and other heavy traffic.

Another key advantage of Acrow bridges is that they are cost-effective. Their modular nature and efficiency of assembly make these bridges attractive for project with limited budgets or for temporary solutions where cost control is important. The durability and strength of the bridges ensure that they are reliable even for long-term temporary applications (Acrow | Temporary, z.d.)

The temporary bridge will be set up with a maximum speed of 90 km/h and a capacity of 1300 vehicles per hour. There is only room for one lane, as there is insufficient space next to the existing bridge for a temporary bridge with more than one lane. The set speed limit of 90 km/h ensures smooth traffic flow even within the constraints of a temporary bridge. This speed is reasonable for a highway environment and helps avoid excessive delays. The restriction to one lane means that only one direction of traffic will travel over the temporary bridge, while traffic in the other direction will use the part of the current bridge that is not under construction (Rijkswaterstaat, 2015).

While temporary bridges like Acrow offer many advantages, there are also some disadvantages to consider. Despite being cost-effective compared to other temporary solutions, temporary bridges still involve significant costs. These include the costs of installation, maintenance, and eventual removal. The deployment of a temporary bridge may require the construction of additional road infrastructure. This includes temporary access roads and modifications to the existing road network to accommodate the new bridge. These additional constructions can increase the project's complexity and cost. The construction and installation of this temporary bridge can also have environmental impact, including disruption to local ecosystems and increased noise pollution during the construction phase.

6.2.2 Difference plots

In this section, the differences in traffic intensities and I/C ratios are analysed for the three different alternatives compared to the complete closure. The analyses are based on colour-coded figures and the attached table showing the intensities and I/C related to them.

In the figures, each colour represents a particular range of decrease in traffic intensity or I/C ratio:

1. Green lines
    - I/C ratio: A decrease indicating a significant reduction in congestion and a significant improvement in traffic flow.
    - 24-hour intensity: A decrease indicating a great reduction in traffic intensity and a drastic improvement in traffic flow.
2. Orange lines
    - I/C ratio: A decrease indicating a moderate reduction in congestion and a positive impact on traffic flow.
    - 24-hour intensity: A decrease suggesting significant relief in traffic intensity.
3. Yellow lines
    - I/C ratio: A decrease indicating minimal improvement in traffic conditions but still contributing to better traffic management.
    - 24-hour intensity: A decease indicating a moderate reduction in traffic intensity.

The tables below show the different traffic intensities and I/C ratios for each alternative. Table 3 shows the difference in 24-hour traffic intensities for each scenario, while Table 4 shows the difference in I/C ratios both compared with the complete closure of the Zwartewaterbrug.

Table 3: Decrease in 24-hour intensities per alternative

24-hour intensities (veh/24h)	**Full single lane**	**Lane shift**	**Temporary bridge**
Green	8000 - 27000	8000 - 18500	8000 - 32000
Orange	4000 - 8000	4000 - 8000	4000 - 8000
Yellow	2000 - 4000	2000 - 4000	2000 - 4000

Table 4: Decrease in I/C ratios per alternative

I/C ratios	**Full single lane**	**Lane shift**	**Temporary bridge**
Green	0.3 - 0.6	0.3 - 0.75	0.3 - 0.68
Orange	0.2 - 0.3	0.2 - 0.3	0.2 - 0.3
Yellow	0.1 - 0.2	0.1 - 0.2	0.1 - 0.2

6.2.2.1 Full single lane closure

From the difference plots of the single lane closure, where one direction of traffic continues to drive normally and the other direction must find alternative routes due to the closure, we can observe the following changes in traffic intensity and I/C ratio. It is important to note that the results may be skewed because the comparison is made between the worst-case scenario, where all lanes are completely closed and an alternative where one driving direction remains completely open. This means that in the situation with a full closure, all traffic has to detour, resulting much higher I/C ratios and traffic intensities on the alternative routes. In contrast, in the single-lane closure situation, there is one driving directions that can continue to operate normally, resulting in significantly lower congestion in that direction and possibly showing distorted improvements in the difference plots.

Figure 14 shows green lines in the centre of Zwolle, indicating a significant reduction in congestion. This suggests that traffic flow here improves significantly under the half closure. This improvement could be because this stretch of road was first closed and now it is not, allowing commuters to drive normally in this direction.

Along the southern ring road, especially at the junctions near Hattemerbroek, orange and yellow lines become visible. This indicates moderate to slights improvement in traffic flow. These improvements are mainly due to the reopening of one carriageway. Commuters that would normally seek alternative routes made this decision at this intersection. This is no longer needed for one direction, resulting in decreased congestion. The routes towards Wijthmen and further east on the N35 show yellow lines, suggesting that the half-closure has a positive effect here, although less pronounced than in the city centre.

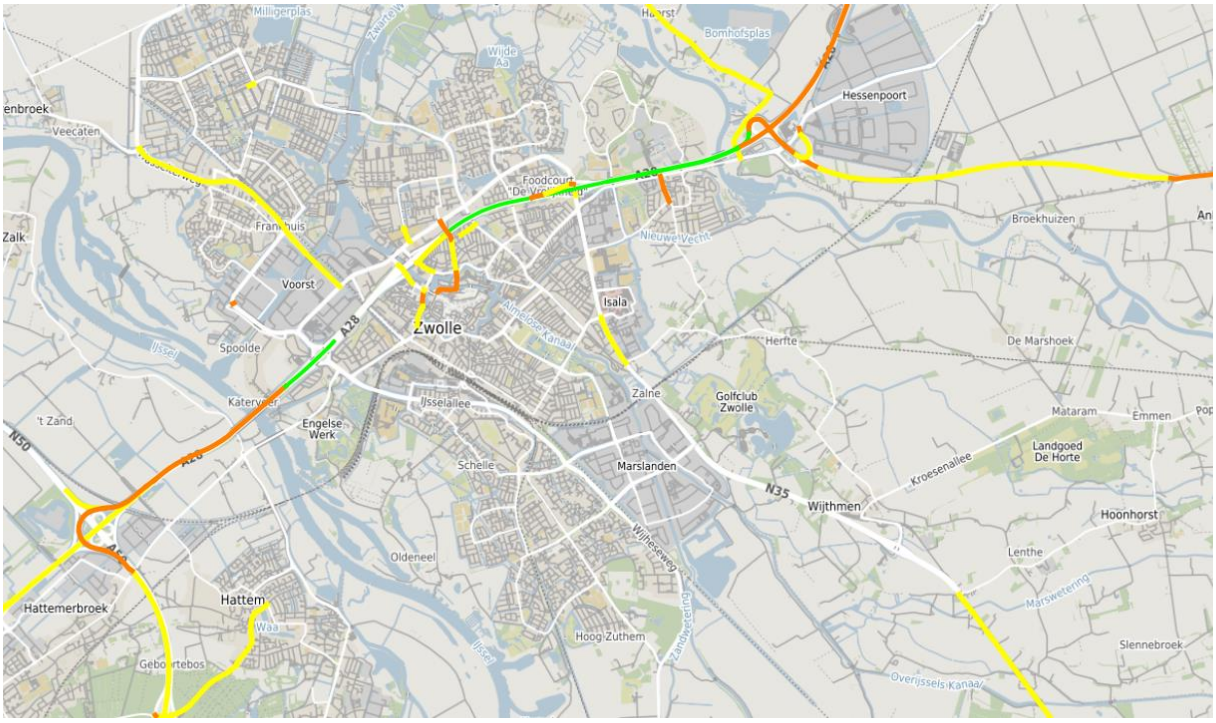

Figure 14: Difference plot I/C ratios single lane closure

The following figure shows the 24-hour changes in intensity. A significant reduction in traffic intensity can be seen on the northern routes, particularly towards Hessenpoort and further north. This is represented by yellow and orange lines, indicating moderate to significant relief. Towards the west, especially along the N331 towards ‘s Heerenbroek, the yellow lines show moderate relief on these routes. The decrease of 2.000 to 4.000 vehicles per day indicates that traffic pressure on these roads has been reduced, although the impact here is less than on the northern routes. This is probably because traffic volumes on these roads were already lower and the reopening of one lane has a less dramatic effect.

The green line visible in the centre of Zwolle is not located on the A28, but on a road parallel to it, called the Zwartewaterallee. In the I/C comparison, this road did not show less congestion only this comparison does show a significant decrease in intensity. This is because the closure cause so many cars to take this alternate route that even with a half-opening there is still congestion. The green lines do show that there is a significant difference already compared to the full closure in terms of intensities on this specific road. For the IJsselallee in the south the same accounts.

Figure 15: Difference plot 24-hour intensities single lane closure

The analysis points to significant improvements in traffic flow, especially in the centre of Zwolle and along the northern routes. Although the improvement is less pronounced on the western and eastern routes, these changes still contribute to better traffic management compared to a full closure. The results confirm that the half closure is a feasible and effective alternative to a full closure, with widespread positive effects on traffic conditions in both Zwolle and the surrounding regions. Only it needs to be noted that one direction has still severe congestion with this alternative.

6.2.2.2 Temporary lane shift

If the figure below, a difference plot visualizes the change in I/C ratio between the complete closure and the temporary lane shift (3-0 system). From this plot, the following insights can be extracted.

The green lines in the plot indicate that the I/C ratio in these areas decreases between 0.3 and 0.6. This means that traffic in these areas experiences significantly less congestion under the 3-0 system compared to a full closure. The improvement in these areas is substantial, indicating better traffic flow and fewer delays. The green lines are mainly concentrated in the centre of Zwolle, suggesting that that the 3-0 system significantly improves traffic conditions in the city centre.

The orange lines represent a decrease in the I/C ratio between 0.2 and 0.3. These areas also see an improvement in traffic conditions under the 3-0 system, although the improvement is not a pronounced as in the green areas. Nevertheless, these reductions are still favourable and indicate that the 3-0 system helps to alleviate congestion to some extent. The orange lines are visible along the southern ring road, particularly again at the junctions at Hattemerbroek.

The yellow lines show a reduction in the I/C ratio between 0.1 and 0.2. These areas experience a minimal improvement in traffic conditions. Although the positive impact here is minimal, it still contributes to better traffic management compared to a full closure. Yellow lines are found on routes towards Wijthmen and further east. Towards the city centre, yellow lines are visible too, alleviating the smaller roads in the city centre.

Figure 16: Difference plot I/C ratios 3-0 system

The following figures show the difference in 24-hour intensities between the complete closure and the 3-0 system. The colours in this figure represent the different levels of decrease in traffic intensity.

The following figures shows the difference in 24-hour intensities between the complete closure and the 3-0 system. De colours in this figure represent different levels of decrease in traffic intensity. Yellow means a decrease of 2.000 to 4.000 vehicles, showing areas where traffic intensity decreases moderately. These can especially be found in the centre of Zwolle, alleviating the traffic intensity in the city. This will result in a safer environment for pedestrians and cyclists in this area.

Orange indicates a decrease of 4.000 to 8.000 vehicles, which means that there is a significant relief in traffic intensities in these areas. These can be found all over the network most of the time in relation with yellow links. Areas such as the junctions at Hattemerbroek and parts of the A28 towards the south show this moderate improvement.

The green lines represent the largest decrease in traffic intensity, ranging from 8.000 to 18.500 vehicles, indicating a very significant improvement in traffic flow in these area under the 3-0 system and drastic reduction in congestion. Just as at the half-closure, a great improvement is found at the IJsselallee, but at this alternative, it is in both directions.

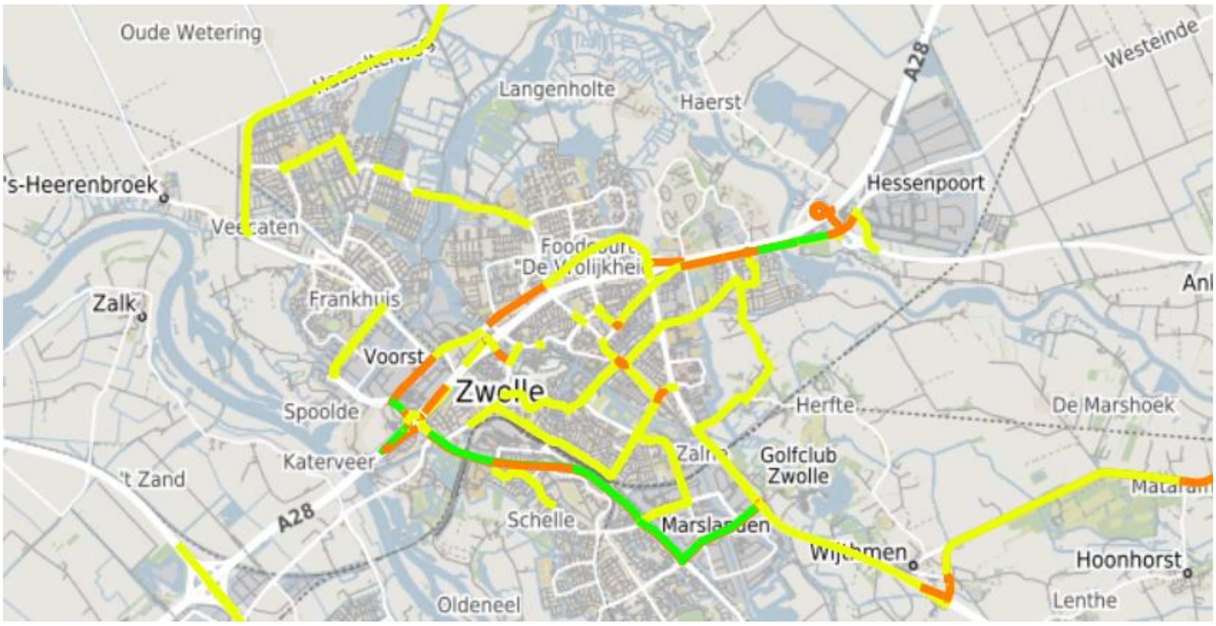

Figure 17: Difference plot 24-hour intensities 3-0 system

Not only Zwolle itself impacted, also the surrounding region. Significant relief from traffic congestion can be observed along major arterial roads such as the A6 and the N50. These improvements are particularly important because they show that the positive effects of the 3-0 system extend far beyond Zwolle, contributing to improved traffic flow on a regional scale.

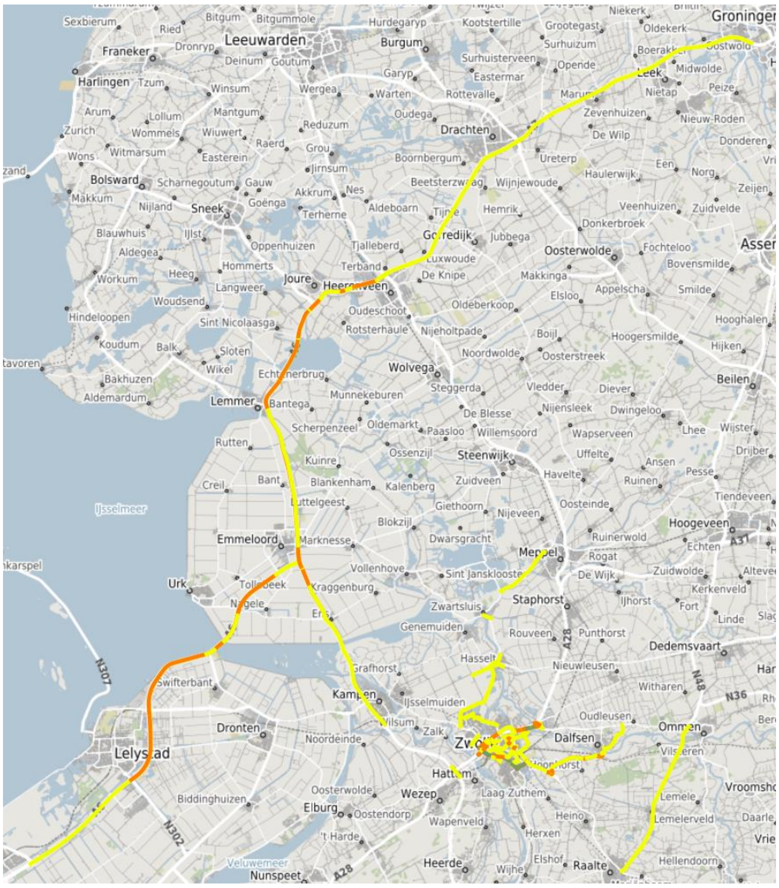

Figure 18: Difference plot 24-hour intensities 3-0 system entire region

The comparison with the previous analysis, which focussed on the decrease in I/C ratios, shows that the 3-0 system generally leads to an improvement in traffic conditions compared to a full closure. Both analyses show consistent positive effects, with the new analysis highlighting an absolute reduction in the number of vehicles on the roads. This confirms the conclusion of the previous part that the 3-0 system is a feasible and effective alternative to a full closure. It will improve the overall traffic flow and minimize disruptions and delays.

6.2.2.3 Temporary alternative bridge

The figure below shows the difference in the I/C ratio between the full closure and a temporary bridge. The colours again represent different levels of decrease in the I/C ratio, the following specific insights can be derived.

The green lines are mainly visible along the A28 and in the immediate vicinity of the bridge. This indicates a significant reduction in congestion in these areas under the temporary bridge compared to a full closure. For example, the route along the A28 towards the south clearly benefits from the improved traffic flow, resulting in fewer delays and smoother traffic. The Hofvlietbrug, previously mentioned, also benefits from this alternative, improving conditions on some road in the city centre. The yellow parts are spread over several secondary roads and in the centre of Zwolle, such as the IJsselallee and the routes towards Marslanden.

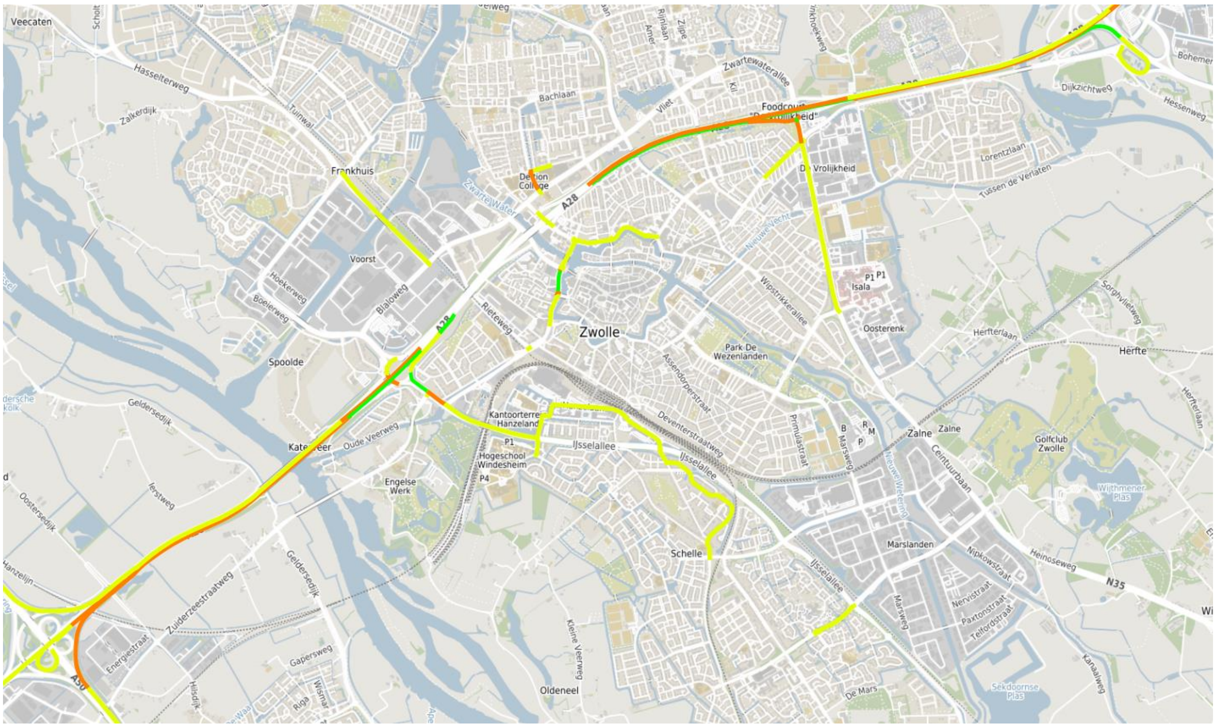

Figure 19: Difference plot I/C ratios temporary bridge

In Figure 20, the difference in intensities is shown, with a significant number of green links generated. These green links are especially prominent on the main roads of Zwolle, indicating that the alternative significantly helps in alleviating congestion on these roads. The IJsselallee and Zwartewaterallee are the most positively affected by the alternative. In the city centre, mainly yellow and orange links become visible, but there are more of them compared to the other alternatives.

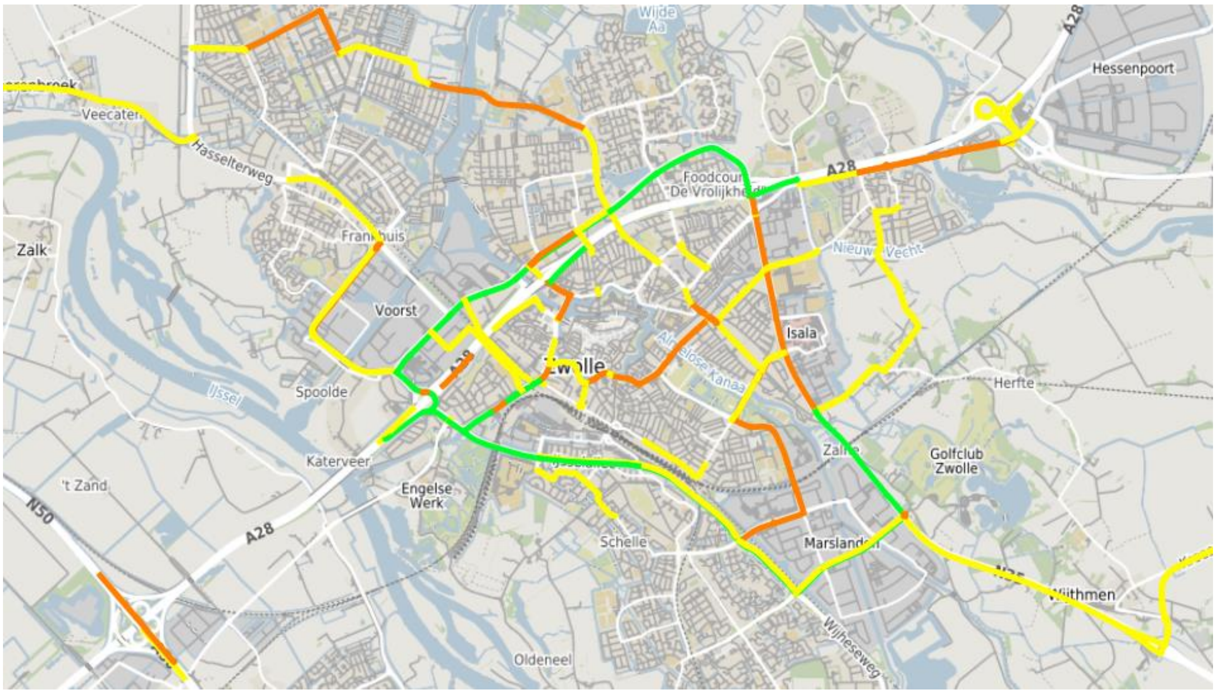

Figure 20: Difference plot 24-hour intensities temporary bridge

Regionally, green lines are visible on routes towards the norths, such as the N50 towards Emmeloord and further towards Lemmer. Indicating that this alternative has a great impact on this alternative road that was previously used. Around these roads, orange and yellow links are present on the A7 and A6 highway, decreasing the congestion that was present due to the closure. Commuters from Groningen are using the A28 again instead of this alternative.

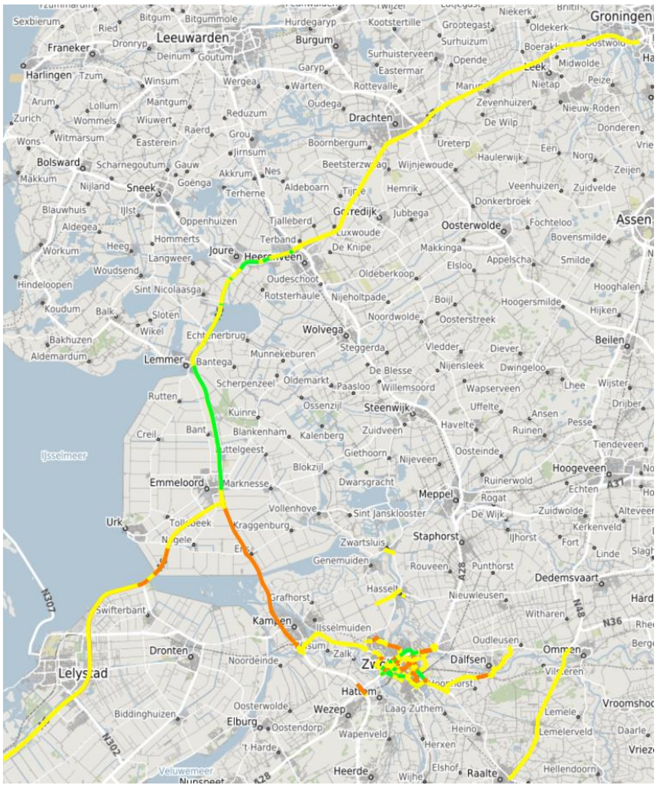

Figure 21: Difference plot 24-hour intensities regional temporary bridge

6.2.2.4 Benefits of the bridge closure

While closing the bridge entirely worsens traffic congestion, it presents several significant benefits, particularly regarding the overall project timeline. Firstly, a complete closure can significantly shorten the project duration. Without the need to accommodate traffic, construction can proceed unimpeded, leading to a more efficient workflow and quicker completion. Secondly, a full closure enhance safety for workers. With no traffic on the bridge, the construction site becomes safer, reducing the risk of accidents and improving working conditions. The full closure might offer cost savings. It eliminates the need for complex traffic management systems necessary for partial closures or lane shifts. By reducing the expenses associated with traffic management, the overall project costs may be lower, despite the initial increase in congestion-related expenses.

6.2.3 MCDA

A MCDA is conducted to evaluate and prioritize the potential alternatives for managing traffic flow during the closure. After conducting extensive modelling exercises to understand the impact of the closure on traffic patterns, it became crucial to identify the most effective solution to mitigate these impacts. The modelling exercise provided quantitative data on traffic disruptions, which served as the basis for evaluating various alternative. However, the modelling alone was insufficient to determine the best course of action due to the multifaceted nature of the problem, which includes considerations of cost, implementation feasibility, safety, and regional impact.

The primary reason for conducting the MCDA is to integrate multiple dimensions of evaluation into a coherent framework that allows for a balanced decision-making process. While the modelling exercise highlighted the changes in traffic flow and intensities, the MCDA helps in understanding the broader implication of each alternative. The scores for each criterion are determined based our own judgement, date from the modelling exercise, and relevant literature.

1. **Traffic flow improvement:** Ensuring that any chosen alternative effectively manages and improves the traffic conditions during the bridge closure. Scores were based on the projected improvement in traffic flow derived from the modelling results. Alternatives that showed significant reduction in congestion receive higher scores.
2. **Travel times:** Evaluating how each alternative impacts the travel times for commuters and freight operators. Alternatives are evaluated on their ability to minimize additional travel time caused by the bridge closure. Lower increases in travel time result in higher scores.
3. **Regional impact:** Assessing the wider effects on the regional transport network, beyond the immediate area of the bridge. Score reflect the extend to which each alternative affect the broader regional network. Solutions that minimized negative impacts on surrounding areas score higher.
4. **Implementation ease:** Considering the practicality and ease of implementing each alternative, including potential disruptions during the implementation phase. Practical aspects of deploying each alternative were considered. Easier and faster implementations are given higher scores.
5. **Safety:** Ensuring that the chosen alternative does not compromise road safety. Each alternative is assessed for potential safety risks. Solutions maintaining or improving safety standard receive higher scores.
6. **Costs:** Comparing the financial implications of each alternative to ensure cost-effectiveness. Financial assessments are made for each alternative, with lower-cost solutions receiving higher scores.

Table 5: Scores MCDA

Criteria	**Full single lane closure**	**Temporary lane shift**	**Temporary bridge**
Traffic flow	2	4	5
Travel times	3	4	5
Regional impact	2	4	4
Implementation ease	5	3	1
Safety	3	3	3
Costs	5	4	2
Total	**20**	**22**	**20**

Table 5 shows a summary of results, together with the total score per alternative, assuming a simple summation of individual scores, i.e., no weighting of individual scores. Based on the MCDA that is carried out, it appears that the temporary lane shift is the most suitable alternative for the traffic situation. Although the temporary bridge scores highest on some individual criteria such as traffic flow a travel times, the high cost and complexity of implementation make this alternative less feasible. The 3-0 system offers an excellent balance between cost, ease of implementation and significant improvements in traffic flow and safety, making it the most appropriate and effective solution for managing traffic flows during the maintenance of the Zwartewaterbrug. On the other hand, if cost and complexity are not relevant constraints for the future project, then the temporary bridge also emerges as a alternative to consider and evaluate in a more comprehensive cost-benefit analysis.

6.2.4 Alternatives in travel behaviour

Based on insights from previous studies and interviews on travel behaviour during road closures, measures are generated to influence travel behaviour. These measures range from promoting the use of public transport and working from home, to encouraging cycling and walking. Each measure is explained in detail and ranked according to its effectiveness. By carefully applying these strategies, policymakers and traffic managers can create a more efficient and resilient transport environment.

Promoting the use of public transport

- **Discounts and incentives**: offering discounted or free public transport tickets during the closure of the bridge, we can significantly increase the use of public transport. The 'ervaar het ov' campaign in Gelderland showed that attractive discounts caused up to 70% of participants to consider using public transport more often in the future. By offering similar discounts or free tickets, commuters are more likely to switch from car to bus or train, leading to fewer vehicles on the road.
- **Increased services**: Increasing the frequency and capacity of busses and trains can accommodate increased demand. Temporary express busses can be used to serve direct routes affected by the closure, providing a fast and reliable alternative travel option.

Promoting working from home

- **Partnering with businesses**: Collaborating with local businesses to promote working from home can effectively reduce commuting. Businesses can be encouraged to offer flexible working hours or home working opportunities, especially during peak hours. During previous road closures, allowing working from home proved to be an effective strategy to reduce the number of cars on the road.

- **Governmental campaigns**: Awareness campaigns highlighting the benefits of working from home, such as reduced stress and increased productivity, can convince more employees and employers to embrace this practice.

Promoting cycling and walking

- **Improved infrastructure**: Developing and improving cycling and walking paths provides safety and convenience for cyclists and pedestrians. Temporary bicycle lanes and well-marked footpaths can make these options more attractive. This alternative is mainly for the residents of Zwolle.
- **Bike sharing programmes**: Expanding bicycle-sharing systems provides flexible and accessible transport options for short distances. Such programmes can be particularly effective in urban areas with good cycling facilities like Zwolle.
- **Incentives**: Subsidies for the purchase of e-bikes or discounts on bicycle rentals can further encourage cycling as an alternative means of transport.

Promoting carpooling and ridesharing

- **Carpooling initiatives**: Promoting carpooling through dedicated apps and websites can significantly reduce the number of vehicles on the road. Offering incentives such as lower priority lanes for carpool cars can further encourage this behaviour.
- **Corporate programmes**: Encouraging companies to launch carpool programmes among their employees, with benefits such as reserved parking spaces for carpool cars, can also help reduce traffic congestion.

Promoting alternative routes

- **Navigation apps**: Working together with navigation apps such as Google Maps and Waze to provide real-time updates and suggested alternative routes can help distribute traffic evenly across the network and reduce congestion on major diversion routes.
- **Signage**: Placing clear and prominent signs well in advance of the closure can direct commuters to alternative routes and help them avoid the closed bridge.

Effective communication campaigns

- **Information distribution**: Using various media channels to provide timely and accurate information about the closure and alternative routes is crucial. Social media, local radio and community newsletters can effectively reach a wide audience to ensure road users are well informed.
- **Personalized communication**: Implementing personalized communication strategies, such as the ‘kitchen table talks’ where mobility advisers visit households to provide tailored advice can have a significant impact on travel behaviour. Direct contact and personalized advice can influence individuals to consider alternative transport options. This alternative only is very much time consuming

Temporary measure to reduce traffic

- **Variable Message Signs (VMS)**: Using VMS to provide real-time traffic updates and alternative route suggestions can help manage traffic more effectively.

By implementing these strategies according to their effectiveness, we can manage commuters travel behaviour and minimize the inconvenience caused by the closure.

7 CONCLUSION

The aim of this study was to evaluate the impact of the closure of the Zwartewaterbrug in Zwolle on the city's transport system and identify possible solutions to mitigate the resulting problems. Using the models from Rijkswaterstaat, empirical data and a Multi-Criteria Decision Analysis (MCDA), it aimed to understand the changes in traffic flows, travel patterns and accessibility resulting from the closure of this vital bridge. In addition, the study focussed on examining the wider impact on nearby areas and the regional transport network and proposing and evaluating different strategies to address these issues.

The complete closure of the Zwartewaterbrug would have a significant impact on the traffic flow in and around Zwolle. The bridge forms a major traffic artery of the A28, connecting parts of the city and the surrounding region. A complete closure would force commuters and freight traffic to seek alternative routes, leading to increased traffic pressure on secondary roads and other main roads. This would result in severe congestion, longer travel times and increased risk of traffic incidents. In addition, accessibility to different parts of the city and neighbouring communities would be affected, causing economic and social disadvantages.

The MCDA provided a structured approach to evaluate the three main alternatives: a full single-lane closure, a temporary lane shift and a temporary bridge. The criteria included traffic flow, impact on travel times, regional impact, feasibility, safety and cost. The 3-0 system proved to be the best solution. This system showed significant improvement in traffic conditions compared to a full closure. Both intensity and I/C ratio analyses confirmed that this system is a viable alternative as it improves traffic flow and reduces congestion. By making use of the existing road capacity and utilising it optimally, the 3-0 system offers an efficient way to relieve traffic pressure without the need for extensive infrastructure modifications. On the other hand, installing a temporary bridge proved to be the most effective strategy to reduce traffic disruptions, but it is more costly and complex to implement. All-in-all, the temporary lane shift presents a reasonable balance between congestion relief effects and cost and easiness of implementation.

In the study, it also highlighted the importance of effective communication strategies and personalized advice in managing commuters behaviour during disruptions. Initiatives such as personalized communication and real-time traffic updates via Dynamic Route Information Panel were crucial to influence travel behaviour and ensure smooth traffic flow. An important aspect of the behavioural solutions was to encourage travellers not to travel during the peak hours or to opt for working from home if possible. By educating commuters about the benefits of avoiding travelling during peak hours and using alternative transport methods, pressure on the transport network could be significantly reduced.

In summary, the study highlights the importance of a multi-faceted approach to traffic management during major disruptions to the transport network. Encouraging behavioural changes, such as avoiding travel during peak hours and working from home, plays a crucial role in reducing pressure on the network. The findings from this study can serve as a valuable reference for future infrastructure projects and the management of transport networks, minimizing disruptions and maintaining optimal traffic conditions.

8 DISCUSSION

Despite the comprehensive approach and robust methodologies applied in this study, several limitations need to be recognized to provide a balance understanding of the findings and their implications.

One of the main limitations concerns data quality and availability. The accuracy and reliability of the models used depend heavily on the quality and availability of input data. Incomplete or outdated data can affect the accuracy of predictions. Currently the most up-to-date version of NRM is used but it was not possible to validate these data ourselves. In additions, there are limitation in the models, as both LMS and NRM assume that traffic behaviour remains static over time, which may not reflect dynamic changes in driving behaviour due to new regulations, economic conditions or infrastructure developments. Furthermore, the models often assume homogeneity in driver behaviour and preferences, which may overlook diversity in driving patterns influenced by socio-economic backgrounds, cultural differences and individual preferences. The models also contain assumptions about future infrastructural development. If these developments do not take place as planned or unexpected changes occur, the accuracy of the model predictions may be affected. For eexample, airport Lelystad is incorporated in the current model, but at this moment in time it is not sure whether this project will be completed.

Methodologically, there are some simplifying assumptions in the models regarding traffic flows and congestion that may not fully capture the complexity of real traffic systems. These assumptions include the behaviour of traffic under different conditions and the impact of smaller roads on the overall traffic network. Validation of the LMS and NRM models is limited by the availability of historical traffic data. Any inconsistencies between model predictions and observed data may highlight areas where the models may not perform optimally. Moreover, focusing on specific regions or corridors may limit the generalisability of the findings to other areas with different traffic patterns and infrastructure characteristics.

Practical constraints also play a role. Some proposed solutions for reducing traffic delays and congestion may face practical implementation constraints, such as budgetary constraints, political considerations and public acceptance. The study’s reliance on stakeholder input may be limited by the availability and willingness of stakeholders to participate, which may affect the completeness of the data collected and the inclusiveness of the proposed solutions. Eventually, a more comprehensive cost-benefit analysis should be undertaken to decide on the most appropriate alternative for traffic management during the project.

Finally, there are external factors that can affect the results. Unpredictable events such as economic recessions, natural disasters or significant policy changes can affect traffic patterns and infrastructure use, which can make the study’s finding less applicable in the future. Rapid technological advances in transport, such as the adoption of autonomous vehicles or new transport systems can change traffic dynamics in ways that were not anticipated during this study.

The current research has provided valuable insights, but it is clear that several future studies are still needed to get a complete picture and develop effective mitigation strategies. These studies are essential to better understand the complex interactions between traffic, environment, economy and the community. This will lead to more informed and effective policy decisions, contributing to an integrated and sustainable approach to the traffic and infrastructural challenges posed by closures.

One of the most important future studies concerns the environmental impact of diverting traffic to secondary roads as a result of the closure of the Zwartewaterbrug. It is essential to understand how increased traffic on minor roads affects air quality and noise pollution. This research would focus on measuring pollutant emissions such as nitrogen oxides and particulate matter in these areas, as well as noise levels generated by the additional traffic. Moreover, the study should assess the extent to which the increased load on these roads leads to faster wear of the surface and possible structural damage.

Another crucial study concerns the analysis of the disturbance caused by other infrastructure projects taking place simultaneously with the reconstruction of the Zwartewaterbrug. The aim of this is to identify and mitigate potential conflicts. This includes mapping all planned construction projects in the same period and their potential impact on traffic flows. By coordinating these project, policymakers and engineers can ensure that alternative routes remain free of additional traffic volumes and that disruption is minimized. This research would involve great communication and cooperation between different municipal and provincial agencies.

Understanding how road users adapt their behaviour during the closure of the bridge is key. This research would aim to analyse the effectiveness of the different measures that are used such as public transport promotions, carpooling, remote working and the use of alternative transport. By combining surveys and traffic data, this research can provide insights into which measures are most effective in reducing traffic pressure and how they can be optimized.

The economic impact on local businesses due to the bridge closure is a major concern. This research would focus on quantifying the reduced accessibility and increased transport costs for businesses in the region. By analysing interview with local business owners and economic data, this research can help determine which sectors are most affected and what measures are needed to support them. For example, temporary tax reductions or subsidies for alternative transport solutions could be considered to mitigate the economic impact.

Evaluation of various traffic management measures taken to minimize the impact of the closure is essential. This study would focus on the effectiveness of temporary traffic signs, dynamic route information panels and other management techniques to optimize traffic flows during the construction period. By analysing traffic data before, during and after the implementation of these measures, it would be possible to determine which techniques were most successful and where improvements could be made. This would give decision-makers valuable insights for future projects involving similar challenges.

While the current study has identified general bottlenecks in the traffic system, it is important to carry out a more detailed and dynamic analysis in the future. This could be done by using a dynamic traffic model instead of a static model as used now. A dynamic model can simulate real-time traffic flows and patterns, enabling more accurate predictions about traffic congestion and the effectiveness of different solutions. This research would focus on analysing traffic data at intersections and developing targeted measures to reduce congestion. Such detailed analysis would allow traffic engineers to better understand how specific intersections function under different conditions and design more effective solutions.

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10 APPENDIX

10.1 A – LITERATURE RESEARCH MODAL SWITCH

Table 6: Literature research modal switch

Study	Location	Planned	Type of disruption	Duration of disruption	Modes affected
(Marinelli et al., 2009)	Brisbane, Australia	Yes	Closure expressway	Several days	Road transport
(Marsden et al., 2016)	York, England	No	Flooding	Several days	Roads and rail
(Szarata & Hoy, 2019)	Warsaw, Poland	No	Fire on bridge	Several months	Road transport
(Guiver, 2011)	Workington, England	No	Flooding	Two months	Road transport
(Kemmerer et al., 2023)	Mains, Germany	Yes	Closure bridge	One month	Road transport
(Drabicki et al., 2021)	Krakow, Poland	No	Public transport disruptions	One day	Rail transport
(Zhu et al., 2010)	Minneapolis, United States	No	Bridge collapse	Three months	Road transport
(Yap & Cats, 2022)	Amsterstam, the Netherlands	Yes	Public transport disruptions	One week	Public transport
(Zhu et al., 2008)	Los Angeles, United States	No	Earthquake	One year	All transport
(Zhu et al., 2008)	Calgary, Canada	Yes	Bridge closure construction	Three months	Road transport
(Yun et al., 2011)	Sacramento, United States	Yes	Reconstruction freeway	Nine weeks	Road transport
(Blumstein et al,. 1983)	Pittsburgh, United States	No	Transit strike	5 days	Bus services
(Lin et al., 2013)	Athens, Greece	Yes	Metro line closure	Five months	Public transport

Study	Route change	Time change	Trip cancellation	Modal switch	Destination change	Comments
(Marinelli et al., 2009)	51%	38%	7%	14%	N/r	
(Marsden et al., 2016)	19%-20%	N/r	23%-26%	15%-25%	5%-11%	
(Szarata & Hoy, 2019)	24%	36%	19%	14%	N/r	Trip cancellation at least one trip
(Guiver, 2011)	N/r	N/r	39%	13%	23.3%	Trip cancellation is only for shopping trips
(Kemmerer et al., 2023)	N/r	N/r	N/r	22%	N/r	
(Drabicki et al., 2021)	26%-41%	N/r	1%-3%	26%-33%	N/r	
(Zhu et al., 2010)	39.72%	N/r	7.8%	3.55%	41.13%	
(Yap & Cats, 2022)	67%	N/r	33%	33%	N/r	Mode change and trip cancellation is a combined value
(Zhu et al., 2008)	31.2%	N/r	N/r	5.8%	N/r	Duration for full recovery
(Zhu et al., 2008)	15-30%	N/r	4.4%	6.6%	N/r	
(Yun et al., 2011)	44%	21.7%	21.3%	8.4%	20.3%	
(Blumstein et al,. 1983)	14%-18%	25%-46%	13%	24%-37%	N/r	
(Lin et al., 2013)	58%	N/r	Nr	9%-13%	N/r	

10.2 B - INTERVIEW JORIS KESSELS

This interview was conducted with Ir. Joris Kessels, who has been with Rijkswaterstaat for 14 year, the last 10 of which as consultant and project leader in the field of smart mobility and behavioural change. In this role, he focusses on optimizing traffic flows and minimizing traffic disruption by implementing innovative and behavioural solutions. His experience and expertise make him a valuable source of knowledge in this field.

10.2.1 Interview questions

- Hoe reageren verkeersdeelnemers over het algemeen op wegafsluitingen en omleidingen?
- Welke psychologische factoren spelen een rol bij de keuze van alternatieve routes of transportmodi?
- In hoeverre veranderen mensen van transportmodus bij langdurige wegafsluitingen?
- Welke rol speelt informatievoorziening bij het helpen van mensen om alternatieve routes te vinden? En wat zijn de meest effectieve manieren om dit te doen?
- Zijn er langdurig gedragsveranderingen bij verkeersdeelnemers als gevolg van tijdelijke wegafsluitingen?
- Wat kunnen we leren van eerdere wegafsluitingen en renovatieprojecten om toekomstige verkeersproblemen beter aan te pakken?
- Hoe effectief zijn financiële prikkels bij het veranderen van rijgedrag, denk hierbij aan tolheffingen of kortingen

10.2.2 Interview summary

In de initiële fase van het project wordt een volledige afsluiting van de brug overwogen. Alternatieven zoals een tijdelijke brug en gecombineerde rijbanen worden bekeken. Voor deze analyse wordt gebruik gemaakt van het NRM, hoewel volgen Joris Kessels ook andere modellen zoals TomTom, die Floating Car Data gebruiken waardevolle aanvullende inzichten kunnen bieden.

Weggebruikers reageren verschillend op afsluitingen, afhankelijk van de mate van hinder en de beschikbare alternatieven. Goede informatievoorziening helpt echter aanzienlijk om verkeershinder te verminderen. Om deze hinder te beperken worden diverse flankerende maatregelen ingezet, waaronder verkeersmanagement, communicatie, reisroute-informatie en mobiliteitsmanagement. Voorbeelden hiervan zijn omleidingsroutes, stimulering van fiets- en OV-gebruik en het gebruik van financiële beloningen.

Evaluaties van eerdere projecten, zoals de Haringvlietbrug en Heinenoord, tonen aan dat goede maatregelen een verkeersreductie van 30-40% kunnen bewerkstelligen. Gedragsverandering zoals minder reizen of veranderen van modaliteit hebben daarbij meer impact dan het simpelweg kiezen van andere routes. Internationale vergelijkingen zijn beperkt beschikbaar, maar het is duidelijk dat de lokale context sterk bepalend is voor de effectiviteit van maatregelen.

Het onderzoek combineert verkeersmodellen met empirische data uit tools zoals TomTom, waarbij een selected link analysis waardevolle inzichten bieden in de herkomst en bestemming van het verkeer. Beelden van alternatieven zoals spoorverbindingen, fietsroutes en potentieel sluipverkeer zijn daarbij belangrijk voor gedetailleerde evaluaties.

Structurele gedragsverandering, zoals blijvende verschuivingen naar fiets- en OV-gebruik, blijkt essentieel voor langdurige oplossingen. Het meten van het exacte effect van maatregelen op lange termijn is echter complex en vaak moeilijk te bepalen. Desondanks tonen evaluaties van projecten zoals de A73 en spits mijdt projecten aan dat gedragsveranderingen, vooral naar andere modaliteiten of thuiswerken, duurzamer zijn dan simpelweg andere routes kiezen.