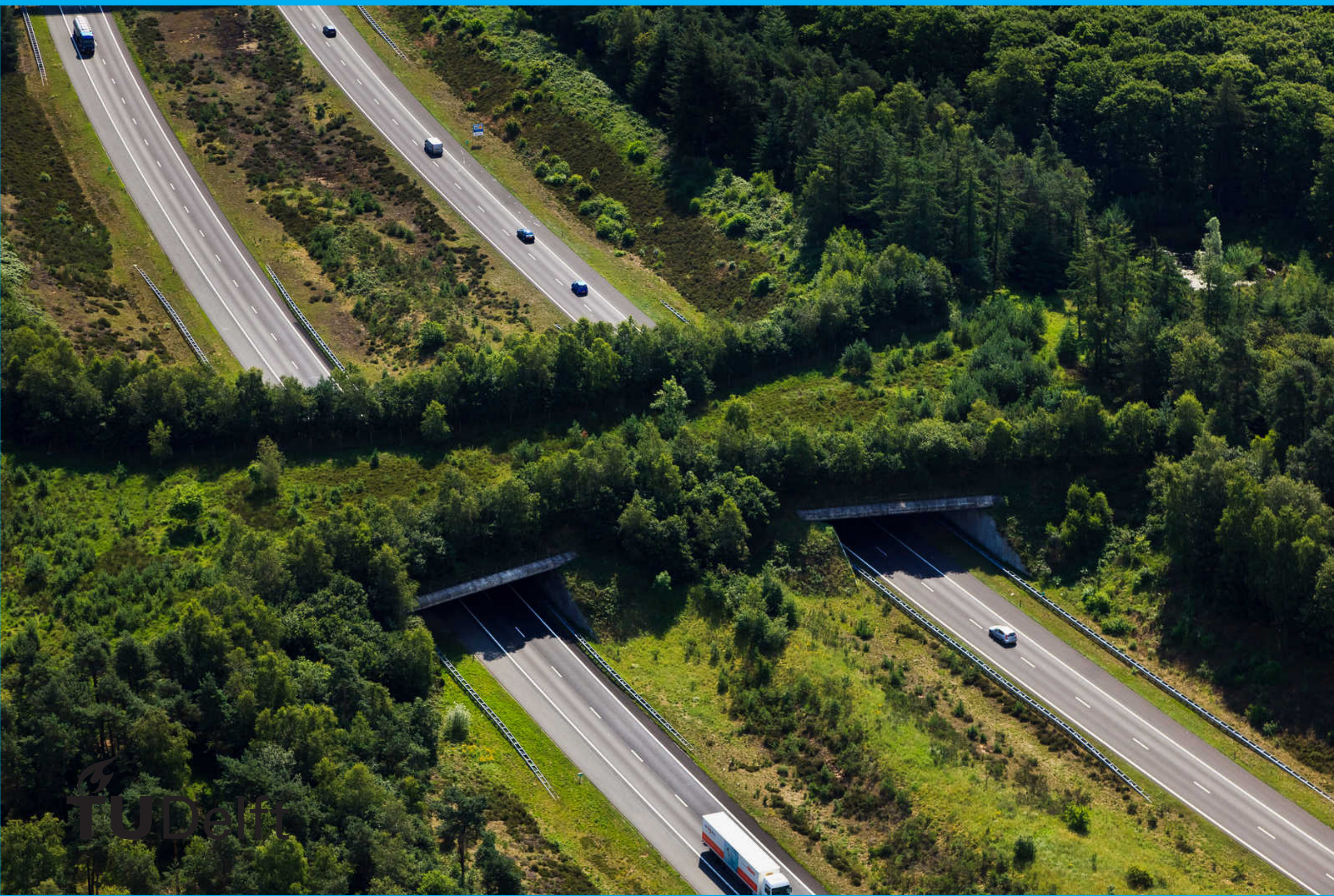
Reducing nitrogen deposition at Natura2000 through mobility solutions

TIL5060 Thesis

Jesper Vos



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TIL5060 Thesis

by

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Master of Science - Transport, Infrastructure & Logistics
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Contents

List of Figures

Preface

This thesis is the final assessment for the MSc Transport, Infrastructure & Logistics at Delft University of Technology and marks the end of my academic journey. The research explores relevant subjects within and beyond the study programme. Sustainability and travel behaviour are such topics and will always stay current. My longstanding interest for infrastructure and transport, both for passengers and cargo, has always been there along with the passion for maps and topography.

I would like to thank the colleagues at MuConsult for their help and confidence in me, and especially my supervisor Dennis van Soest for his time and coaching, as well as my former colleague Casper Stelling. My gratitude also goes to the supervision of the thesis committee and their valuable feedback: Bert van Wee, Jan-Anne Annema and Adam Pel. I appreciate everyone's patience and dealing with my lack of focus. That also accounts for my family and friends who kept the pressure on me to keep writing. A final thank you is for the team behind the MOVE Meter tool and their support in the configuration and application of it in my research.
Writing up the findings proved more challenging than I had imagined when they departed from my initial expectations, but I am pleased that alternative insights emerged and hope that policymakers will take note of the conclusions presented here.

Jesper Vos
Almere, June 2025

Summary

The Netherlands has been debating the effects of nitrogen deposition. Excessive nitrogen deposition harms ground-level ecosystems. Natura2000 areas, crucial for preserving biodiversity, are heavily impacted by excessive nitrogen. The Netherlands has 162 Natura2000 areas, covering about 2.2 million hectares. Reducing nitrogen deposition is crucial for these sensitive habitats. National and local policies are now shifting focus towards improving the living environment by reducing nitrogen emissions from all sources. Agreements aim to address the nitrogen issues, but local measures have been insufficient. Current tools and data need to be applied to specific cases to determine the impact of local mobility measures on nitrogen deposition.

While the element nitrogen itself is harmless and makes up 78% of our atmosphere, when it combines with other elements like hydrogen and oxygen, it forms compounds such as nitrogen-oxides and ammonia. These compounds, emitted by vehicles, industry and livestock, settle on the ground and increase nitrogen levels in the soil, a process known as nitrogen deposition. Nitrogen acts as a nutrient for plants, but in excess, it disrupts natural ecosystems. Species that thrive in low-nitrogen environments are overshadowed by grasses, nettles, and brambles, leading to reduced biodiversity. Excessive nitrogen causes eutrophication, disturbance, and acidification of soil and water, leading to unwanted byproducts like nitrous oxides. High levels of nitrogen deposition occur within 200 meters of the source. Wind speed and direction, temperature, and humidity significantly influence nitrogen-oxide concentrations. For nitrogen deposition at Natura2000 areas in the Netherlands, 11% is attributed to traffic, compared to 68% from agriculture. Despite the low share of traffic-related nitrogen emissions, reducing these emissions from vehicles is crucial for protecting sensitive habitats and reducing overall nitrogen deposition below critical values.

Local governments play a crucial part in implementing mobility measures that reduce emissions while also improving accessibility and liveability. This is also where some of the relevance of this research rests. Local governments can implement measures faster than the national government can and do so in a more flexible and targeted manner. National measures are less effective in targeting bottlenecks in nitrogen deposition. One of the goals of this research is improving the policy-making and the effectiveness of measures to reduce nitrogen emissions. Additionally, it is uncertain if the (judicial) correct models and data are used in national research and policies, which is thus also a point of interest. Current practice involves a lot of modelling of this kind and to a lesser extent on-site measurements. There are doubts about the diffusion patterns of deposition for example. A part of this are the uncertain effects of national policies and the location where they bring changes, hence the focus on local solutions in this research.

Protecting native species and habitats is a key goal, with a focus on sensitive Natura2000 areas. The primary goal of this research is to identify and evaluate effective transport policy and traffic management measures to reduce local nitrogen deposition near Natura2000 areas. The research intends to provide municipalities and provinces with actionable steps to reduce vehicle nitrogen emissions, thereby improving the quality and recovery of natural areas in the Netherlands. Aside from a starting point to further investigate possibilities in the mobility domain, the research compares and reflects on the use of a local spatial level compared to previous studies. It also shows to which extent the tools and data are adequate enough. The main research question in this research is: *What are effective local mobility measures to reduce nitrogen deposition at Natura2000?*

The MOVE Meter is used to measure the before-and-after effects on emissions and nitrogen deposition from various mobility measures as a quickscan tool. Besides the ease of importing O-D matrices, it also provides great visuals of the analysis. It integrates data from multiple traffic models focusing on vehicles, public transport, and cycling. Emission calculations are based on national data from the ministry, updated in cooperation with PBL and TNO. The NRM (Netherlands Regional Model) is used for traffic modelling data, specifically the NRM Oost RP23 dataset for the eastern provinces. The tool uses emission factors from 2025 and breaks down data by speed classes and road types. The WLO (Welfare and Living Environment) scenarios are used for future predictions, with high and low scenarios for 2040. 2040 is also the future year used for the modelling and calculations. Similarly, the research uses values for the morning commute, where most measures can be applies to. The MOVE Meter presents results quantitatively and spatially through tables and figures. It differs from other traffic modelling programs by not using the general gravity model but instead distributing trips based on imported origin-destination matrices and researcher-defined demarcation options. Additionally, evaluating the economic effects of mobility measures is common practice and a short cost-effectiveness analysis (CEA) will be used to assess the cost-effectiveness of different measures. CEA costs

include infrastructure and technology investments, such as smart traffic lights and cycling paths. Vehicle-Loss Hours are not part of the equation. Operational costs are also not included due to their complexity and relatively minor impact on the overall cost.

New equilibrium assignments, through dynamic traffic modelling, could benefit the research but also take more time and effort with added complexity. The tool is a static assignment with long-term projections using average values for traffic volumes based on the calculated situation. New traffic assignments help aid in mapping the new volumes on the network links and thus also the flow and routes chosen by vehicles, especially during delays . This would impact mobility measures on road sections and their value of nitrogen deposition reduction. This is also relevant for the subject mentioned earlier in this chapter: the values for freight traffic on a road section do not change and have to be assigned manually for a mobility measure. The foremost challenge is also the analysis of operational traffic management measures, as these require more dynamics compared to strategic and tactical solutions. More and different resources are needed to analyse mobility measures with dynamic modelling. Traffic volumes need auto-updating with consistent time intervals based on the intensity-capacity status of road sections. If a road gets crowded with delays, some travellers seek different routes. Although complete dynamic modelling would provide more accurate and detailed data for specific road sections, the MOVE Meter provides a great balance in modelling aspects for the scope of this research on nitrogen deposition reduction at Natura2000.

This research is a case-study approach zooming in on two specific Natura2000 areas in Gelderland. One is the Binnenveld, nestled in between four cities and the other is a larger, combined study area of De Bruuk and Sint Jansberg with a slightly more rural setting. The research targets local geographical levels, analyzing regional and municipal roads rather than national roads (Rijkswegen). Local measures are aimed at provinces and municipalities, which manage most road kilometers in the Netherlands. Focus is on passenger transport, with different solutions for nitrogen deposition. Inland shipping and waterways are excluded due to modelling restrictions. The same accounts for freight traffic on the roads as the tool does not include changes for trucks, but they are statically present in the model.

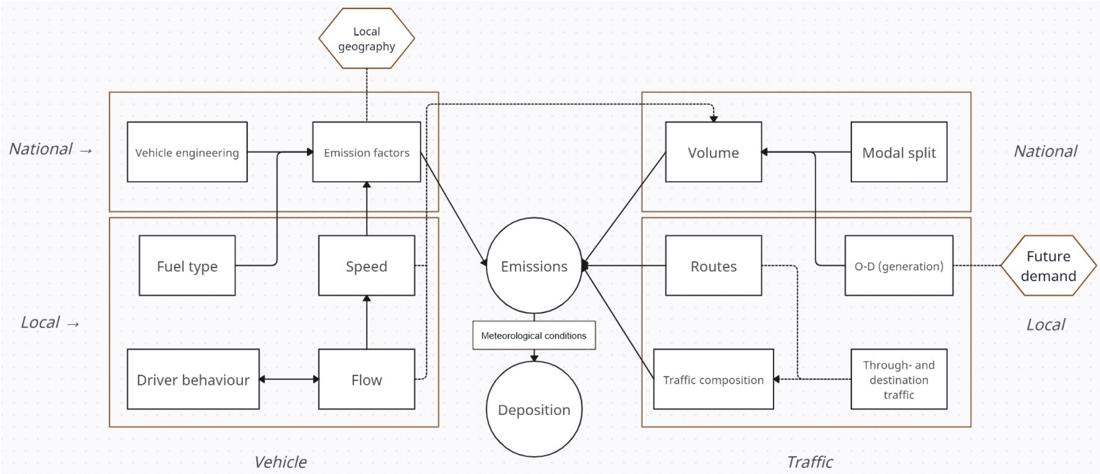

Figure 1: Conceptual Model divided into a national/local level as well as vehicle/traffic related components.

The conceptual model in Figure 1 helps in identifying factors that influence nitrogen emissions from traffic and how local mobility measures can reduce nitrogen deposition. It is based on literature and theories on traffic modelling, emissions, and vehicle characteristics. The measures in this research originate from the Conceptual Model and a brainstorm, stipulating which parameters could be adjusted to provide changes in emissions and deposition. The parameters can be adjusted deterministically in task-setting manner inside the MOVE Meter tool. The list of mobility measures is shown in Table 1

Table 1: List of mobility measures

Measure	**Block in CM**
Intelligent traffic light systems (iVRI)	Flow
Road downgrading	Speed
Driving behaviour campaign	Driver behaviour
No-entry zones passenger vehicles	Routes
Bypasses	Routes
Electrification passenger vehicles	Fuel type
Carpooling	Volume
Flexible office times (peak-hour avoidance)	Volume
Stricter emission standards ecological zones	Vehicle engineering
Park & ride, hubs and shared mobility	Modal split
Cycling incentives for modal shift	Modal split
PT incentives for modal shift	Modal split
Parking regulations in/for Natura2000	Modal split
New bicycle through-routes	Modal split
Mandatory cycling on short distances	Modal split
Teleworking	O-D (generation)
Mandatory work-from-home	O-D (generation)

Reducing congestion can lower vehicle emissions. Poor traffic flow, frequent decelerations, and accelerations at traffic lights, roundabouts, and highway ramps lead to higher nitrogen-oxides emissions. Research shows that without congestion, nitrogen-oxides emissions are significantly lower on urban roads. Also, diesel vehicles emit ten times more nitrogen-oxides than gasoline vehicles, which as been accounted for in the emission factors. Diesel-electric hybrids and LPG-fueled vehicles have lower emissions than diesel vehicles. In the future, new Euro-7 vehicle standards are expected to further reduce emissions from vehicles. Emissions are highest at speeds between 0 and 20 km/h. Emission rates decrease up to 60-80 km/h and increase again above 80 km/h. Heavy-duty trucks emit significantly more nitrogen-oxides in urban driving conditions compared to passenger cars. Driver behaviour, especially aggressive pedal usage, can cause up to six times greater nitrogen-oxides emissions as well. Novice drivers tend to produce more emissions like this because of aggressive driving habits.

Policies like ecological zones, stricter emission standards, and fuel type regulations can influence vehicle emissions. Meanwhile, reducing emissions from trucks and public transport buses remains challenging due to high production costs and inadequate charging infrastructure. There is a positive linear relationship between traffic volume and pollution concentrations. Higher traffic volumes and intensities correlate with roadside emissions. Larger roads, such as highways, see the most emissions per kilometer due to the higher number of vehicles. Increasing road capacity to tackle congestion can lead to more emissions though if not combined with measures to manage private vehicle trips. Extra traffic demand can eliminate the emission savings from capacity increases. Managing road projects with additional ideas is crucial to avoid increasing emissions.

Influencing the modal split through policies can lead to a transition from private vehicle use to public transit or cycling, reducing traffic volume and emissions. Tactical measures include routing, closures, and restrictions, which can impact emissions by redirecting traffic. Restricting certain fuel types or vehicles, like heavy-duty trucks, can reduce emissions on specific routes as well. Restricting through-traffic (vehicles using a road as part of a longer route) can help manage emissions, with cars being more sensitive to route adjustments than trucks.

Figure 2 shows the results of the measures in reduction of nitrogen deposition and estimation of implementation cost. The values for the reduction are in mole N/ha/year and are relative to one another. The costs are also relative to each other and are based on bandwidths, since the cost differ for each case and implementation. Results of the mobility measures show that the no-entry zones for passenger vehicles near Natura2000 is by far the best scoring measure in the research. It is aided by the focus on proximity to the Natura2000 areas compared to measures that focus on traffic volume. The reduction in traffic volume occurs relatively far away from the Natura2000 hexagons for example. Other measures that score well on cost-effectiveness are parking regulations, carpooling and teleworking. The same accounts for cycling incentives, but to a lesser extent. The research also showed that four of the measures have a high monetary cost while their effectiveness in reducing nitrogen is low.

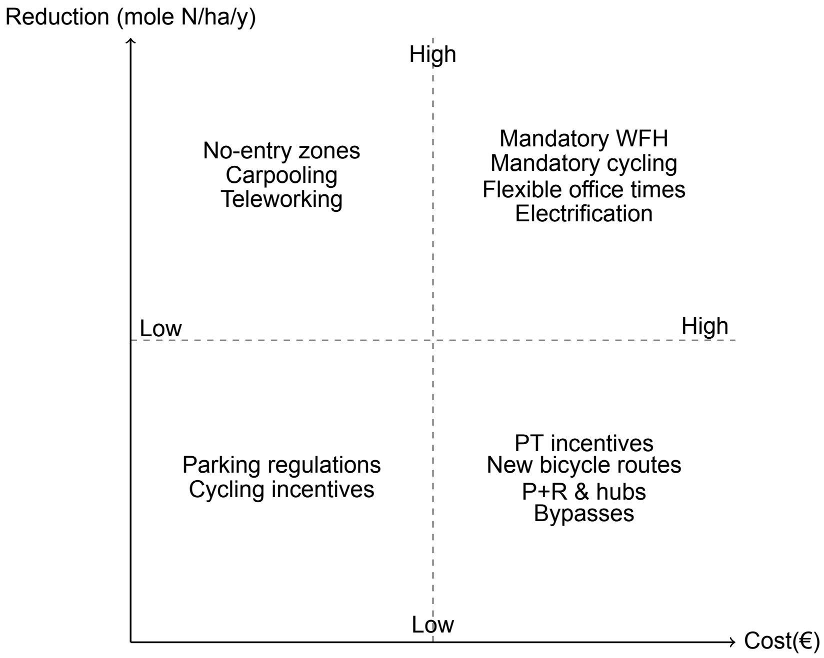

Figure 2: Diagram showing quadrants with the measures, sorted by costs and reductions

Effective measures on a local scale to reduce nitrogen deposition are either aimed at short proximity to natural areas or induce strong reductions in traffic volume next to Natura2000 areas. One measure scored exceptionally well in the reduction of nitrogen deposition. This was the no-entry zone measure, also known as a road closure. Taking away almost all of the direct vehicle emissions in or next to Natura2000 areas reducing the deposition at a very local scale. A key finding is that nitrogen deposition is highly localized, making proximity between roads and other emission points to the Natura2000 crucial.

The results of this research were influenced by a modelling restriction around the vehicle speed and emission factors. Some of the measures could not be calculated accordingly. A change in speed in the MOVE Meter tool led to contradicting results. The change in speed resulted in the traffic model signalling different road types with a change in emission factors. Consequently, further development of modelling tools, both for traffic and the broader dispersion of emissions, as with the AERIUS model, is recommended. Such improvements should focus on the local scale, allowing for more precise analyses of sensitive areas like Natura2000 sites, where local interventions may yield a more effective reduction in nitrogen deposition aside from distorting background levels originating from other sources and areas.

Essentially, although mobility measures can help reduce nitrogen deposition, their effectiveness is constrained by the wider environmental context and by emissions dispersing to and from beyond the immediate study area. Consequently, more localised research and refined modelling are required to develop measures that adequately safeguard sensitive ecosystems.

Samenvatting

De Nederlandse discussie over stikstofdepositie benadrukt de negatieve invloed van overtollige stikstof op de bodem en Natura2000-gebieden. De Natura2000-gebieden, die essentieel zijn voor het behoud van biodiversiteit, worden aangetast door te hoge stikstofniveaus. Er zijn 162 Natura2000-gebieden in Nederland, die ongeveer 2,2 miljoen hectare beslaan. Het verminderen van stikstofdepositie is cruciaal om deze gevoelige habitats te beschermen. Dit onderzoek richt zich op het identificeren van effectieve mobiliteitsmaatregelen om de stikstofdepositie in Natura2000 te verminderen. Het is bedoeld voor het beleid van provincies en gemeenten, via op maat gemaakte oplossingsrichtingen. De wetenschappelijke bijdrage van het onderzoek betreft de vergelijking van maatregelen en verschillende ruimtelijke niveaus, maar ook het analyseren of de tools en data goed genoeg zijn.

Hoewel stikstof als element onschadelijk is, vormen verbindingen zoals stikstofoxiden en ammoniak, die worden uitgestoten door voertuigen, industrie en veeteelt, een probleem doordat ze bijdragen aan verhoogde stikstofniveaus in lucht, water en bodem. Dit leidt tot eutrofiëring, verstoring en verzuring van bodem en water, waardoor de biodiversiteit afneemt. Verkeer stoot vooral stikstofoxiden (NOx) uit en de agrarische sector ammoniak (NH3). Grassen, brandnetels en bramen zijn bijvoorbeeld planten die goed gedijen op de extra stikstof en zo gevoelige soorten verdrijven. 11% van de stikstofdepositie in Nederland komt door wegverkeer en 68% door de agrarische sector. Beleid is zich al meer gaan richten op het verbeteren van de leefomgeving door de stikstofuitstoot van alle sectoren te verminderen. Echter ligt de focus vaak op de snelwegen vanwege de hoge intensiteiten en niet op lokale toepassingen.

Lokale overheden spelen een cruciale rol bij het implementeren van mobiliteitsmaatregelen die de uitstoot verminderen en tegelijkertijd de toegankelijkheid en leefbaarheid verbeteren. Daar ligt ook een deel van de relevantie van dit onderzoek. Lokale overheden kunnen sneller maatregelen implementeren dan de nationale overheid en kunnen dit op een flexibelere en gerichtere manier doen. Nationale maatregelen zijn in die zin minder effectief in het aanpakken van lokale knelpunten in stikstofdepositie. Een van de doelen van dit onderzoek is het verbeteren van de beleidsvorming en de effectiviteit van maatregelen om de stikstofuitstoot te verminderen. Daarnaast is het onzeker of de (juridisch)

juiste modellen en data worden gebruikt in nationaal onderzoek en beleid, wat dus ook een aandachtspunt is. De huidige praktijk omvat veel modellering en in mindere mate metingen ter plaatse. Er zijn bijvoorbeeld twijfels over de verspreidingspatronen van depositie. Een onderdeel hiervan zijn de onzekere effecten van nationaal beleid en de locatie waar dit veranderingen teweegbrengt, vandaar de focus op lokale oplossingen in dit onderzoek.

Effectieve lokale maatregelen en nauwkeurige verkeersmodellering zijn nodig om de stikstofdepositie te reduceren en de kwaliteit van natuurgebieden te verbeteren. Ondanks het lage aandeel van verkeersemissies in de totale stikstofdepositie, is het verminderen van deze emissies van belang om gevoelige soorten en leefgebieden te beschermen. De hoofdvraag luidt: *Wat zijn effectieve lokale mobiliteitsmaatregelen voor de reductie van stikstofdepositie bij Natura2000?*

De MOVE Meter wordt gebruikt om de effecten van mobiliteitsmaatregelen op emissies en stikstofdepositie te meten, door gegevens te integreren uit verschillende verkeersmodellen en nationale data. Herkomst-bestemming matrices zijn eenvoudig te importeren in deze tool en samen met het tekenen van het studiegebied, worden de ritten overzichtelijk verdeeld met veel visuele analyses. Het onderzoek maakt gebruik van toekomstscenario's voor bandbreedtes. De MOVE Meter is in dit onderzoek een quickscan tool met statische toewijzing voor de analyse van maatregelen en de effecten op de stikstofdepositie. Het onderzoek richt zich op de directe effecten van mobiliteitsmaatregelen en de MOVE Meter-tool biedt een goede balans in de modellering. Dynamische toewijzing zou het onderzoek ten goede komen, zeker voor operationele maatregelen, maar deze modellering brengt meer complexiteit en rekentijd met zich mee. Voor de data is gebruik gemaakt van NRM Oost 2040 versie RP23, inclusief een hoog en een laag WLO scenario voor de bandbreedte. Er wordt alleen gesleuteld aan personenvervoer en niet aan vracht. Vrachtverkeer is wel statisch aanwezig in het model. De case-study benadering zoomt in op twee specifieke Natura2000-gebieden in Gelderland: het Binnenveld en een groter gecombineerd studiegebied van De Bruuk en de Sint Jansberg.

Het conceptueel model in Figure 3 vormt de basis voor het opstellen van de maatregelen die doorgerekend worden in combinatie met een brainstorm. De maatregelen raken aan verschillende parameters die in de MOVE Meter tool bewerkt kunnen worden. Dit gebeurt op een taakstellende en deterministische manier.

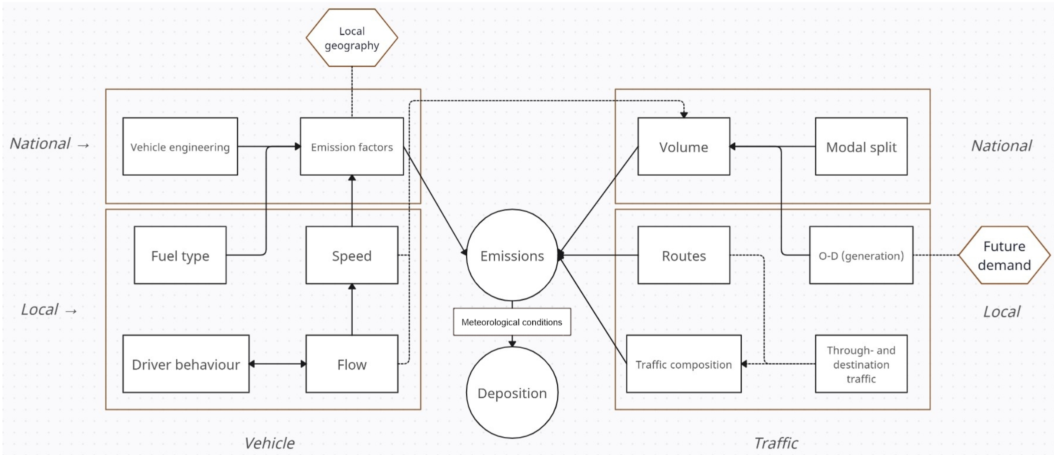

Figure 3: Conceptueel Model met onderscheid tussen een nationaal/lokaal niveau en voertuig/verkeer componenten.

Slechte verkeersdoorstroming en vertragingen leiden tot hogere stikstofemissies. Ook dieselvoertuigen stoten tien keer meer stikstofoxiden uit dan benzinevoertuigen. In de toekomst zullen nieuwe Euro-7 voertuignormen naar verwachting de uitstoot verder verminderen. Daarnaast leiden opstoppingen en agressief rijgedrag tot een hogere uitstoot en daarmee depositie. Beleidsmaatregelen zoals eco-zones en strengere emissienormen kunnen voertuiguitstoot beïnvloeden, naast een algehele vermindering van het aantal voertuigen in of vlakbij Natura2000. Er is een positieve lineaire relatie tussen verkeersvolume en emissieconcentraties. Een ander type verband is er voor de snelheid van voertuigen, die optimaal is tussen de 60 en 80 kmh. Er vindt meer stikstofuitstoot plaats bij hele lage en hoge snelheden. Verder kan het beïnvloeden van de modal split via beleid leiden tot een verschuiving van autoritten naar openbaar vervoer of de fiets, wat het verkeersvolume en de uitstoot vermindert. Alle theorie over voertuigen en verkeer komt samen in het conceptueel model, te zien in Figure 3. De mobiliteitsmaatregelen die in dit onderzoek worden doorgerekend zijn te vinden in Table 2

Figure 4 toont de resultaten van de vergelijking in depositiereductie en kosten tussen de maatregelen. Het toont in enige mate de kosten-effectiviteit, omdat er voor de kosten gewerkt wordt met bandbreedtes. De kosten verschillen namelijk voor elke casus en implementatie. De waarde voor de reductie is de gemiddelde reductie mol N/ha/jaar over de vier berekende scenarios en de kosten zijn enkel voor de implementatie. Maatregelen die beinvloedt zijn door de problemen met de emissiefactoren zijn uit de figuur gelaten omdat er geen conclusies uit de modelresultaten te halen zijn. De resultaten geven aan dat een maatregel met een wegafsluiting verreweg de beste cijfers oplevert voor

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Mandatory work-from-home	O-D (generation)

de vermindering van stikstofdepositie. Een groot aandachtspunt hierbij is namelijk de nabijheid van deze maatregel, die daardoor beter scoort dan maatregelen die zich enkel richten op het verminderen van het verkeersvolume. Dat verminderen van het verkeersvolume betreft namelijk (vooral) ook verkeer op grotere afstanden van de Natura2000. Andere maatregelen die relatief goed scoren voor kosten-effectiviteit zijn parkeerbeleid, carpoolen en thuiswerken. Ook zijn er vier maatregelen die hoge kosten bevatten terwijl ze slecht scoren op de reductie van stikstofdepositie.

Effectieve maatregelen op lokale schaal om stikstofdepositie te verminderen zijn gericht op sterke nabijheid bij natuurgebieden of zorgen voor een sterke reductie van het verkeersvolume nabij Natura2000 gebieden. Eén maatregel scoorde uitzonderlijk goed in het verminderen van stikstofdepositie: de 'no entry zone' maatregel, ook wel een wegafsluiting (voor personenvoertuigen) genoemd. Deze maatregel elimineert vrijwel alle directe voertuigemissies in of naast Natura2000-gebieden, waardoor de depositie op zeer lokale schaal wordt verminderd.

De resultaten van dit onderzoek werden beïnvloed door beperkingen in de modellering met betrekking tot de voertuigsnelheid en de emissiefactoren. Hierdoor konden sommige maatregelen niet op de gewenste manier worden berekend. Een verandering in snelheid in de MOVE Meter-tool leidde tot tegenstrijdige resultaten, doordat het verkeersmodel hierdoor andere wegtypen signaleerde met aangepaste emissiefactoren. Bijgevolg

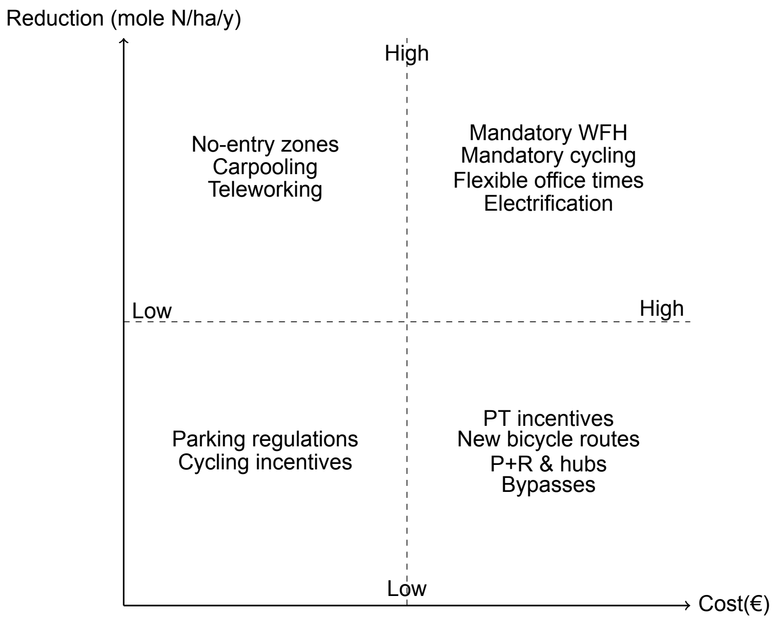

Figure 4: Diagram die de maatregelen in vier hoeken toont, gesorteerd op effectiviteit en kosten

wordt verdere ontwikkeling van modelleringstools aanbevolen, zowel voor verkeer als voor de bredere verspreiding van emissies, zoals met het AERIUS-model. Deze verbeteringen dienen gericht te zijn op lokale schaal, zodat er nauwkeurigere analyses uitgevoerd kunnen worden van gevoelige gebieden zoals Natura2000-sites, waar lokale interventies mogelijk effectiever kunnen leiden tot een verlaging van de stikstofdepositie, los van verstoringen van achtergrondniveaus uit andere bronnen en gebieden.

Kortom, hoewel mobiliteitsmaatregelen kunnen bijdragen aan het verminderen van stikstofdepositie, wordt hun effect beperkt door de bredere context en de verspreiding van emissies vanuit gebieden buiten het directe studiegebied. Daarom is meer lokaal onderzoek en verfijnde modellering nodig om maatregelen te ontwerpen die gevoelige ecosystemen op passende wijze beschermen.

1

Introduction

There has been a heated debate in the Netherlands regarding the origins and effects of nitrogen emissions. These emissions lead to excessive nitrogen deposition and the nitrogen levels are way too high for the soil and water to handle. Nitrogen deposition is a critical environmental issue that directly affects ecosystem integrity, biodiversity, the overall health of landscapes and is especially an issue in the Netherlands. Transport and mobility is one of the sectors that emit nitrogen. The Dutch debate has had an extra spark from political discussions, prompting an increase in the urgency of reducing nitrogen emissions and pushing policymakers to seek effective strategies for mitigation (NOS Nieuws, 2019). These strategies have not been clearly identified yet. Excessive nitrogen has been a long-standing issue, with the main concern being the harmful effects of nitrogen deposition at ground level. These harmful effects have an impact on nature and in the meantime implicitly create other concerns. A council ruling led to protests by the agricultural sector and nature conservation organizations, but effects of mobility have also been subject to discussions again in the last couple of years as the ruling implies that the assessment methods for nitrogen deposition were incorrect. The methods used to measure the nitrogen started in 2005 after it was concluded that the country was not doing enough to comply with EU rules and researchers mentioned in 2017, two years before the council ruling, that the Dutch measurement- and assessment methods were inaccurate and the policies to protect natural areas are inadequate (Meindertsma, B., 2017). Various articles have since been published about the deteriorating state of habitats due to excessive nitrogen deposition (PBL, 020b; Meindertsma, B., 2017). Recently, national policy documents from different countries have addressed the change in their aim as well regarding the state of water and natural areas (Hamers et al., 2021; Umwelt-Bundesamt, 2020; UK-Department-Transport, 2007). The reduction of nitrogen deposition perfectly fits into the policies from nowadays, which focus more on the living environment, safety and a reduction in emissions.

One of the concerns raised is the impact of supplementary nitrogen deposition on natural areas. Apart from national parks, the Netherlands has Natura2000 areas which are assigned to protect core areas of a species and are monitored more because of their sensitivity. Natura2000 is a comprehensive network of habitats that are of importance to the European Union (Natura2000, 2023). The bird- and habitat directives are also part of the European rules for Natura2000 areas. Management plans have been put in place to keep the habitats healthy and retain the variety of animal species. In the Netherlands, there are 162 Natura2000 areas and profiles have been assigned to each habitat type and species to conserve (Natura2000, 2023). The combined size of all Natura2000 in the Netherlands is roughly 2.2 million hectares. Lastly, the Netherlands has a relatively large number of natural areas for its surface- and water area compared to other European countries as a result of its coastal location (PBL, 2021). Not only are there local differences between Natura2000 sites, but the origin of nitrogen emissions differs from site to site (Backes, 2023). Throughout this research, the importance of reducing nitrogen deposition in Natura2000 areas will be stressed by showing the relevant information and figures, as well as the effects of supplementary nitrogen on biodiversity. This will be depicted in this chapter, chapter 2 and chapter 3.

Aside from the important ecological aspects and deterioration of biodiversity, the exceedance of nitrogen emissions also poses economic risks and implications (Sanders et al., 2020). The underlighted nitrogen issue became more upfront when permits for housing, infrastructure and business expansion projects were denied in 2019 (Sanders et al., 2020; NOS Nieuws, 2018). The issue still lingers and in late August 2023 it was reported that the Critical Deposition Values of nitrogen should be even more strict in fifty percent of the Dutch Natura2000 areas to provide nature with the ability to recover (Bürmann and Spekschoor, 2023). The CDV is the maximum amount of nitrogen that may settle per hectare of natural land. Additionally, the new 2023 coalition agreement of the province of Gelderland addresses the nitrogen deposition issues at her Natura2000, but not all of them (Coalitie-Provincie-Gelderland, 2023; Drenth, 2022). The report mentions future measures for the Veluwe, Achterhoek and Rijntakken areas only. Meanwhile, it has also become clear that municipalities do have the power to intervene in mobility. Elsewhere in the Netherlands, a municipality closed a local road for the duration of two years to reduce nitrogen deposition at the Natura2000 it's situated in (NOS, 2023). This local power to act against nitrogen emissions is exactly what will be upfront in this research, as it has not been focused on yet. Especially in the field of mobility, which is one of the contributors of nitrogen emissions.

Figure 1.1: Sensitive humid alluvial forest in the Sint Jansberg N2000 area (Leeuwen and Boesveld, 2015)

1.1. Gap and aim

The absence of region- and location-specific mobility measures is highlighted by the fact that drastic actions make headlines. Previous emission studies focused on a broader scale, with policy- and traffic management on national roads where intensities are greater. While nationwide policies have a broad reach, research is needed whether locally implemented mobility interventions can serve as targeted and efficient solutions. chapter 2 will provide further information. A search for 'local measures' and 'nitrogen deposition' in existing scientific literature did not yield any results. Scientific reports have only focused on the main road network, such as the multi-year infrastructure plans from the government. Results for more specific routes and roads in the sub-network are mostly accompanied by research into new (house) construction plans and not with mobility measures (Fenten, 2022). Effects of local measures at specific municipal roads and the deposition at nearby Natura2000 have not been profiled yet. It is yet unclear what nitrogen-oxide emissions and resulting nitrogen deposition rates look like at different road types such as regional and local roads as well as other transport modes, and how strong a reduction could be through mobility solutions. New research needs to prove whether currently devised solutions work on a more local scale as well. The tools to measure the nitrogen emissions already exist, but have not been applied to local cases. Detailed indications of the distribution will help identify relative contributions of proposed solutions. With mobility and traffic being the third largest source of nitrogen deposition (Figure 2.3), there is both potential and a responsibility to reduce it locally (van der Maas et al., 2023). Similar to other types of emissions, the location of mobility measures is important as they diffuse widely after an airborne transport distance where the highest intensities are found closer to the source, and nitrogen deposition is thus a local issue (MuConsult, 2022; APIS, 2016). It has been stated before that the focus has to be on local sources and targeted measures, but mobility has been overlooked for this (Delbaere et al., 2014). Local governments play a crucial part in implementing mobility measures that reduce emissions while also improving accessibility and liveability. This is also where some of the relevance of this research rests. Local governments can implement measures faster than the national government can and do so in a more flexible and targeted manner. National measures are less effective in targeting bottlenecks in nitrogen deposition.

A further contribution of this research to the knowledge gap is the in-depth exploration on the similarities and differences between study areas. There is currently a lack of tangible solutions in governance too, such as minimal plans in coalition agreements for example (Coalitie-Provincie-Gelderland, 2023). One of the goals of this research is improving the policy-making and the effectiveness of measures to reduce nitrogen emissions. Additionally, it is uncertain if the (judicial) correct models and data are used in national research and policies, which is thus also a point of interest. Current practice involves a lot of modelling of this kind and to a lesser extent on-site measurements. There are doubts about the diffusion patterns of deposition for example. A part of this are the uncertain effects of national policies and the location where they bring changes, hence the focus on local solutions in this research.

Protecting and preserving native species is part of the social contribution of this thesis research. Reducing nitrogen deposition goes hand in hand with the remedial work Staatsbosbeheer is doing to protect habitats and species (Staatsbosbeheer, 2023). Serious concerns are present for the Binnenveld Natura2000 area for example, where some of the most endangered Dutch habitats are located. Quaking bogs are sensitive to excessive nitrogen deposition and the peat moss reedlands even more so, which are some of the most sensitive habitats found (Bobbink, 2021). In addition, the amount of bluegrasslands has been rapidly decreasing since the last century and the province of Gelderland has multiple of these habitats, also in the Bruuk area Figure 1.2. Outside the Netherlands, this habitat has been becoming more sparse in the EU and thus the Netherlands bears great responsibility to preserve this. The Sint Jansberg area in Gelderland also hosts some valuable habitats in the sensitive beech-oak forests with holly. For these oak forests the situation is alarming as they receive way too much nitrogen in the Netherlands to be able to recover and can mostly be found in lowlands, which gives more importance to the Netherlands as host to preserve. A similar note can be made for calcareous fens and alluvial forests (Figure 1.1) (EEA, 2023b). Many more habitats and species in Gelderland are in trouble because of the surplus in nitrogen deposition such as (degraded) raised bogs (EEA, 2023b). A broader overview of the natural collection in the study areas will be given in section 3.4. Delbaere et al. (2014) listed a couple of ecosystem changes due to excessive nitrogen deposition based on the research of Bobbink and Hettelingh (2011) and for Gelderland this includes: increase in tall grasses, vascular plants and sedges, as well as a decrease in overall biodiversity. More information on values of nature and wildlife will be given in the first half of this research to highlight the issues if policies do not reduce nitrogen deposition, and how specific species react to increased nitrogen levels. All nitrogen emitting sectors could contribute to a reduction in nitrogen deposition to reduce the stress on threatened habitats and species.

Figure 1.2: Meadow Thistle, on the red list of Dutch plants, found in bluegrasslands (EEA, 2023b)

The goal of this research is to identify the measures in the transport policy and traffic management departments that reduce local nitrogen deposition and which ones are most effective in doing so. It will also report on the importance of proximity between source and nature, a relevant part of focusing on local measures. Results of the research will consult municipalities and provinces, and recommend steps to be taken to reduce nitrogen emissions near Natura2000. The aim of the thesis is to address the research gap by exploring the most effective mobility measures that can be implemented to reduce vehicle nitrogen emissions near N2000, which in theory leads to a reduction in nitrogen deposition. It will then contribute to the ongoing efforts to reduce deposition in the Netherlands and improve both the quality and recovery of natural areas. This research can act as a starting point for fellow academics to further investigate possibilities of local mobility measures to reduce emissions. Also, to uncover which measures work best on a local spatial level compared to previous studies and studies on the main road network and its higher intensities. Additionally, the effectiveness of measures will be displayed in relation to their monetary cost. This research also shows the extent to which current tools and data are adequate enough to chart measures for the reduction in nitrogen deposition.

1.2. Research questions

The main research question here and connecting to the protection of Natura2000 is: **What are effective local mobility measures to reduce nitrogen deposition at Natura2000?** Adding to this question is the cost-effectiveness analysis of the mobility measures. 'Effective' addresses the absolute reduction in nitrogen deposition at Natura2000 compared to the base scenario and thereafter the costs are taken into account. Other questions to be answered with this research include;

- How can we model mobility measures for a reduction in nitrogen emissions originating from road traffic?
- To what extent are current tools and data suitable to research local mobility measures?
- What are the components and characteristics of vehicles and traffic leading to nitrogen emissions?
- What are the potential local mobility measures and what is their implementation cost?
- How does one study area relate to another and to what extent can results be translated and adapted in other regions?

2

Theory and literature

The information in this chapter functions as a background into what nitrogen deposition is and where it comes from. The chapter not only includes the correlations between nitrogen emissions and the sources, but also addresses the theory on vehicles and traffic that lead to a Conceptual Model that will be used for the list of measures and analysis. This chapter exhibits what is already known or not known yet about various nitrogen deposition relations in the current scientific literature. Specifically subjects such as the formation of nitrogen deposition, how it originates from vehicles, the position of nitrogen deposition in international context and other (background) emission sources.

2.1. Search terms and keywords

The search for existing literature and articles was not only done in Scopus as library, but also through the usual search engines such as Google, which for example lead to articles posted on Researchgate or public documents and databases. Keywords in this search include, in no particular order: *nitrogen, deposition, traffic, emissions, mobility, measures, private vehicles, trucks, Natura2000, urban, roads, roadside, transport, acidification, ammonia, nitrogen-oxides, restrictions, air quality, electrification, behaviour, fuel type, smart mobility, eutrophication, policies, work-from-home, emission standards, factors, modal shift*. These keywords were often combined to find more applicable and specific documents. Snowballing from one article to the other in Scopus was also common practice. A similar path could be walked in Dutch news articles, where NOS News uses a 'collection' on the nitrogen dossier for example. Institutions like RIVM, TNO, PBL and CBS also have larger cases online with multiple informative articles and sections on the Dutch nitrogen subject. 'Local research' was included in the search queries but did not provide any suitable sources.

2.2. Nitrogen emission and deposition

This section addresses the difference between nitrogen-oxides and ammonia as well as the meaning of the Critical Deposition Value for vegetation species. The second part of the section is about the Dutch approach and how it differs from other countries. The difference between the ammonia and nitrogen-oxide compounds is important for the understanding of later sections in this research.

2.2.1. Introduction to nitrogen

Even though the discussion is about a nitrogen-crisis in the Netherlands and (international) research is aimed at nitrogen emissions, the topic of this research is not directly nitrogen itself. The element nitrogen is harmless and can be found in the air around us, where it makes up 78% of the atmosphere (Xu et al., 2019; Greaver et al., 2016; Delbaere et al., 2014). Nitrogen can be bound to other elements however, such as hydrogen and oxygen. Resulting compounds such as nitrogen-oxides and ammonia are emissions from processes and different origins. While cars and industry emit mostly nitrogen-oxides, livestock leads the production of ammonia for example (Vries et al., 2021; Zhang et al., 2018; Dai et al., 2024). These nitrogen compounds do not stay airborne but settle onto the ground, increasing the amount of nitrogen in the soil. This is the phenomenon of nitrogen deposition. Nitrogen is in basis a nutrient for plants (Zhang et al., 2018; Stevens et al., 2020; Kuypers et al., 2018). Various organisms react in complex networks on the nitrogen compounds, such as nitrate and ammonium, which is a reactive result of ammonia and water. However, many natural areas worldwide are low in nitrogen, or at least used to be. Special species grow in these areas, which have adapted to the soil and live with small amounts of nitrogen. Grasses, nettles and brambles can thrive if large amounts of nitrogen are inserted, leaving too little light and nutrition for the original vegetation (Greaver et al., 2016). This process violates the balance of nature as insects and birds will disappear with the plants for example. Eventually, nature becomes more and more of the same and biodiversity declines. Research shows that an increased deposition rate and duration worsens the effects on habitats (Zhang et al., 2018). Key processes in the decrease of species diversity are eutrophication, disturbance and acidification of soil and water, evoked by the nitrogen deposition (Stevens et al., 2020; Pannek et al., 2015; Delbaere et al., 2014). These processes also result in unwanted byproducts both on land and in waters such as nitrous oxides (Zhou et al., 2023). Effects of three-year long eutrophication due to excessive nitrogen deposition are shown in Figure 2.1 (Bobbink and Hettelingh, 2011).

Nitrogen deposition can be separated into dry- and wet deposition (PBL,

Figure 2.1: Multi-year eutrophication effects in Dutch grassland (top) and Swedish taiga (bottom) habitats. Control condition on the left and after N addition on the right. (Bobbink and Hettelingh, 2011)

020b). Dry nitrogen deposition is direct (atmospheric) uptake in soil and vegetation while wet deposition is absorption through precipitation. The distribution pattern between ammonia (NH_3) and nitrogen-oxides (NO_x) is also different. The highest ammonia rates are very close to the source because of molecular weight although some of the share transports very far (Fenn et al., 2018). A quarter of all ammonia emissions deposits within 25 kilometers of the source, mainly because the sources are always close to ground level. Nitrogen-oxides travel further and are able to cross seas and borders more easily, only 8% of the emissions deposits within 25 kilometers. Moreover, of the nitrogen estimations on Dutch soil, 68% emerges from the Netherlands itself while four times more nitrogen is been put onto other countries' soil originating from the Netherlands (RIVM, 2023; CPB and PBL, 2023). Figure 2.2 illustrates the intensity of the deposition close to the source, underpinning the locality issue. The highest intensity of mole/ha nitrogen deposition takes place within 200 meters, regardless of the quantity (Backes, 2023; RIVM, 2023). Ammonia and nitrogen-oxides can only be summed up together in mole or adjusted kilograms since they have different molecular weights. This deposition-distance will be subject in this research for distinct individual contribution of mobility measures. The surface underneath ammonia is overall larger in the figure because this compound weighs and contributes more to the nitrogen deposition. Ammonia weighs more than nitrogen-oxides and the latter travels longer distances and the line in Figure 2.2 theoretically stretches out way further.

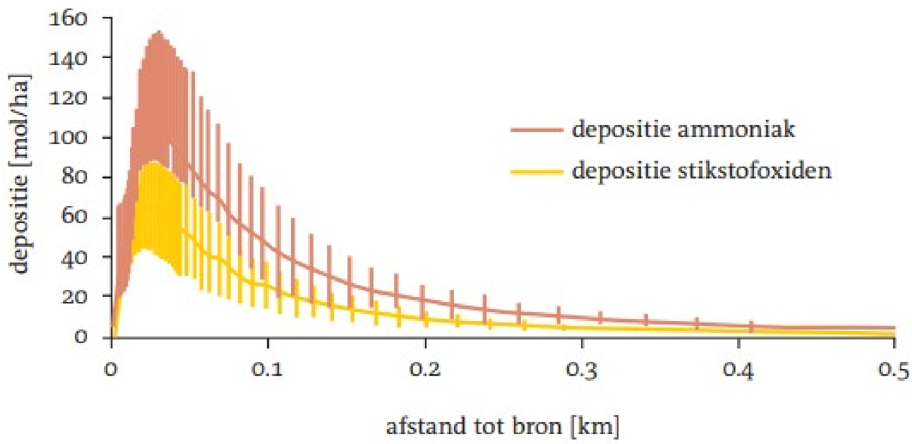

Figure 2.2: Deposition of nitrogen-oxides and ammonia up until 500 meters from the source in mole/hectare (intensity). (Backes, 2023; RIVM, 2023)

Also, wind speed and direction significantly influence concentrations of traffic-related nitrogen-oxides (Sayegh et al., 2016; Kamińska, 2019). Research has demonstrated that emissions spread further under higher wind speeds and concentrations are greater at individual locations when winds are calm. Other meteorological conditions with an effect on nitrogen-oxide concentrations are temperature and humidity, of which the latter has a strong relationship with precipitation and the accumulation of wet nitrogen deposition in the soil (Kamińska, 2019; Grange et al., 2019). The impact of meteorological conditions on ammonia distribution is smaller than for nitrogen-oxides however, but follows similar patterns year after year (Kryza et al., 2011; Fenn et al., 2018). The meteorological conditions are a key factor between emissions and deposition in the Figure 2.7, which will be discussed in section 2.7.

For the analysis and effects on nature, a threshold is used for a critical value, indicating if the deposition is damaging or not. This Critical Deposition Value is abbreviated to CDV, or KDW in Dutch. The CDV is used as an instrument in the permit granting by the relevant authorities (AanpakStikstof, 2023). The critical value has as unit mole per hectare per year and the amount of nitrogen deposition above which deterioration of natural quality cannot be ruled out. For each type of species and habitat a CDV has been identified. For Dutch Natura2000 this list has been compiled in the report of van Dobben and van Hinsberg (2008). In the Netherlands, the national government initiated an exploratory study on the substitution of the CDV towards a more legally sustainable indicator, also incorporating the importance of soil- and water quality (AanpakStikstof, 2023).

2.2.2. International context

The issues around nitrogen deposition are not completely unique and research is being done in different countries stemming from these issues or air pollution (Donovan et al., 2022; Wang et al., 2018). The case of the Netherlands stands out in Europe and possibly the rest of the world as came up in an interview with environmental law professors (Tiekstra, 2023). The same laws apply throughout the European Union but interpretations vastly differ on dealing with legal frameworks. However, there are some EU countries who consider the nitrogen emissions not even as a problem and thus do not track the sources, whilst others operate a very different threshold than the Netherlands. Germany uses a nitrogen threshold of 21 mole per hectare a year before they investigate and assess nitrogen emission further. Meanwhile the Netherlands uses a threshold of 0.005 mole N/ha/year and thus a vastly different assessment (Tiekstra, 2023). This very low threshold has been put in place on purpose so that every exceedance has consequences and requires monitoring, assessment or approval. The Netherlands is already at its limits and can not allow any extra nitrogen deposition. Contributions below this value of 0.005 are considered negligible in authorization procedures. The government has launched a study to see if the legal threshold can be adjusted and what the implications could be. The phenomenon of nitrogen deposition is not unique, but the juridical approach the Netherlands is carrying out is though, leading to a unique 'nitrogen-crisis' (Backes, 2023).

Moreover, the Netherlands has a relatively large amount of special and unique natural areas in the European context due to its location in multiple deltas (PBL, 2021). These areas include coastal nature such as salt marshes, dunes and wet heathlands, but also (dry) grasslands. Additionally, the Netherlands is internationally an area for wintering and transiting waterbirds as well as diurnal butterflies (Sanders et al., 2020). The nitrogen emissions in the Netherlands are also relatively large and the most of all mainland EU countries (Mouissie, 2022). The emissions are roughly four times larger than the average of the EU countries. All EU countries have to uphold to an agreement that by 2030, protected habitats and species can't deteriorate in quality however. The relatively large number is not directly linked to traffic though, as data shows that the number of cattle and pigs per hectare is the highest for Dutch regions in the EU context. Also, among a list of the 100 largest emitters of nitrogen, a couple of companies hold some of the top spots. All in all it can be stated that the issue with nitrogen deposition on nature is certainly not unique, but the Netherlands has the largest steps to take in battling the issue relative to other EU countries.

2.3. Sources of nitrogen emissions

For all the nitrogen deposition in the Netherlands, research has been done on its origin. Mostly through the use of models with some validation field measurements. This has also been reported for nitrogen-sensitive Natura2000 areas and is visualized in Figure 2.3 (RIVM, 2023). The figure illustrates that only 11% of all deposition at Dutch Natura2000 areas is at the hands of mobility. This percentage is slightly higher than industry and built environment, while it is four times smaller than agriculture. Next to agriculture, traffic and sources abroad there are more sectors with nitrogen emissions as shown in Figure 2.3. Industry and the built environment hold a small percentage as well as ammonia from the sea for the Netherlands. On top of that, other sources are part of larger sectors (AERIUS, 2023). The AERIUS Monitor, used in the Netherlands to keep track of nitrogen deposition per hexagonal hectare, has additional sector sources and differs from Figure 2.3. Besides industry, agriculture and (road) traffic there are also 'transport and other mobility', 'marine shipping' and the 'other' category. A category like marine shipping is also divided into different sources for example, as inland- and offshore shipping and ports all account for nitrogen emissions.

In the last couple decades, the emissions from traffic have greatly reduced (Mouissie, 2022). Although ammonia emissions saw a slightly less extreme reduction compared to nitrogen-oxides and sulfur dioxide (Aksoyoglu et al., 2020). Between 1990 and 2005, nitrogen-oxides concentrations were reduced by 40% in all of Europe, while the ammonia concentration only decreased by 30% in the Benelux and Italy, which are stipulated as high-emission areas (EEA, 2023a). Results of the research by Aksoyoglu et al. (2020) indicate that the reduction in emissions until 2030 will be less noticeable albeit still ongoing (Rijksoverheid, 2023a).

While livestock production contributes by far the most to the ammonia emissions in the Netherlands, there are also ammonia emission sources in urban environments (Reche et al., 2015). Biological sources such as waste containers, industry and water- and waste treatment plants emit amounts of nitrogen. Emissions from industry include energy production, which contains multiple damaging compounds including nitrogen oxides (Luo et al., 2021). It is important to note however that source distributions

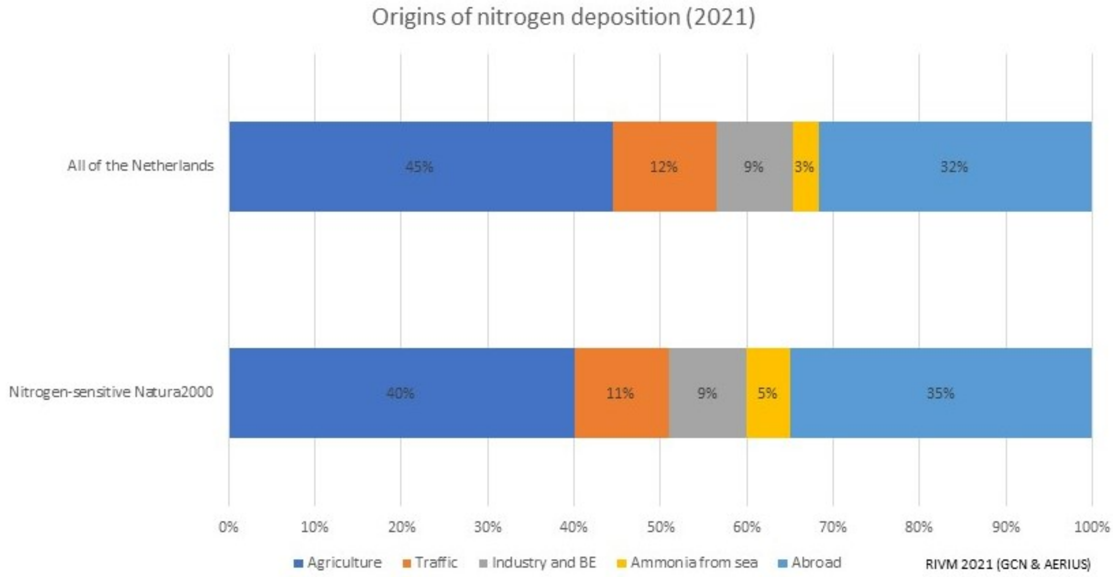

Figure 2.3: Origin of nitrogen deposition in the Netherlands (RIVM, 2023)

vary across different countries and regions. A US-study illustrated for example that bio-mass burning and vehicle emissions have a similar distribution in urban environments (Felix et al., 2023). Biomass-burning includes wildfires, which are expected to increase in the future due to climate change. Additionally, the traffic category does not include emissions from mobile equipment in construction, agriculture and industry. These are part of their own category 'transport and other mobility' along with railway transport and aviation, in the AERIUS emission model (PBL, 020b; AERIUS, 2023). In Figure 2.3 these mobile equipment emissions are part of the traffic and industry categories. It is difficult to determine the origin of every bit of nitrogen deposition, hence the usage of models and validation by measurements (LNV, 2020). This topic will be addressed in section 3.2 and chapter 5.

There is also a significant contribution to the nitrogen deposition from inland- and offshore shipping coming from the engines (Zhang et al., 2023; Krause et al., 2023). Monitoring vessel emission control is difficult while measurements show high numbers of nitrogen-oxides emitted on rivers. Models and satellite observations have shown much higher nitrogen-oxides pollution in riverside cities in China for example (Zhang et al., 2023). Emission rates increase with larger vessel sizes and speeds, as well as upstream versus downstream travel of course (Krause et al., 2023). Other research has pointed out that the same applies for coastal areas and harbours, where offshore vessels emit nitrogen-oxides and ammonia through their diesel-engine exhausts (Zhang et al., 2016). Shipping by vessels will not be part of this research into local mobility measures and the focus is on roadside traffic.

2.4. Literature overview

Now that the different emission sources have been laid out in the previous section, this section briefly discusses some existing literature on the emissions and especially traffic as well as the lack of research. However, the two sections after this more thoroughly go in on the theory of vehicles and traffic with more in-depth information about relationships and emissions. The theory and literature is then used for the construction of a Conceptual Model in section 2.7.

A literature review by Fan et al. (2023) points out that most studies on traffic emissions analyzed the total emissions and did not focus on spatial or temporal layers. The same review found that between 1997 and 2023, nitrogen and local measures were absent in the most named keywords and topics. Main topics that were included in scientific research were on the technical side of vehicle emissions and national policies. The review does mention that the past years have further addressed external factors on emissions, such as temperature, congestion and driver behaviour, but not a specific local case or nitrogen-oxides instead of carbon-dioxides. Another meta-analysis on nitrogen deposition by Decina et al. (2020) highlights the need for local measures as their analysis found that the nitrogen cycle in cities has to be addressed. However, one of their conclusions strikes a crux in nitrogen deposition research: a focus is laid onto ammonia because it is the largest proportion of nitrogen deposition for almost all countries and traffic emission studies are then neglected.

One article from 2019 did investigate the local distribution of nitrogen emissions from private vehicles (Plakolb et al., 2019). However, they carried out this research using agent-based modelling in order to investigate the different measures. The focus was laid on the emissions and a comparison between simulations and statistics. Similarly, there have been multiple articles on changes in the air pollution because of decreases in traffic, such as Górka-Kostrubiec and Dudzisz (2023). These focused on the effects of the lockdowns in 2020 where the decrease in traffic was drastic and not accountable to sole mobility measures, which is the topic of interest in this paper.

The lack of local studies on traffic emissions, especially nitrogen and not carbon, and natural areas is one of the reasons why this research focuses on this combination with mobility measures. There is a knowledge gap in the local impact of measures on the deposition reduction. The tools to measure the nitrogen emissions and deposition are already existing, but the contribution of this research is in the application of these tools on smaller, local measures and to see how it adds up to the general goal of deposition reduction. Further contribution to the knowledge gap is the in-depth exploration to the similarities and differences between study areas and for other areas worldwide.

2.5. Theory on vehicles

This section identifies, with the assistance of existing literature and reports, which policies relating to vehicle characteristics are able to decrease the emissions. It will be mentioned explicitly if the topic has an increasing or decreasing effect on nitrogen emissions, or if it only applies to modelling concerns. A similar note can be made for the next paragraph, section 2.6, which investigates the policy and traffic management effects on traffic.

Reducing congestion is one way to reduce vehicle emissions. The concentration of pollutants emitted varies with the traffic flow, gradient and driving speed of the road (Sarkan et al., 2022). Decelerating and accelerating the vehicle emits pollutants. As such, the worse the traffic flow gets, the more nitrogen-oxides are emitted. This is also the case for stopping at traffic lights, give-ways, roundabouts and highway ramps, which were all found to be hotspots (Hasan Shahariar et al., 2022). Research found peak concentrations of nitrogen in and coming out of traffic tunnels. Peak measurements in both emissions were also found at sections with reduced driving speed and increased vehicle density, because of more frequent decelerating and accelerating (Dai et al., 2024; Abdull et al., 2020). The same increase was found at traffic lights. An American study highlighted extensive differences in driving conditions for heavy-duty diesel trucks through portable measurements (Badshah et al., 2019). Large trucks emit the same amount of nitrogen-oxides as 100 passenger cars in urban driving conditions of less than 40 km/h as they are optimised for highway driving conditions in testing. Measured over the distance of a road section, this urban environment is also the place with the highest relative emission of nitrogen-oxides. Additionally, research pointed out that without congestion and the stop-and-go traffic flow, emissions of nitrogen-oxides were 12% to 28% lower on urban roads (Chen et al., 2022). A prominent cause for this is the high emission at speeds between 0 and 20km/h (Smithers et al., 2016). Both diesel and gasoline show a decreasing graph up until 60km/h and 80 km/h respectively when speed and nitrogen-oxides are plotted against each other and above 80km/h the emissions strongly increase again (Zachariadis, 2008). A similar train of thought has been mentioned in other research (van Wee et al., 2023). Engine rpm (rounds per minute) plays an important role in this correlation. Figure 2.4 also shows that nitrogen-oxide emissions have been lowered through the years by introducing new emissions standards aside from speed effects (Smithers et al., 2016).

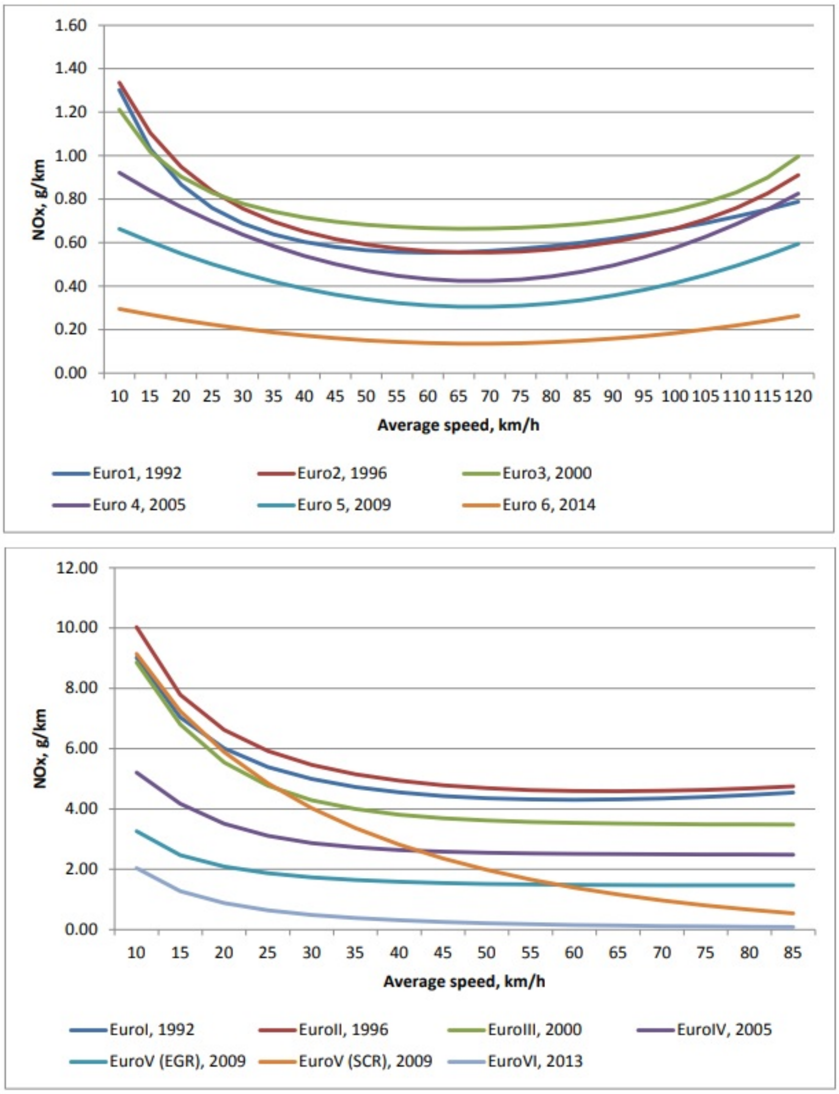

Figure 2.4: V-NOx graphs for a small diesel car (above) and a heavy goods diesel vehicle (below) (Smithers et al., 2016)

Aside from the emission reduction through improved engineering, energy efficiency and stricter vehicle standards, differences in fuel are also

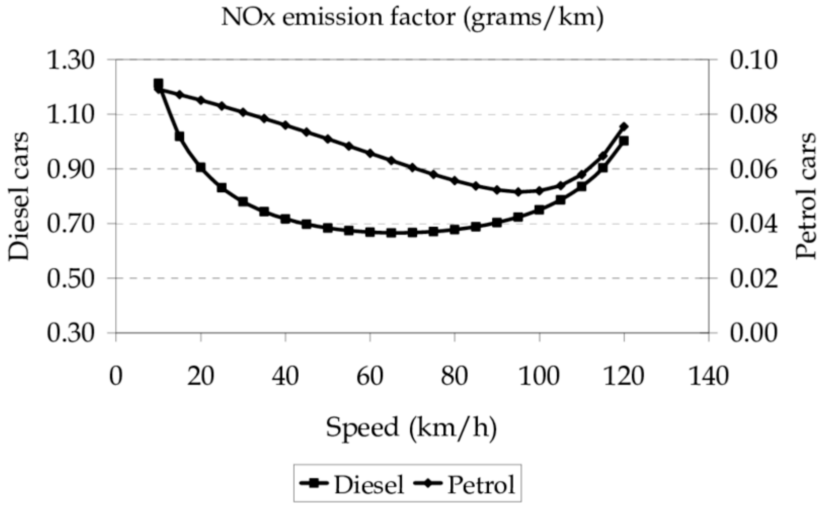

Figure 2.5: Difference between petrol/gasoline and diesel vehicle NOx emissions (older EuroIII technology) (Zachariadis, 2008)

noticeable (Zhao et al., 2013). On average, diesel vehicles emit ten times more nitrogen-oxides than gasoline vehicles, which is partly visible in Figure 2.5, as these values are a couple years older (Archer, 2015; Zachariadis, 2008). A large part of this is also the difference between emissions found in real-life situations compared to the limit achieved in testing. The foremost restriction for vehicles with older standards is the prohibition to drive into (city) eco-zones. These ecological zones are getting more frequent, larger and stricter each year (Kouwenhoven, 2023). New Euro-7 standards are expected in July 2025 and July 2027. Additionally, the MOVE Meter incorporates the emission factors published by the Ministry of Infrastructure and Water Management and this will be explained further in chapter 3 (MOVE Mobility, 2020). The emission factors depend on the number of vehicles using the road section, the share of goods traffic and the traffic flow on the road. These factors are divided up into five 'speed' classes with different values for cars and trucks as well as characteristics. There are some asterisks to nitrogen emission factors however. Research from Grange et al. (2019) pointed out that ambient temperatures matter for nitrogen-oxides emitted by diesel vehicles. The lower the temperature, the higher the nitrogen emission is. The feature was not observed for gasoline cars though. A predicted value of 38% more emissions compared to testing was found.

In addition, recent graphics from agencies have shown more differences in nitrogen emissions by different propulsion systems for passenger vehicles (Environment-Agency-Austria, 2018). Diesel emits three times more nitrogen-oxides than petrol engines during operation. Diesel-electric hybrids still emit two times more than petrol fueled vehicles. Complete electric vehicles do not have operational emissions though and LPG fueled vehicles have lower emissions than petrol and diesel vehicles (Bellin et al., 2022). A side note has to be placed for the origin of the energy used by batteries and plug-in vehicles. While using an electric propulsion system doesn't emit nitrogen emissions on the road, the power plant will do so in case the electricity used isn't green energy (Nopmongcol et al., 2017). The emissions from the power plant are thus deposited elsewhere. Battery electric vehicles are then in between petrol and diesel vehicles in terms of total NOx emissions if the electricity is non-green. As this thesis research is focusing on roadside nitrogen emissions, electric vehicles could be a prominent part of it, while it will be addressed if there are node sources for energy production in the study area. For context; only 514,000 cars out of the 8.8 million are electric in the Netherlands at the start of 2023 (5.8%) (IenW, 2023).

Reducing emissions from trucks has been difficult, including the electrification (Klein, 2023). Production cost is too high compared to the demand, while the charging infrastructure is inadequate still. This is an international problem as HDV's travel across borders and long distances. Electrifying HDV's will reduce nitrogen emissions when diesel isn't the applicable fuel type (Dai et al., 2024; Klein, 2023). Similarly, public transport buses emit anthropogenic agents too if they aren't electrified (Wang et al., 2023). This can accumulate especially at hotspots such as railway stations or other hubs due to frequent engine cooldowns and restarts at stops, traffic lights or congestion. Although, in 2030 all Dutch public transport buses should be zero-emission according to signed agreements and in early 2020 the percentage was 15% (CROW, 2023). Also, in contrast to some beliefs, hydrogen vehicles emit as much nitrogen-oxides as gasoline vehicles upon on-road combustion (Lewis, 2021).

For the same vehicle, differences in nitrogen-oxides emissions can be up to six times greater due to driver behaviour (Hasan Shahariar et al., 2022). Driver behaviour has a correlation with the traffic flow on the road but is also a standalone subject. Novice drivers produced around 17% more nitrogen-oxides in experiments due to 'aggressive' pedal usage and driving behaviour (Huang et al., 2021). Along with a slightly higher fuel consumption for those novice drivers by handling the pedals 'harder' comes this higher emission of nitrogen-oxides. Research from Huang et al. (2021) showed that extreme variations could be found among individual drivers aside from their experience level. Aggressive pedal usage corresponds with stronger acceleration and later braking.

Influencing driving behaviour and traffic flow could thus affect the nitrogen-oxides emissions.

2.6. Theory on traffic

The focus for traffic-related nitrogen emissions is on nitrogen-oxides that are the result of combustion. Ammonia traffic emissions are hundred times smaller than traffic nitrogen-oxides in the Netherlands (MOVE Mobility, 2020; Stelwagen and Ligterink, 2015). The traffic-related emissions of ammonia in the Netherlands are expected to grow slightly until 2030 and the amount of nitrogen-oxides is expected to halve till that year (Felix et al., 2023). The source distribution in Figure 2.3 can heavily vary per region or country, depending on the intensity of activities taking place. For example, in the Chinese province of Henan traffic accounts for only 1% of ammonia emissions while fertilizer application and livestock account for 85% combined (Wang et al., 2018). The ammonia emissions have been trending upwards in the last decade for this region though. For the largest cities in Henan, traffic ammonia could be as high as 6%. The values are comparable to the Dutch situation where 90% of all ammonia emissions is stemming from agriculture and 0.5% from traffic (CBS, 2023). Ammonia is mostly the agricultural department while nitrogen-oxides are related to vehicles. The numbers show that very urban regions could have significant ammonia concentrations as well, but on average it is worth to focus more on nitrogen-oxides. The percentage of annual nitrogen-oxides originating from traffic in the Netherlands is 34%, which is the most of any sector emitting nitrogen-oxides (CBS, 2023). This share is relatively known already since the component is ejected into the air through combustion processes, which is the case in vehicles.

In Canada it was found that nitrogen-oxides from vehicles increased with the amount of traffic and varies for seasons within a calendar year (Donovan et al., 2022). The research indicated that reconsideration is needed for traffic and parking close or inside ecological areas to conserve them, as arriving visitors propose location specific nitrogen deposition issues. A call for better management plans has been made by the researchers. The traffic/mobility share is subject in this research, whereas other shares such as agriculture and nitrogen from abroad will not be reviewed further in this research (RIVM, 2023). Transport of urban nitrogen is a considerable source to adjacent ecosystems and an interesting point for the Netherlands where urban and natural environments alternate. Even though the share of traffic for ammonia emissions in the Netherlands is negligible it should be taken into account that traffic emissions travel to natural areas and are more noticeable in regions with less agricultural activities (PBL, 020b). It has to be said that, since the subject is exceedance of critical values for habitats and species, this share of mobility matters as much as the others. This confirms the need for solutions in the field of mobility to reduce nitrogen deposition beneath the critical values. It is worth noting in advance that this research will focus solely on passenger transport and does not address measures for cargo transport. The tools that will be used do not fit dynamic traffic assignment for trucks, but they are present on the transport network.

There is a positive linear relationship present between traffic volume and pollution concentrations (Zhou et al., 2014). Higher volumes and intensities also correlate with the road capacity. Larger roads and throughput, which is the case on highways for example, see the most emissions per kilometer as there are simply more vehicles on a stretch of road. A note on road capacity has been made by the research of Mangones et al. (2020). Extra traffic demand eliminates the emission savings from capacity increasement. Road projects could lead to more emissions from vehicles if it is not combined with managing private vehicle trips. Increasing road capacity to tackle congestion is thus not advisable if not combined with other ideas. There is also the option to influence the modal split of travelling though policies. This transition is called modal shift and can be reached through varying measures, such as a greater focus on public transit or cycling (Croci et al., 2017). This modal shift has effects on traffic volume for example (Figure 2.7). A tactical dimension for traffic management measures involving routing, closures and restrictions (Lu et al., 2018).

There are differences in the emissions of cars and trucks, often abbreviated to LGV and HDV. Light gasoline vehicles emit more ammonia than nitrogen-oxides in urban environments, while heavy-duty diesel vehicles emit a lot of nitrogen-oxides compared to ammonia under all traffic conditions (Dai et al., 2024; Abdull et al., 2020). Restricting certain fuel types or vehicles, such as heavy duty trucks, impacts the emissions on the intended routes. Alternatively, closing certain roads or adding new ones is also part of the tactical routing subject. The distinction between through-traffic and destination-traffic is also to note. This can be made for cars, light or heavy trucks for example, where a vehicle type is only allowed if its destination is on the specific road and not just part of a route with other routing possibilities. An extra note on this is that cars are more sensitive to route adjustments than trucks, who tend to stay on larger or main routes and not adjust their route dynamically, partly out of a cost-sensitivity point of view (Tillema et al., 2018).

2.7. Conceptual model

To identify the explaining factors of nitrogen emissions from traffic, the following conceptual model in Figure 2.7 is presented. With the help of this figure, it becomes more clear which factors are being adjusted by each local mobility measure. The question to ask when following this conceptual model is 'what measures could lead to a lower nitrogen deposition?'. The conceptual model has been set up with the presented literature in this chapter. An important approach to keep in mind is the 4-step modelling approach of transportation/land-use models and in which step the adjustments are taken for the implementation of mobility measures and Conceptual Model (Rodrigue, 2020; van Wee et al., 2023). The 4-step framework is visualized in Figure 2.6. Trip Generation is the production and attraction of zones and how many trips depart and arrive in which one. Trip Distribution entails the departing trips for each zone and the arriving trips for each zone and is commonly referred to as the flow matrix in which constraints such as distance can be identified. The Modal Split step is the disintegration of the trips into their respective transport modes. The Assignment stage is the loading of all previous steps onto the transport network. Considerations in the assignment are for example to minimize travel time and fitting into the public transit schedules. If the traffic intensity is larger than the capacity, congestion will occur and through the feedback loop, generation and distribution are initiated again. For this process there are differences in static and dynamic modelling and the timing in which decisions are updated (Rodrigue, 2020; van Wee et al., 2023). Most of the effects of mobility measures are put through the two final steps of Modal Split and Assignment such as a shift to another transport mode or changes in routes taken. Some other measures are applying to Trip Generation such as teleworking decreasing the production of trips.

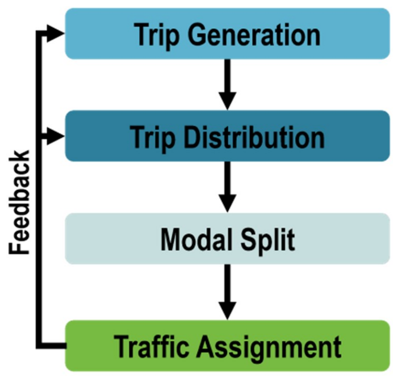

Figure 2.6: The 4-step modelling approach (Rodrigue, 2020)

The following list contains a brief explanation of the blocks in Figure 2.7 as well as a couple other important distinctions.

- **Policies**: This refers to the various regulations, laws, and guidelines that can be implemented. These can directly influence the modal split of trips made as well as demand and trip generation. (Long term) policies are also applicable to the aspects of fuel type and vehicle engineering. Similarly, policies in other sectors such as public transport or aviation can lead to a modal shift and adjustments in O-D generation and thus also increase the road traffic volume and so on. Broader policies could have an effect on traffic management measures, hence the correlating arrow in the conceptual model.
- **Traffic management**: Direct, operational measures to lower nitrogen emissions as well as tactical traffic management affecting allowed fuel- and vehicle types. In contrast to the policies, these measures can be generally be found on roadside signs for example.
- **Modal split**: This block is the distribution of travel demand over the different modes of transportation such as cars, public transit and cycling. Modal split is influenced by other factors: travel time, travel cost, convenience and availability for example.
- **Future demand**: The projected growth in travel is affected by factors like population growth, economic development, changes in land-use, timetables and infrastructure availability.
- **O-D (generation)**: One of the steps from the original 4-step approach (Rodrigue, 2020). Travel demand between origin and destination. O-D generation can be influenced in the same way as future demand. Various factors are applicable: population distribution, locations for work and land-use characteristics.
- **Volume**: The amount of vehicles on a road section. Has an effect on the 'actual' traffic flow in correlation with road capacity and driver behaviour. (Reducing) traffic volume can be achieved on a policy level.
- **Routes**: Similar to the last step in the 4-step approach of assigning traffic over the infrastructure network. Traffic management measures directly influence route choice and options on a tactical level. This block includes closure and adding of roads but is mostly about the routing step of vehicles.
- **Vehicle engineering**: Block concerning the design and engineering of vehicles to reduce nitrogen emissions. Vehicle engineering measures includes engine modifications, technological improvements and especially emission standards (Smithers et al., 2016).
- **Flow**: The 'actual' traffic flow on a road or road section. Has a high correlation with speed and driver behaviour. Flow relates to accelerating and decelerating due to crowdedness or road features (Chen et al., 2022; Dai et al., 2024; Abdull et al., 2020).
- **Driver behaviour**: Actions and decisions made by drivers while operating vehicles like aggressive pedal behaviour. Driver behaviour is related to operational traffic management measures but also has a two-way relationship with the traffic flow.
- **Through- and destination-traffic**: The distinction between traffic that has a destination at the specific road or the traffic that uses the road as part of their route towards another location. In terms of mobility measures, through-

traffic can be excluded if it has unwanted environmental effects and other routes are possible. This could also be detailed further, such as banning agricultural traffic or (heavy duty) trucks for example. Hence why this block has a connection with the traffic composition.

- **Speed**: (Average) travelling speed for vehicles on a road or section, for which different emission factors are accounted for depending on fuel type (Zachariadis, 2008; Smithers et al., 2016).
- **Fuel type**: The different propulsion systems possible for vehicles. Gasoline/petrol, diesel, electric, LPG, hydrogen or hybrid forms. This can be influenced by policies but also touches on the tactical level of traffic management, where certain types of fuel can be excluded on a road or in a zone. Such ecological zones already exist and become more frequent (Kouwenhoven, 2023; Huang et al., 2022).
- **Traffic composition**: The share of cargo traffic on the road and the distinction between light and heavy trucks in this collection of vehicles. There is a correlation between the fuel type of vehicles and a one with the block 'through- and destination-traffic'. In the MOVE Meter tool, emission factors for cargo traffic are based on a distribution of one third medium-heavy vehicles and two thirds heavy duty (MOVE Mobility, 2020).
- **Emission factors**: From a modelling point of view, this is the last step where other factors lead out to, before the effects of traffic are calculated. Often abbreviated to EF and the values in (kilo)grams for compounds (Dai et al., 2024; Abdull et al., 2020).
- **Local geography**: The external influence of local characteristics on nitrogen emissions. This includes roads with uphill gradients for example, which affects the applied emission factors (Sarkan et al., 2022). Local characteristics are subject to differing meteorologic conditions too (Kryza et al., 2011).
- **Emissions**: (Harmful) gasses and compounds that are expulsed from vehicle exhausts into the atmosphere. The focus in this research is on the nitrogen emissions and mainly the nitrogen-oxides (NO_x). Other emission from vehicles include particulate matter (PM_x) and carbon-dioxide (CO_2).
- **Meteorological conditions**: (External) factors that influence the dispersion and intensities of the emission to stipulate how much deposition happens at a specific place. These conditions have been mentioned earlier in this chapter and include wind, temperature and deposition height for example (Kryza et al., 2011; Fenn et al., 2018).
- **Nitrogen deposition**: The combination of nitrogen-oxides and ammonia, with resulting issues such as eutrophication mentioned earlier in section 2.2. Can be divided into dry and wet deposition and the settling from airborne nitrogen emission is called deposition (PBL, 020b).

Figure 2.7 shows the buttons that can be pressed to change the emissions in four quarters. Vertically there is a national and local level shown. This is the level of policies and traffic management, and where they mostly take place. Some of the blocks in the scheme belong to a regional level in between as well. Horizontally there is a division between vehicle related blocks and traffic related blocks, as was the distinction in the literature of chapter 2. The blocks, or buttons so to say, are changeable depending on the measure that

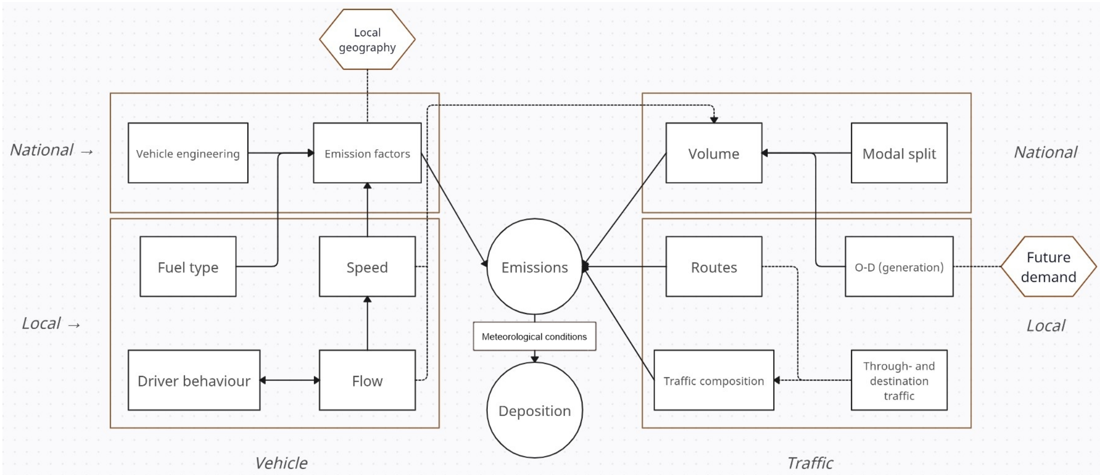

Figure 2.7: Conceptual Model divided in policy & management level as well as vehicle or traffic related blocks

is put in. A certain traffic management type of measure as input will affect the driver behaviour block for example, while adjustments in fuel type could be the result of implementing an environmental zone. Where measures are the input of the Conceptual Model, nitrogen emissions and deposition as its derivative through meteorological conditions are the output of it. The relationship between a block and a measure is also shown in Table 3.1. The Conceptual Model shows how a measure theoretically leads to a change in nitrogen deposition and which other blocks are affected. Volume and modal split are part of a national layer because affecting them on a very local level is just a drop in a whole bucket of vehicle movements over many more zones. Similarly, policies for vehicle engineering and emission factors are mostly enforced on a national level while there can be policies on a local level for fuel types, speed and driver behaviour.

3

Methods

The methodological steps taken in this research are explained in this chapter. The following items describe briefly what will be discussed in the next few sections or has been done previously in the build up towards the analysis in chapter 4 of this case-study research. The second and fourth research questions will be answered with the help of this chapter.

- Firstly, section 3.1 builds upon the Conceptual Model and introduces the **conceptualised measures** and briefly explains how they were drawn up. More details of the conceptualization can be found in Appendix A. The Conceptual Model and measures stem form the theory presented in chapter 2 beforehand.
- Secondly, choosing the tools for the analysis and appropriate datasets. This includes an explanation on differences between **models, tools and data**. This paragraph addresses what the MOVE Meter is and why this tool is used. There is also a short explanation on the projection years in the data and modelling.
- Third, delineating the interaction between mobility measures and the MOVE Meter tool in the analysis. The topic is the **scope of mobility measures** for this research as well as the **spatial level**. It is connected to theory in chapter 2 and the Conceptual Model on nitrogen emissions.
- Fourth, the **study areas** are chosen and explained in detail, including their natural values and nearby transport networks. This occurs in section 3.4. The next paragraph of this chapter on methods also includes the study area demarcation in the MOVE Meter tool, with a short analysis on the traffic flows.
- Fifth, the type of analysis on the **cost of measures** is introduced in section 3.6, which includes the constraints and inclusions of the costs. The analysis on the cost-effectiveness takes place in section 4.3.

- Lastly, the mobility measures are **computed and analysed** and the results are shown for each measure individually and with an overview with reductions in moles and percentages. This all occurs in chapter 4. The discussion and conclusion of the results follows thereafter.

3.1. Measures and solutions

This section spotlights the conceptualization of measures before the analysis starts in chapter 4. Measures were conceptualised through previous research and brainstorming. The measures have been selected based on their feasibility in real life and their feasibility to be modelled using the available tools and data.

Each mobility measure is translated into a set of model parameters. The measures are a composite of 'best guess' and 'optimistic' values. Such values represent the traffic modelling effects, for example the percentage modal shift of a measure on traffic volume. The values are prominently based on those from previous research and key figures from the 'rule of thumb handbook' by MuConsult (2021). In instances where exact values are unknown or applied differently, more optimistic estimates have been adopted for conceptualising the measures. The model parameters and their use are clarified further in section 3.2.

There are a couple fields to look at in order to define 'measures' and 'solutions' which are the same subject in this research: options found in the field of traffic management and policies to alter effects of mobility and traffic. Traffic management entails influencing supply and demand such that the traffic demand and the capacity supply of the transport network match better, both in time as well as in space (NM-Magazine, 2011). It is often also referred to as 'better utilisation' of existing space and infrastructure. Reducing inflow, improving outflow and correctly dividing traffic over the complete transport network are part of traffic management. Keeping travellers informed is also part of traffic management. Transport policies can be referred to mobility-management as well and is cooperative between governments and employers, such as teleworking and avoiding peak-hours, but also applies to the mobility transition in general like 'reduce, rethink and reshape' (NM-Magazine, 2011; MuConsult, 023b). This strategic level consists of influencing the modal split, vehicle technology and trip generation. As the nitrogen deposition from traffic near Natura2000 is a location-specific problem, location-specific measures in these management fields are a point of interest, such as specific municipal roads. Nearby roads with higher traffic density, lower traffic flow and more accelerating/decelerating call for managing solutions to reduce emissions (Abdull et al., 2020; Huang et al., 2022).

An important source of information on existing types of measures is a rule-of-thumb-book by MuConsult (MuConsult, 2021). The data comes from multiple projects and experiences on behaviour and effects. This experience has been converted into key figures from the monitoring & evaluation projects. Of course, this includes some estimation due to differences in situations and area sizes. It is still a rule-of-thumb-book to estimate the effects of measures and not hard figures. It consists of numerous sources related to monitoring and evaluation in different Dutch regions. The operationalisation in Table 3.2 consists more of known computation numbers based on previous research than the measures in Table 3.3. This second table includes more unknown measures and their effects on traffic as well as self-designed measures with even more estimations. The measure of a mandatory work-from-home day is an extraordinary option for example. In theory it could lead to around 20% decrease in trip generation each morning commute if employers were forced to introduce a mandatory day in a workweek of five days. These rigorous measures have been chosen to construct a comparison with larger changes in traffic volume and to see if there is somewhat of a linear effect between smaller and larger measures. The two self-conceived measures are also implemented as a national policy type and are thus in contrast with local measures. A more thorough operationalization of the mobility measures can be found in Appendix A. This includes more details on which group of travellers has to do what outside of the task-setting measure description.

There are also reports and articles that identify existing mobility measures and developments. PBL (2021) states that there is little to no knowledge about the need and effects of local remediation measures for nature. Existing analyses hold a broader scope and entail a national level, which can draw conclusions for averages and not details for specific locations. This problem has been boosted by a lack of (digital) information and modelled data. A report from LNV (2022) covering the design programme for nitrogen deposition reduction includes only a few existing measures for each sector with emissions. These measures are aimed at a national level and included in new laws. An important note for existing measures and policies is that an 'autonomous reduction' has been identified based on these. In the report of LNV (2022) for example, a run-through of the data has been added, indicating an autonomous reduction in the mobility and traffic sector from 2018 to 2030 of 25% towards 127 mole/ha/year. This is thus a reduction based on established and intended policies. Funnily enough, recent reports speak about an expected reduction in nitrogen deposition from traffic 'due to mobility measures domestically and abroad' without mentioning any of the intended possible solutions (Marra et al., 2022). Moreover, examples of autonomous reduction in nitrogen deposition the coming years are the honing of vehicle standards and the sales of electric vehicles according to the climate agreement. The collection of existing measures for mobility is rather disappointing however. One of the four mentioned measures in LNV (2022) apply to roadside traffic and the others to inland waterways and airports. The measure for road traffic is targeted enforcement of faulty and tampered AdBlue systems in trucks (LNV, 2022).

Electrifying personal- and distribution vehicles is already part of ongoing measures to reduce emissions (Tran and Brand, 2021). Additionally, research shows that a lot can be gained from ICT interventions. An example is improving real-time journey information to improve traffic flow. This hasn't been proved on a large scale though and could adversely lead to more traffic demand. More traffic management measures have been researched or are still under investigation. Intelligent traffic light signalling, iVRI in Dutch, and road pricing schemes are options in this genre. Such measures could influence mode choice, traffic flow and driving behaviour of citizens (Tran and Brand, 2021). A road pricing scheme that's been investigated for decades in the Netherlands has been cancelled for now and it was to be implemented in 2030. It involves paying for usage instead of owning the vehicles (Rijksoverheid, 2023b). Similar to the electrification of the vehicle fleet, existing measures include eco-zones in cities. These eco-zones or emission-free zones could also be implemented outside cities to protect nature. Previous research did point out that more groups other than non-local diesel vans should be subject to this policy measure and that local traffic emissions play an important role (Huang et al., 2022). Huang et al. (2022) also found that the highest emission reduction potential was located at intersections and connector roads for the traffic calming measure. The town of Milsbeek in the municipality of Gennep faces this problem for example. Trucks affiliated to a nearby sand extraction location not only cause safety issues locally, but also emit nitrogen-oxides and traffic calming measures are not in place on a connecting road (Gemeente-Gennep, 2022).

More measures are drawn up with the help of the presented literature in chapter 2. The theory on vehicles is the basis for the blocks in the Conceptual Model about speed and emission factors for example. These relate to measures that approach the reduction of nitrogen emissions through road downgrading, driving behaviour and eco-zones. Similarly, theory by Mangones et al. (2020) aided in the finetuning of bypass measures and the counter-effective settings of adding capacity. Zhou et al. (2014) and Croci et al. (2017) give a push in the direction of focusing on lowering traffic volumes through mobility measures with modal shift, while research from Donovan et al. (2022) calls for parking regulations as a mobility measure. A modal shift means they exchange of one transport mode for another, such as picking the bicycle instead of the car for a ride to work.

Table 3.1 illustrates each measure accompanied by the governance level it is related to and to which block or blocks in Figure 2.7 it has the strongest relationship with. In chapter 4 each measure will be analysed in it's own paragraph and after that an overview of the results will be given. A more thorough explanation of the mobility measure will be given there alongside an indication of the cost. The governance level shown in Table 3.1 can be one of three levels: Operational, tactical or strategic. There can always be some overlap though, so the main level is shown. Some of these levels are also mentioned in section 2.7. These governance levels aided in the brainstorm to identify possible mobility measures and the first concepts of the Conceptual Model. These levels helped in the process of narrowing down the search field. These levels could help policymakers in their decision alongside the cost-effectiveness though. The strategic governance level implies focus on the long term and a broader regional application, with more focus on (national) policies. This is the 'highest' level. Operational governance is the lowest and more focused on executive tasks and on-road measures. It has the most 'local' application out of the three levels in terms of mobility measures and is often translated into traffic management. The tactical governance level is an in-between. A combination between roadside measures and policies, such as routing solutions for example. These levels are not shown in Figure 2.7, where the four sectors instead show the level of policy-making and the distinction between traffic and vehicle aspects. The governance levels are somewhat related to this: strategic can be found in all four sectors and the tactical level at the bottom right as a combination between non-roadside and local governance. The operational level exists in the bottom left, signaling a local and short term focus.

Table 3.2 and Table 3.3 show a brief description of the measure by defining the operationalisation for entry into the MOVE Meter tool. The operationalisation of the measures has to check in on the factors of the Conceptual Model. The description illustrates what kind of change will be done in the tool with relation to the network or trip generation. More specific scoping and delimitation of the measures can be found in Appendix A, including selected zones, target groups, distances and absolute amounts of reduction. The tables in this section do not illustrate the specific zones for the measure, but it is convenient to keep in mind that most measure only apply to a selection of all zones. The operationalisation shows deterministic changes to the scenarios and it is

Table 3.1: List of mobility measures

Measure	Level	Block in CM
Intelligent traffic light systems (iVRI)	Operational	Flow
Road downgrading	Operational	Speed
Driving behaviour campaign	Operational	Driver behaviour
No-entry zones passenger vehicles	Tactical	Routes
Bypasses	Tactical	Routes
Electrification passenger vehicles	Strategic	Fuel type
Carpooling	Strategic	Volume
Flexible office times (peak-hour avoidance)	Strategic	Volume
Stricter emission standards ecological zones	Strategic	Vehicle engineering
Park & ride, hubs and shared mobility	Strategic	Modal split
Cycling incentives for modal shift	Strategic	Modal split
PT incentives for modal shift	Strategic	Modal split
Parking regulations in/for Natura2000	Strategic	Modal split
New bicycle through-routes	Strategic	Modal split
Mandatory cycling on short distances	Strategic	Modal split
Teleworking	Strategic	O-D (generation)
Mandatory work-from-home	Strategic	O-D (generation)

the same operationalisation to compare between study areas. Tailor-made measure values for each differing context are not only unachievable with the MOVE Meter tool because of the task-setting nature, it also keeps some of the variables constant in order to research different outcomes. Simultaneously, local context has been added to the measure with a short analysis of the zones and network, leading to variations in the specific zones or roads used in the MOVE Meter mobility measure. The limitations of the tool for the implementations and how the measures could better fit local context follows in chapter 5. The scoping of this paper is still on local measures and effects with the use of average values and figures to set up the implementation in the tool. More on this topic follows in section 3.3, as the focus is on local roads and effects of mobility measures on these roads, while the scoping is thus not to differentiate the implementation for each and every local context.

Table 3.2: Operationalisation of previously estimated mobility measures

Measure	Operationalisation
Intelligent traffic light systems (iVRI)	Adjustment in free flow and peak hour travel speed for road sections by 5%
Road downgrading	Downgrade 100 km/h and 80 km/h roads to the optimal emission speed (60 km/h) in and within 10 kilometers of the N2000
Driving behaviour campaign	Improved traffic flow on roads in the study area by 40% as more efficient driving
No-entry zones passenger vehicles	Capacity and travel speed of specified roads at 0 to obtain no vehicles in the model
Bypasses	Addition of one or more new roads to relieve roads in or near N2000 from traffic accompanied by a 10% local demand increase
Carpooling	Reduction in traffic volume of the commute by 12.5% from car-sharing promotion
Flexible office times (peak-hour avoidance)	10% decrease in car trips during peak-hours
Stricter emission standards ecological zones	A 2% decrease in vehicle intensity at specific roads in or near the N2000 area along with a 10% reduction in speed and capacity
Cycling incentives for modal shift	8% of trips between 5 and 15 kilometers with a modal shift towards cycling in the study area
PT incentives for modal shift	A modal shift of 6% from passenger vehicles to public transit
Parking regulations in/for Natura2000	Decrease amount of car trips by 15% for destinations at or within N2000 through modal shift
New bicycle through-routes	Addition of one or more new bicycle paths along with a 14% modal shift from car to bicycle
Teleworking	10% decrease in traffic generation during peak hours from work-at-home incentives

Table 3.3: Self-identified and best-guess mobility measures

Measure	Operationalisation
Electrification passenger vehicles	8% less vehicle demand to simulate an extra 10% increase in electric cars
Park & ride, hubs and shared mobility	A value of 3 and 5 less cars in the trip generation at all zones in the study area, especially shorter distances
Mandatory cycling on short distances	50% modal shift to cycling for trips under 10 kilometer in all Dutch zones
Mandatory work-from-home day	20% decrease in traffic generation from spread-out mandatory WFH-day in all Dutch zones

3.2. Models, tools and data

Analysing the list of mobility measures will be done using an external tool called MOVE Meter. In this tool it is possible to measure the before and after effects on the emissions and nitrogen deposition (delta). It is important to formulate the measures clearly in order to implement it into the tool, which has a task-setting nature for the measures. Usage of the tool will lead to tables and figures and thus help to present the results of varying mobility solutions quantitatively and spatially.

The MOVE Meter is an existing tool that incorporates data from traffic models focusing on vehicles, PT and cycling (MOVE Mobility, 2020). Utilization of modalities as output will lead to changes in emissions, which can be calculated upon further. For every subgroup of travellers, the most optimal roundtrip or trip-chain is found using travel time, cost and discomfort. Numbers on the hexagons and nitrogen deposition can be retrieved through a couple of steps which are also illustrated in Figure 3.1, where it should be noted that the output of modality usage concurs with the 'effects on choices and trips'. Additional features to calculate modal split include the public transport network and timetables, bicycle network and separate links for transfers. Subgroup characteristics have been added through earlier research in the Netherlands (CE Delft and MOVE Mobility, 2019). The tool considers attributes in the choices for transport modes. In principle, the imported O-D matrices, and thus the transport demand in the model and scenarios, remain constant. However, the measures may adjust the transport demand in a task-setting manner. Importantly, the emission model integrated in the tool and used for nitrogen deposition is AERIUS. Emission factors used in the tool are retrieved from the ministry who updates these figures in cooperation with PBL and TNO every couple of years (MOVE Mobility, 2020; Geilenkirchen et al., 2023). The emission factors used in the MOVE Meter tool are figures for 2025. In the tool the settings are also set to 2025. The use of future years for these emission factors is not appealing because the factors show a strong consistent decrease in emissions and there is a concern of overestimation. The breakdown to speed classes and road types is similar to the emission factor reports and international literature, also shown in Table 3.4 (Geilenkirchen et al., 2023). Emission factors refer to average values per kilometer driven for an average traffic situation of the specified type of road section. Possible combinations for the emission factors consist of vehicle category, road type and speed regime. The use of average values fits the task-setting nature of the tool and its simplified usage for the implementation of measures. A similar and alternative tool is the MobilityScan, owned by the Dutch Ministry of Infrastructure and Water Management. It uses the same modelling principles and options for traffic data input. It is also possible to compare base and measure scenarios in this online tool. One difference is that this MobilityScan can only visualize the emissions and not the nitrogen deposition as there is no relation with the AERIUS calculation tool (I&W, 2023).

The AERIUS calculation tool is also the one being used in the beforementioned PAS policy in the Netherlands. Other calculations can be made using key figures and reduction in traffic intensities as is a common practice in emission research (Brouwer et al., 2014). Another aspect of the MOVE Meter tool is the friendly visualizations and delineation of the study area. Within this area in the model, results will be more specific while the outer areas see less calculation and faster processing times due to zones being aggregated. A reference scenario is made on which the different measure scenarios are applied to, followed by the resulting effects compared to the reference scenario (MOVE Mobility, 2020). Different to other traffic modelling programs, MOVE Meter does not use the general gravity model for all of the trips as is common for the 4-step modelling approach (MOVE Mobility, 2020; Rodrigue, 2020; van Wee et al., 2023). Trips non-affected by measures are still distributed by the imported origin-destination matrix, while the researcher can choose how new trips are distributed. Different distribution options are possible under the name of Spatial Development measure. MOVE Meter can use the data for 4-step models however, as assignment results of the traditional model can be imported as the baseline scenario, such as the NRM network. MOVE Meter then calculates a new assignment step for the situation post-implementation. An important note to this is that the tool does not calculate the new assignment for cargo trucks and that measures regarding freight traffic have to be manually distributed over the road network with proper reasoning.

Additionally, some of the results and highlights of this research are presented in mole N/ha/y and Natura2000 areas consist of many hectares, presented as hexagons. To arrive at an average value for the nitrogen deposition reduction caused by a mobility measure, a workaround is necessary. The output in the MOVE Meter from the AERIUS calculations is an old and a new value for each and every hexagon in the N2000 area, in the mole N/ha/y unit. All of these values will be put in an Excel file, whereafter the differences between the base- and measure scenario and the corresponding average value for the whole study area will be calculated. The tool only plots hexagons for Natura2000 coverage, in line with the process of the AERIUS tool.

Measures can also be applied to different distance-classes, which is implemented into the MOVE Meter tool. In case of a modal shift, the percentage change can be set for 0-3 kilometer, 3-7, 7-10, 10-15, 15-30, 30-60 and even longer O-D distances to simulate travel purposes appropriately. Similarly, analysis tools are also split into time slots of 10 minutes for travel times. The operationalisation of the mobility measures in section 3.1 is also using these distance classes. Measures will be analysed as standalone solutions and not in 'packages'. Analysing packages of measures has the danger of overlapping effects and not being able to point out which measure has which effect in the scenario (NM-Magazine, 2011). Contextual comparisons between the two study areas and their differing geographical distinctions will also be included in the analysis. More model parameters can be adjusted for the measures in the MOVE Meter tool besides trip generation for each zone and within that zone there are thus these multiple distance classes. The trip generation option also helms the option to make it a modal shift towards a different transport mode. Other changeable parameters are speed and capacity of vehicle road sections and bicycle paths. There is also the option to add in new roads and bicycle paths with specified speed and capacity. Lastly, new zones with residents and jobs could be added, but this is not relevant for any of the mobility measures in this research.

This research inspects the direct effects of mobility measures and not the indirect or seepage effects. Indirect effects occur as a result of the direct effects. An adjustment in route taken by one traveller indirectly affects all other road users. Indirect effects of measures, such as increased traffic volumes or impacted flow, need an extra step in the analysis for each measure. The choice to only analyse direct effects matches the choice to look into standalone measures and not packages. Comparatively, it is important to avoid double counting. For instance, traffic cannot both be enticed to use bicycles and be diverted via diversion routes at the same time. This sounds logical, but in the calculation of effects of each measure, the target group, the percentage of travellers on which a measure acts and, if necessary, whose behavioural response is expected, has to be identified.

The significance of evaluating the economic effects of mobility measures has been underpinned and is common practice in the Netherlands (Wortelboer van Donselaar, P., 2018). The province of Gelderland has also previously stated in documents and frameworks that their focus is on measures with the best cost-efficiency (Drenth, 2022). One of the quick-scan methods to visualize differences in the measures is a cost-effectiveness analysis. This could give more insights into the feasibility of certain measures and solutions for the budget and it also informs about less effective measures for the reduction of the nitrogen deposition (MuConsult, 023a). This CEA (in Dutch a KEA) usually results in factors between cost and effectiveness for the target. With the bandwidth, complexity and variance in each situation, the measures will be divided in four quadrants for this research instead. Alternatively, improved health and air quality should be considered in a cost-benefit analysis for example and evaluation of financial consequences, but can be more difficult to monetize and take up a lot more time and research (Tran and Brand, 2021). Effectiveness of a measure is given in the reduction of mole nitrogen per hectare per year. Only the implementation costs are taken into account and thus there is no need to distinguish short- and long term effects. This would have been the case when the vehicle-loss-hours and maintenance costs were taken into account. More substantiation is noted down later in section 3.6.

This difficulty in monetizing applies to mobility measures themselves as well. Some measures can be verified values based on prior research for example, while others can only be estimated. It is necessary to properly determine the target population of the measure in question for a proper CEA (MuConsult, 023a). Monetizing the measures can lead to too much investigation into the details. Hence why, for the consideration of the most cost-effective mobility measures a figure with four quadrants with the costs and effectiveness will be presented. A table with the costs ranked by CE-score could be envisioned, but still requires relatively exact estimations of the cost for each measure, while bandwidths are more appropriate. Mobility measures that are not verified well enough are left out of this figure to avoid conclusions about them. The cost-effectiveness analysis will be a secondary recommendation or filtering as the reduction in nitrogen deposition is an absolute showing. A thought to keep in mind is that a set of measures can be more effective than a standalone solution, especially when implemented at certain hotspots (Gehrke et al., 2023).

For future predictions and especially for traffic generation, trends and uncertainties, the Netherlands utilizes 'high' and 'low' scenarios abbreviated in WLO Hoog and Laag. It translates to predictions based on the outlook of prosperity and the living environment and is compiled by two national planning agencies (CPB and PBL, 2023). WLO Hoog uses a relatively strong growth in population and high economic growth of 2% per year. WLO Laag involves a limited increase in population and a moderate economic growth of 1% per year. Studying the effects these scenarios have on generation and the physical environment, four themes are looked at: regional developments & urbanization, climate & energy, agriculture and mobility. The WLO scenarios from 2015 by the agencies are projections up until the year 2040 as of now. The higher economic- and population growth coincide with an increase in passenger- and cargo transport (CPB and PBL, 2023). For this research on nitrogen deposition, 2040 estimates will be used for the traffic models and the calculations. The goal is to work with bandwidths in values of deposition reduction. The WLO scenarios of 2030 do not consist of both 'high' and 'low' anymore. Only 2030 High is available for data reading because this projection year is creeping closer already. The high and low options are still there for 2040 and this projection year fits with a long-term strategic planning horizon that comes with large mobility- and infrastructure investments. In the most recent AERIUS platform, modelling data is not approximations and interpolations anymore as it was in previous years and versions (AERIUS, 2023). Bandwidths will be given in the analysis of mobility measures using the 2040 Low scenario as the lower end of the range and the 2040 High scenario as the upper range of deposition reduction values. chapter 5 and chapter 6 will address the different results for these two economic scenarios.

Similarly, traffic modelling is available in the morning or evening commute as well as 24h figures for the intensities. These are the common time options. For this research on nitrogen deposition, data from the morning commute will be used. Doubling values of the morning or the evening commute roughly results in the same numbers as arrivals and departures are balanced and comparable to 24-hour data. However, analysing the morning commute has a couple advantages, which have been confirmed in a publication of de Haas (2020). 80% of passenger vehicles is using the network for work-related travel in the morning commute, compared to a mere 57% in the evening. Another 14% is on the road to drop-off or pick-up other people during the morning peak hours. This high percentage in the morning peak is important because the mobility measures are mostly aimed at employers and employees.

Furthermore, for this research the traffic modelling data is used in the shape of 'NRM Oost', where NRM stands for Netherlands Regional Model and 'Oost' indicates three eastern provinces of the country as it is divided in four parts for transport models. This source model of the main road network includes national highways, (inter)regional roads and some of the largest collector roads in cities for roadside traffic and corresponding calculations. NRM is a tour-based choice model that stands further away from 'just' taking average values as the premises (Cellissen et al., 2025). The NRM models are already being used in more research regarding the effects of policy implementation and adjustment scenarios as well as long-term predictions (Rijkswaterstaat, 2020). For even more local roads, analysis is reliant on urban traffic models. Basis of the traffic- and transport model (data) is the intensities on the roads. Scale of the traffic count output is detailed and at the scale of road sections. The basis of the NRM models is ODiN, a large scale travel behaviour research in the Netherlands and a continuous survey with periodic actualisation. Factored into the projections by the NRM model are socio-economic statistics such as population and workplaces, network characteristics like capacity and speeds, origin-destination matrices and travel time matrices. These matrices are present for both passenger vehicles, freight trucks and public transit (Rijkswaterstaat, 2020). NRM Oost is thus the dataset used for the modelling with MOVE Meter. The NRM version used is RP23 and is the latest one. The dataset is calibrated and validated each year with new information, hence the numbering on the versions. Alternative traffic models are more detailed but smaller models such as other regional models they have for provinces and metropole regions. These may include more roads, but lack inter-regional modelling options and larger volumes.

There are also barriers in information on nitrogen emissions due to privacy laws, at least in the Netherlands. Companies may be mentioned by name and location in publications, but (livestock) farms are not (Heesterbeek, 2022). There is thus data with locations for the largest emitters of nitrogen-oxides and ammonia for industry and airports, but these (field) measurements are not present for agricultural activity. This correlates with the disadvantage of working with computer models and thus some uncertainties. An advantage of working with models is the option for future predictions and the large-scale database compared to field measurements only. ”It is impractical to measure everywhere on a local scale” (LNV, 2020). The instruments and consortium of the government are also aimed at national and regional scales for the overview of emissions and not at a local scale, except for the largest industrial emitters which is according to European guidelines on Emission Rights (LNV, 2020). Smaller industry, with less than 10,000 kilograms nitrogen-oxides emissions per year, is calculated via activity data and emission factors. Measurement coverage of nitrogen-oxides is similar to the countries around the Netherlands, while the Netherlands measures ammonia more intensively than these countries of Denmark, Germany and Belgium. Simultaneously, monitoring stations in Germany and Denmark measure wet deposition more frequently and these include also concentrations for multiple nitrogen components, whereas in the Netherlands the focus is more on concentrations of ammonia and nitrogen-oxides only (LNV, 2020). The LNV (2020) report also concludes that the Dutch nitrogen deposition modelling instruments are valid and adequately substantiated, but more field monitoring and satellite-data usage is advised, including particulate matter composition and other dry deposition components.

Satellite measurements are currently used for nitrogen-oxides and ammonia via concentrations in the atmospheric column. The satellite data is also used to validate modelling results (KNMI, 2022; LNV, 2020). The aerial data cannot replace models since it doesn't measure deposition directly at the ground. It can however provide valuable data for the identification of nitrogen sources and dissemination. Dutch institutions are researching additional incentives of using satellite data in the nitrogen deposition field, while they also focus on the possibility to combine models and decrease the uncertainties. Currently, the research, results and publications are executed based on a combination of computer models and field measurements (KNMI, 2022; LNV, 2020). Similarly, in other countries research and development is in progress to add on these non-model solutions, such as the mobile open-path instrument to measure road emissions by Dai et al. (2024), of which a miniature version is already in operation in Dutch measurements (LNV, 2020).

New equilibrium assignments, through dynamic traffic modelling, could benefit the research but also take more time and effort with added complexity. The tool is a static assignment with long-term projections using average values for traffic volumes based on the calculated situation. New traffic assignments help aid in mapping the new volumes on the network links and thus also the flow and routes chosen by vehicles, especially during delays (Rodrigue, 2020; van Wee et al., 2023). This would impact mobility measures on road sections and their value of nitrogen deposition reduction. This is also relevant for the subject mentioned earlier in this chapter: the values for freight traffic on a road section do not change and have to be assigned manually for a mobility measure. The foremost challenge is also the analysis of operational traffic management measures, as these require more dynamics compared to strategic and tactical solutions. More and different resources are needed to analyse mobility measures with dynamic modelling. Traffic volumes need auto-updating with consistent time intervals based on the intensity-capacity status of road sections. If a road gets crowded with delays, some travellers seek different routes. Although complete dynamic modelling would provide more accurate and detailed data for specific road sections, the MOVE Meter provides a great balance in modelling aspects for the scope of this research on nitrogen deposition reduction at Natura2000 (MOVE Mobility, 2020).

3.3. Scoping and spatial level

The scope of this research is nitrogen deposition in Dutch Natura2000 areas caused by emissions stemming from traffic on Dutch roads. More on the specific study areas follows in section 3.4. The research has a case-study method approach and the main scoping point is the delimitation to Dutch territory for both the causes and effects, as nitrogen deposition is able to cross borders through the air and water.

This research focuses on a local geographical level. Many studies on impacts of measures and activities take place on a larger, or 'zoomed out' scale. Studies on emissions for example, often focus on national and some regional roads, as traffic intensities are higher. These national roads, 'Rijkswegen', will not be subject of measures and are part of larger national and provincial policies. They will however be included in the network calculations as intensities could differ from the base scenario due to measures elsewhere. A local level and measures are aimed at regions and municipalities. By far the most kilometers of road surface are managed by the municipalities in the Netherlands (NWB, 2024). The content of this local spatial level is limited by the modelling data used in this research. The NRM data does not include all of the roads desired to be analysed, as mentioned in section 3.2 (Rijkswaterstaat, 2020). This implies that the 'localness' of the analysis will also slightly vary between study areas and municipalities. For some of the municipalities, more road data is available than others. For example, the local level of one municipality is restricted to a provincial road passing through and a narrow 5-kilometer long connector road, while another municipality has its arterial and collector roads mapped in the NRM dataset. Roads included in different spatial levels are shown in Table 3.4, which also shows possible overlap in the level of analysis.

To add on this spatial scaling, the effective range of the mobility measures will be 5 kilometers from the source point and hence when road sections are subject, measures will apply up to a 5 kilometer radius from the middle of the N2000 area, unless specified otherwise. The AERIUS Calculator uses the same principles and this distance fits the local scope of this research. Limiting the area for the measure also keeps the computation time in check. AERIUS takes into account that deposition can take place 25 kilometers from the source, but is the strongest within 5 kilometers and especially within the first 200 meters as was mentioned in chapter 2 (AERIUS, 2023). The 5 kilometer mark is also a limit up to which emissions are distinguishable from background levels and other sources.

Table 3.4: Spatial scale

Spatial scale	Types of roads	Emission factors
National	Highways, provincial roads	SRM2 motorways, SRM1 rural roads
Regional	Provincial roads, arterials	SRM1 rural roads, SRM1 urban through traffic
Local	Provincial roads, arterials, collectors, ring, local roads	SRM1 rural roads, SRM1 all urban traffics

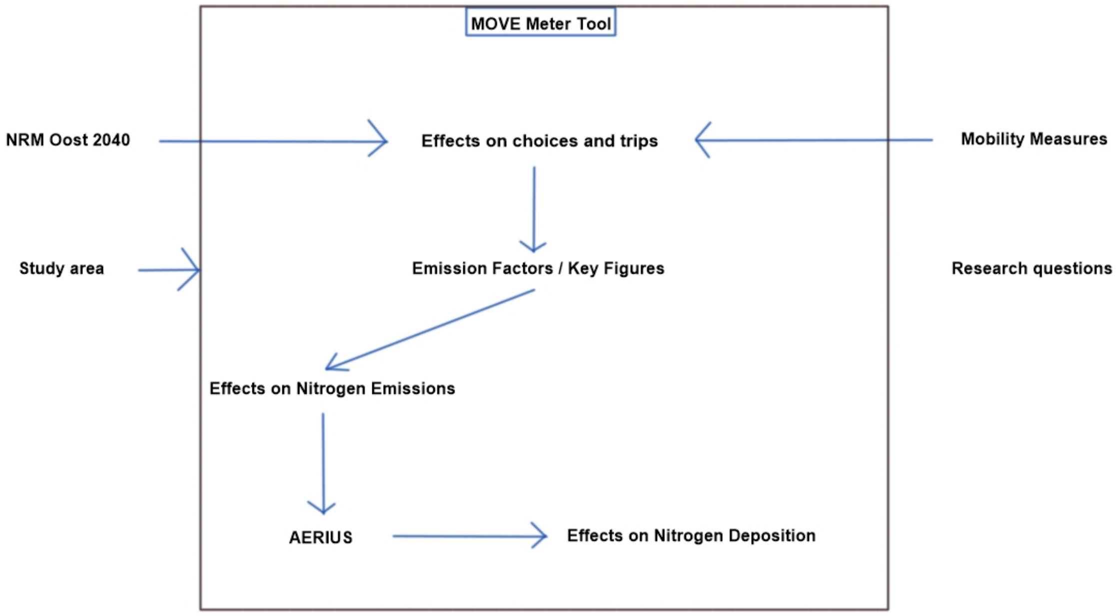

Figure 3.1: Schematic view of the modelling, data and tools. The NRM data- and choice model is put into the MOVE Meter tool along with mobility measures. AERIUS is incorporated in the tool for the calculation of nitrogen deposition.

As an additional note, this research will focus itself on passenger transport and less on roadside cargo. They will have different options for solutions and effects on the nitrogen deposition. The tool in this research does not include automatic changes for trucks, but they are present in the traffic volume. Inland shipping and waterways are not part of this research because of modelling restrictions. The (national) tools and data put much more focus on roadside emissions. Research on nitrogen deposition requires both a different approach and measures based on new data and modelling techniques. It can fully hold its own research paper.

Figure 3.1 illustrates the relation between the tools and data discussed in section 3.2. Outside of the box, along with the choice of the MOVE Meter tool, is the selection of the study areas and research questions. The NRM traffic choice model is being put into the MOVE Meter tool along with the mobility measures. The measures have been scoped to suit the task-setting nature of the tool after a brainstorm to put together a list of them. The change in traffic volume can be translated to a reduction in emissions using key figures for emissions (standards). The nitrogen emissions are then translated to deposition using the AERIUS tool using key figures. These key figures include numbers on aerosol travel and scaling local deposition. Key figures aid in the conversion to other values. Other key figures, such as the step between traffic and trips towards emissions, address the composition of the traffic in terms of fuel type, cargo and private vehicles as well as travel speed. Those values are implemented into traffic modelling and databases and updated regularly (Geilenkirchen et al. (2023)).

3.4. Study areas

This will be a case-study research on two different study areas. The selected areas are under pressure of excessive nitrogen deposition and there are opportunities to reduce this through mobility solutions. The study area contains one or two Natura2000 areas. An in-depth introduction to the study areas will be given in this section, starting off with an overview of N2000 areas in the province of Gelderland. The introduction in the section will mainly focus on the road network and natural or geographical characteristics. The relation to the MOVE Meter tool will be then presented in section 3.5.

The study areas do not have to be limited to a single province, as nitrogen deposition is able to cross provincial borders as well. It is highly possible that measured nitrogen stems from other regions or that provided mobility solutions also contribute to a reduction in deposition at other Natura2000 areas. The province of Gelderland is the starting point in the search for suitable study areas because there is plenty of data available and a significant amount of N2000 areas in differing sizes. This research will not limit itself to measures and effects within the borders of Gelderland though. Some mobility solutions will involve cross-border approaches or cooperation. All of the Natura2000 areas of Gelderland are visible in Figure 3.2. This province is partly chosen because of the generalisability to other regions based on the traffic intensities and deposition origin distribution. The province is also further in research on effects of measures for 'point sources' for example, stating their willingness to improve (Gelderland, 2024a). Because traffic outside of Gelderland impacts the N2000 areas inside the province, it is not a problem to choose study areas at the provincial borders or shared N2000 areas. Figure 3.8 indicates that the study areas are on the edge of the provincial borders and also shows regional partnerships and programmes in Gelderland.

Figure 3.3 and Table 3.5 show relevant data on Natura2000 nitrogen deposition and critical values in 2025 (Drenth, 2021). These values have been researched in 2021 and have been updated in recent new reports. KDW is the Dutch translation for Critical Deposition Value. Even though every natural area needs a helping hand, not all of them are in the same extreme need of measures like others. The figure and table underpin the choice of the two study areas. Additionally, the region and characteristics around the Natura2000 area should lend themselves for measurements of the difference in nitrogen levels with and without mobility measures. An area without any traffic in proximity makes it difficult to map the differences for example. Similarly, the traffic models and tools used should be able to show the roads and traffic intensities near the N2000 area. This also applies to the availability of bicycle and public transit networks to replace road traffic. It should be known which share of the nitrogen deposition in the Natura2000 area originates from which sector and thus what the relative improvement is on the critical nitrogen values and not only absolute improvement. Another criteria for the choice of study area is that the Natura2000 area can't be too large. The bigger the N2000 area, the more hexagons there are to calculate and the further away some of the hexagons get from roads.

Table 3.5: Current N2000 data Gelderland (AERIUS (2023), Wamelink et al. (2023))

N2000 area	Average deposition value	CDV	Average surplus of nitrogen	Area with exceeded CDV	Surface area (ha)	N-deposition from traffic
Bekendelle	25.7	15	10.7	88%	88	2.2%
Binnenveld	16.1	11	5.1	53%	111	6.9%
De Bruuk	17.1	10	7.1	92%	99	4.3%
Korenburgerveen	19.4	7	12.4	88%	459	2.5%
Landgoederen Brummen	21.9	7	14.9	81%	677	4.6%
Lingegebied & Diefdijk Zuid	23.0	16	7.0	50%	750	6.7%
Loevestein, Pompveld & Kornsche Boezem	17.0	17.5	−0.5	2%	750	5.7%
Rijntakken	17.4	17.5	−0.1	4%	23047	5.1%
Sint Jansberg	29.0	15	14.0	98%	226	4.3%
Stelkampsveld	21.5	7	14.5	88%	102	3.2%
Veluwe	23.1	10	13.1	99%	88436	6.5%
Willinks Weust	24.3	10	14.3	91%	52	2.0%
Wooldse Veen	18.3	7	11.3	100%	63	2.2%

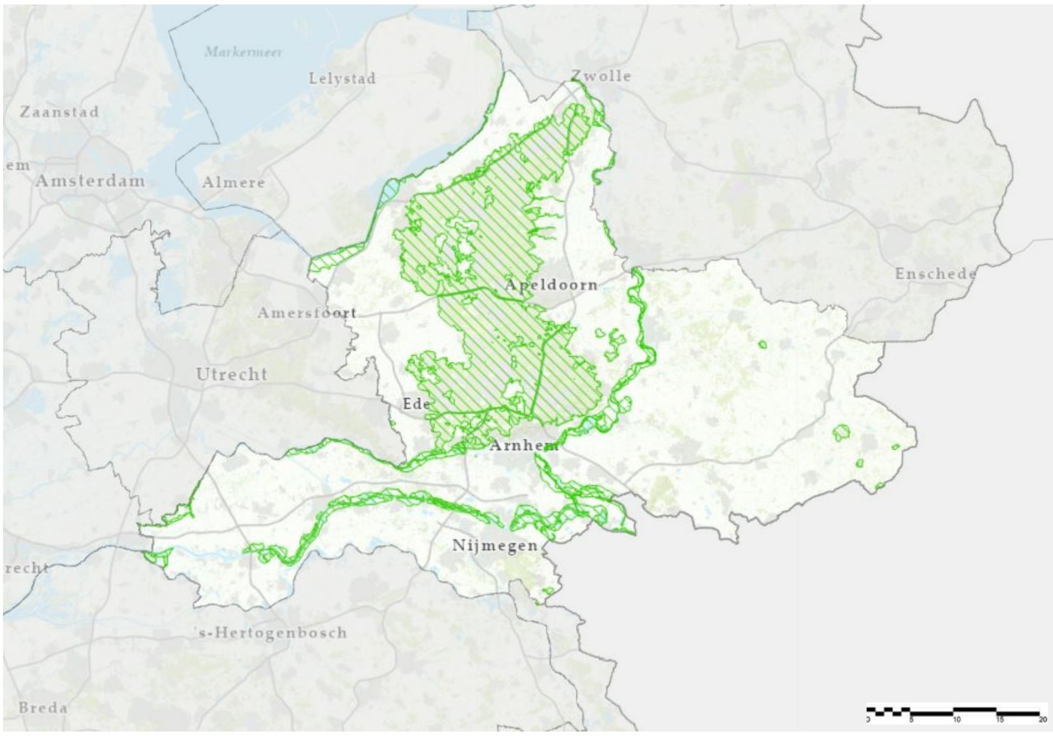

Figure 3.2: Natura2000 areas in Gelderland (Natura2000, 2023)

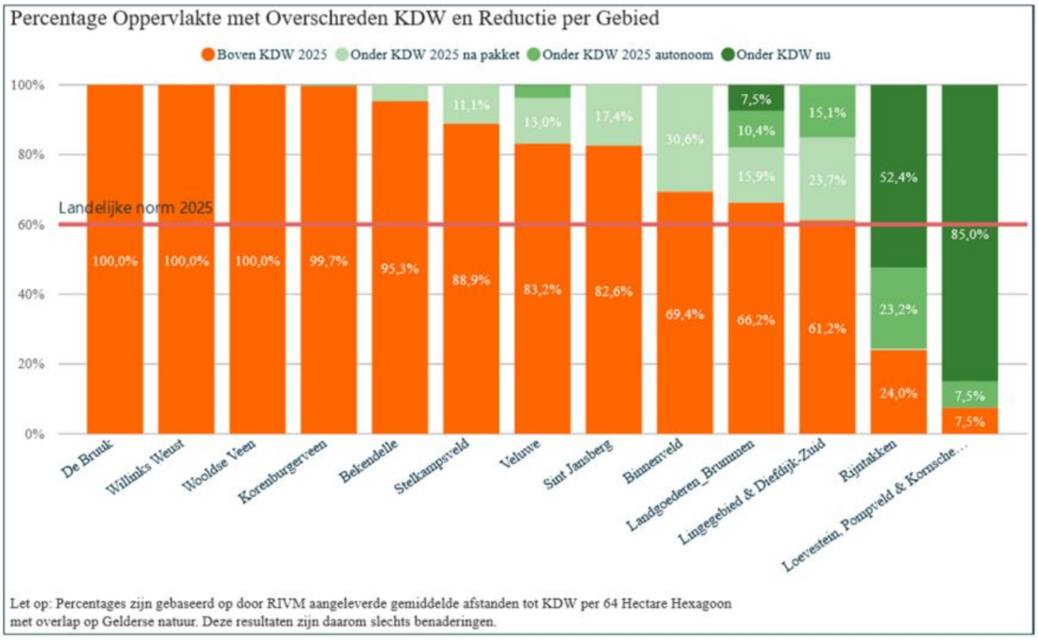

Figure 3.3: Approximated 2025 percentages of critical deposition values for Natura2000 in Gelderland (Drenth, 2021)

Figure 3.3 corresponds to the numbers found in Table 3.5 which are a composite of 2023 data and 2025 prognosis. Measurements are from the AERIUS Monitor, updated in October 2023 and January 2025. The Critical Deposition Values are from a 2023 revised report (AERIUS, 2023; Wamelink et al., 2023; van Dobben and van Hinsberg, 2008). The same researchers from 2008 have investigated nitrogen at Natura2000 later and have compiled an updated list in 2023, indicating that these Critical Deposition Values are still relevant with some tweaks (Wamelink et al., 2023). Values for nitrogen are denoted in the table with the units of kg/ha/yr which is kilograms per hectare per year. The average deposition value is the average found over all modelled hexagons of the area, which is the dimension of the measured area in AERIUS. However, the deposition value of a hexagon can be twice the average of the complete area for example depending on the distance from sources (Backes, 2023). An extra note has to be provided on the units of these average and CDV, as modelling and AERIUS provide the deposition in mole/ha/y. Slightly more information will be given in section 4.2 on this topic. The third column shows the CDV from van Dobben and van Hinsberg (2008); van Dobben et al. (2012); Wamelink et al. (2023) and the next column the resulting average surplus in the area. Column four shows the percentage of the N2000 area where CDV are being exceeded. The CDV is based on the habitat with the least 'resistance' against a surplus of nitrogen and is taken from the revised version of July 2023. Lastly, from the breakdown of origins in the AERIUS monitor the share of traffic is shown at the end of the table. This value includes emissions from highways, regional roads and local roads. From the AERIUS Monitor, values shown in Table 3.5 are the prognosis for 2025 (AERIUS, 2023). This year is the closest to the current date as 2021 has already been a couple years. The difference between percentages of 2021 and 2025 is very small nonetheless.

Figure 3.4: De Bruuk - Sint Jansberg (Natura2000, 2023) (Google Earth, 2023)

Figure 3.5: De Bruuk (Meeuwissen, 2020)

3.4.1. De Bruuk - Sint Jansberg

One of the study areas will be the combination of De Bruuk - Sint Jansberg Natura2000 areas in the south of Gelderland. These are relatively small with 99 and 226 hectares and close to each other. The latter is shared with the province of Limburg and both are near the border with Germany. Especially the Sint Jansberg area shows a high average amount of nitrogen deposition value while both areas approach the 100% exceedance of CDV mark. In the AERIUS Monitor it is indicated that 4.3% of the nitrogen deposition in these areas is a result of traffic (AERIUS, 2023). Figure 3.4 shows the two areas outlined in red and their relative position in the country. Other characteristics that are visible are the Maas river, the A73 highway and the N271 provincial road directly adjacent to the Natura2000 area. The study area is located in the municipalities of 'Mook en Middelaar' and 'Berg en Dal' with a total population of 43,000 (Citypopulation, 2023). Other municipalities closeby are 'Land van Cuijk', 'Malden' and 'Gennep'. Only ten kilometers away, Nijmegen is the nearest major city with a population of 182,000 (Citypopulation, 2023). The Land van Cuijk municipality is home to one of the largest industrial emitters of nitrogen-oxides in the province of Noord-Brabant and the bio-energy plant emits 45,817 kilograms directly west of the Natura2000 areas (Heesterbeek, 2022). Incidentally, the surrounding area is aware of the nitrogen problems and, for example, nitrogen deposition has been studied for a new bypass road at Milsbeek to relieve another unsafe road of local trucks (Gemeente-Gennep, 2022). Along road infrastructure, there is a rail line between Nijmegen and Venlo, passing Cuijk. It is mostly situated west of the Maas but crosses the river just north of Cuijk. A new cycling bridge has been built next to the rail bridge in 2020 as part of a cycling through-route in a north-south direction. This connection does not appear in the traffic models yet, but will be used as input in subsection 4.1.14.

The Natura2000 areas are at a height of 15 to 85 meters above sea level and belong to some of the more elevated parts of the Netherlands (Actueel-Hoogtebestand-Nederland, 2023). The Bruuk is a marshland area fed by seepage water in the basin of Groesbeek. It is one of the best examples of the so-called maggot- or meden- landscape, characterized by small-scale alternation of wet hay meadows, thickets and wooded banks (Natura2000, 2023). The Bruuk is one of the most botanically richest natural areas in northwestern Europe with many plant species every square meter, but is also declining in richness due to nitrogen deposition (NatureToday, 2021). After remedial work in 2021 and the raising of water levels, different orchids and plants have been sighted in the area like the Black Sedge, Marsh Violet and Bog Star. Butterflies are dependent on the Marsh Violet for example. A part of the Bruuk N2000 area is shown in Figure 3.5. The Sint Jansberg is a lateral moraine that consists of old deciduous forests, coniferous forests and spring forests. Characteristics of this lateral moraines are the skewed layers in the soil of the area. In the rougher permeable layers, the runoff groundwater exits as source and seepage zones. There are several source areas and peat bogs in the area, while at the bottom of the area, near Plasmolen, it is a marshy lowland. There are mostly steep slopes and therefore sharp transitions from dry to very wet land present (Natura2000, 2023). Four different large habitats can be found here: calcerous fens, Atlantic beech forests with Taxus, bog woodlands and alluvial (wet) forests. The areas are inhabited by different (endangered) animal species such as the Desmoulin's Whorl Snail, Jumping Spider, Southern Skimmer, Dale's Oak Clearwing, White Underwing, Melodious Warbler and various grasshoppers (EEA, 2023b; ObservationInternational, 2023).

3.4.2. Binnenveld

A second study area is the Binnenveld. The name originates from the location in between four towns and cities in the center of Gelderland, just north of the Rhine river. It concerns Veenendaal, Ede, Wageningen and Rhenen. The four places in the direct vicinity accumulate to 200,000 citizens in total (Citypopulation, 2023). This southern part of the valley between the hills west and east is rich in bluegrass (Natura2000, 2023). The protected Natura2000 area itself is positioned near the city of Veenendaal, is flat in general but has a lot of micro-relief. The historical richness of rare bluegrassland and marsh plants in the Binnenveld is related to its complex water regime. The low elevation between two reservoir basins led to seepage flows, causing base-rich water to drain into the area. The wide variation in soil and water conditions was reflected in the occurrence of plant species that rarely grow in bluegrasslands elsewhere in the Netherlands, in particular several orchids and other flowers. The area also provides a breeding habitat for marsh birds and insects. Species found in the Binnenveld natural area include the Mud Loach, Varnished Hook-moss, Spotted Darter dragonfly and the Red-footed Falcon (EEA, 2023b; ObservationInternational, 2023).

The Natura2000 part of the Binnenveld consists of two small disconnected 'fields', which together are 111 hectares in surface area. The area is a shared protected area between the provinces of Utrecht and Gelderland as each one has a 'field' under its jurisdiction (Natura2000, 2023). The study area ranges from four to seven meters above sea level (Actueel-Hoogtebestand-Nederland, 2023). Roads with significant traffic volumes nearby include the national highways A12 and A30, and provincial roads N233, N225 and N781. Aside from more local roads neighbouring the natural area, there is a large industrial district to the west and the Rhine river with inland shipping circa six kilometers away to the south. Visible in Table 3.5, the Binnenveld area has the highest percentage N-deposition from traffic in the province with 6.9%. Compared to the others, it already has a smaller average deposition value in 16.1. slightly more than half of the area has an exceeded CDV, but the surplus is small and as such there is a good opportunity to bring the nitrogen values down to favored numbers. Industry and shipping add up to a similar percentage as road traffic for the Natura2000 area (AERIUS, 2023). Even though this location is central in the country, a quarter of the nitrogen deposition originates from outside the Netherlands. Notable large emitters in the region are an industrial paper factory in Renkum, 11 kilometers to the southeast and emitting 152,988 kilograms nitrogen-oxides. Additionally, four high-emission livestock farms in the municipalities of Ede and Barneveld within 14 kilometers to the north and northeast for ammonia (NOS, 2022). There is an alternative in place for car traffic in the shape of the Veenendaallijn, a rail line between Rhenen, Veenendaal and Utrecht. Additionally, Ede is a large stop on the west-east rail line between Utrecht and Arnhem. An overview of the area with the Natura2000 is shown in Figure 3.6 with a picture of one of the subareas in Figure 3.7.

Figure 3.6: Binnenveld (Natura2000, 2023) (Google Earth, 2023)

3.5. Demarcation of study areas in MOVE Meter

To bring the study area better into the picture inside the MOVE Meter tool, a quick look at the O-D flows for zones and selected links has been taken. This short analysis helps in the process of identifying which zones can be aggregated and which zones cannot in the tool and draw in the study area.

A north-south oriented selected link between the Sint Jansberg and De Bruuk in Figure 3.9 shows that the main traffic flows remain east of the Maas river. However, other selected link do show a large demand in traffic

Figure 3.7: Binnenveldse Hooilanden (Winkel, 2021)

between Groesbeek and Cuijk, affecting the Sint Jansberg Natura2000 area. Similarly, the provincial road through Plasmolen also hosts a lot of traffic between Gennep and Nijmegen. An O-D analysis further indicates relevant traffic flow with the municipality of Bergen, Beuningen and Wijchen. These will be included in the detailed study area within MOVE Meter. The cities of Venlo and Venray also show traffic demand east of the Maas, but are too far away for the study area and can be modelled as a nearby region. An important note for this study area in MOVE Meter is the inability to include German cities just over the border in detail. These are modelled as larger aggregated zones similar to Dutch provinces further away.

Analysing a link on the southeastern side of Veenendaal near the protected Binnenveld area shows more than local traffic on the roads (Figure 3.10). There are noticeable traffic intensities between Veenendaal and Rhenen including origins and destinations further away. This can foremost be explained by the fact that there is a bridge crossing the Rhine river south of Rhenen to the Betuwe area. The selected link also shows traffic flows towards the region of Arnhem and towards a large

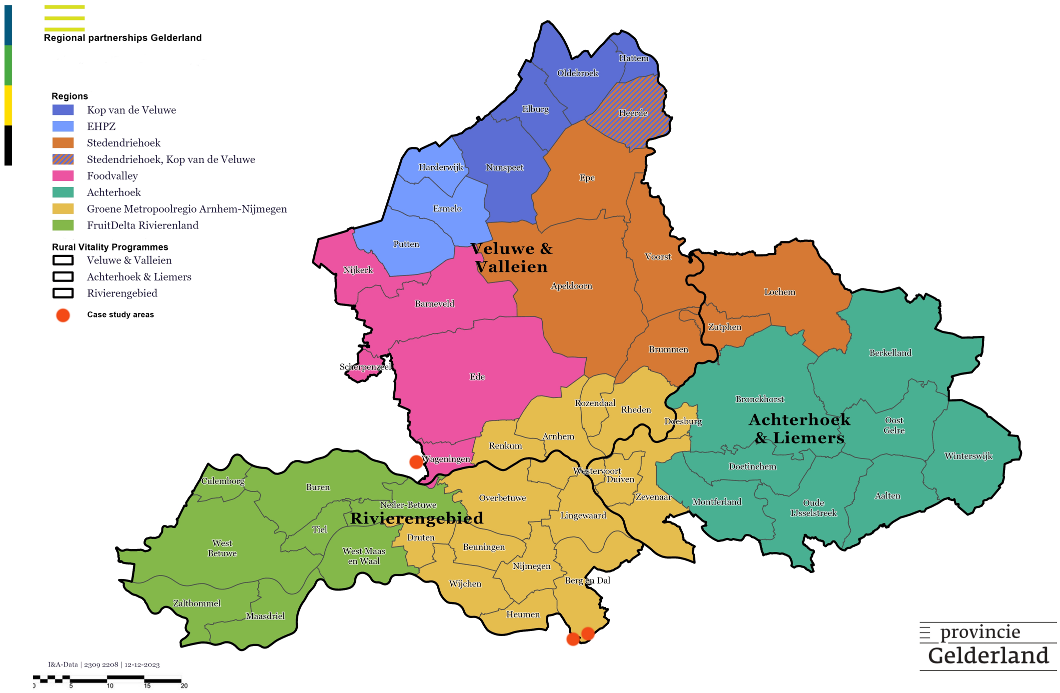

Figure 3.8: Regions and partnerships in Gelderland (Gelderland, 2024b)

Utrecht/Amersfoort zone. Since these are aggregated zones, the circles are not on the exact location but represent these greater zones with multiple municipalities. An O-D analysis in MOVE Meter for these areas showed that most relevant traffic demand is with the municipality of Barneveld. There is also traffic demand between Ede and some larger zones such as Amersfoort and Leusden, but this doesn't require driving in the vicinity of the N2000 area. Additionally, the O-D flows show traffic between Utrecht and three of the main municipalities near the Binnenveld. However, this zone is too big and too populous to include with details into the study area and is better kept as a region.

Other selected links firstly point out that most other roads in the N2000 area are used between the O-D pair of Veenendaal and Wageningen, an east-west connection. Secondly, a short analysis shows that there is traffic demand between the Betuwe and Wageningen, accompanied by traffic from Veenendaal and Rhenen, on the roads bordering the southern end of the Binnenveld. Hence why the study area will not just include the four municipalities nearest to the Binnenveld, but also the Neder-Betuwe, a large part of the Buren municipality and built-up areas to the north and west; Leersum, Amerongen, Wijk bij Duurstede and Barneveld. Carefully

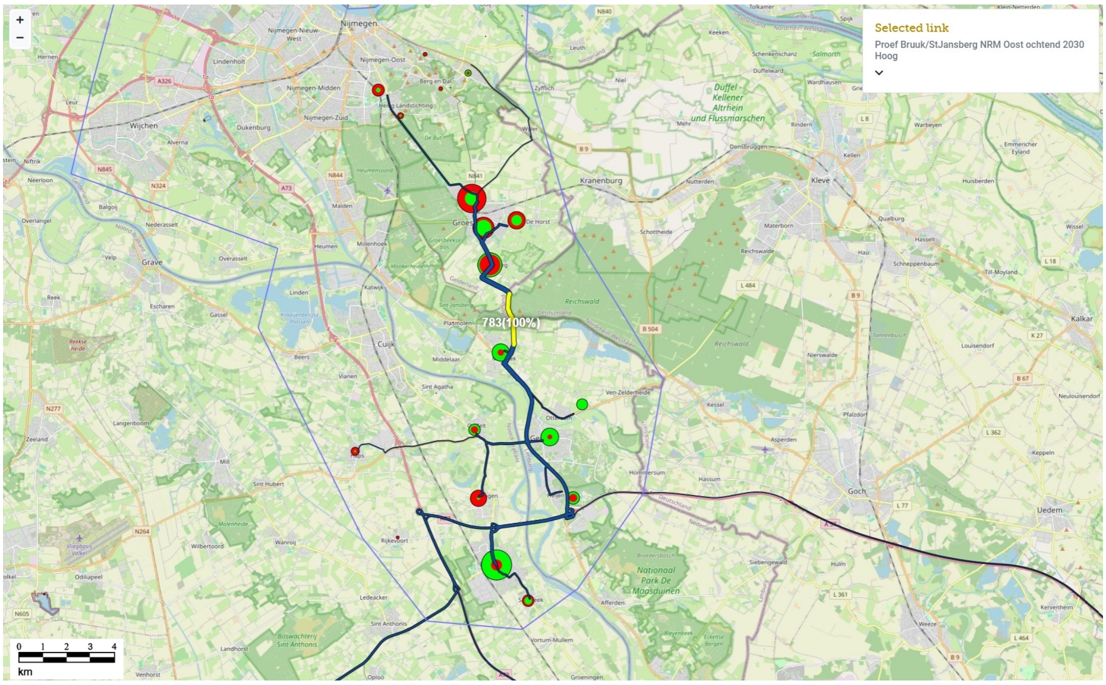

Figure 3.9: Selected link analysis near the St.Jansberg / Bruuk area in the base scenario

selecting the study area in MOVE Meter will also define Utrecht and Amersfoort as separate regions for a better analysis.
Initializing the study area in MOVE Meter does not only involve the demarcation, but also requires some more settings in terms of zones and aggregations as was explained in section 3.2. The settings for the study areas in this research are shown in Table 3.6. They are needed to replicate the scenarios in the tool to construct the correct zones for the area. The maximum amount of zones in the tool is 250. The bottom two rows in the table address the aggregation of multiple smaller zones into larger zones. The tool uses this option to reduce computation times but also provides customization options for the user of the tool. For zones further away from the study area this can be convenient since the traffic flows use the same road sections on higher-level roads in the network anyway and for zones close to the important roads near Natura2000 it is helpful to keep all the details.

Setting	Binnenveld	Bruuk/St.Jansberg
Total zones	250	250
Zones within study area	125	110
Distance where zones are aggregated into regions (km)	100	55
Distance where zones are aggregated into provinces (km)	100	80

Table 3.6: Study area settings in the MOVE Meter tool

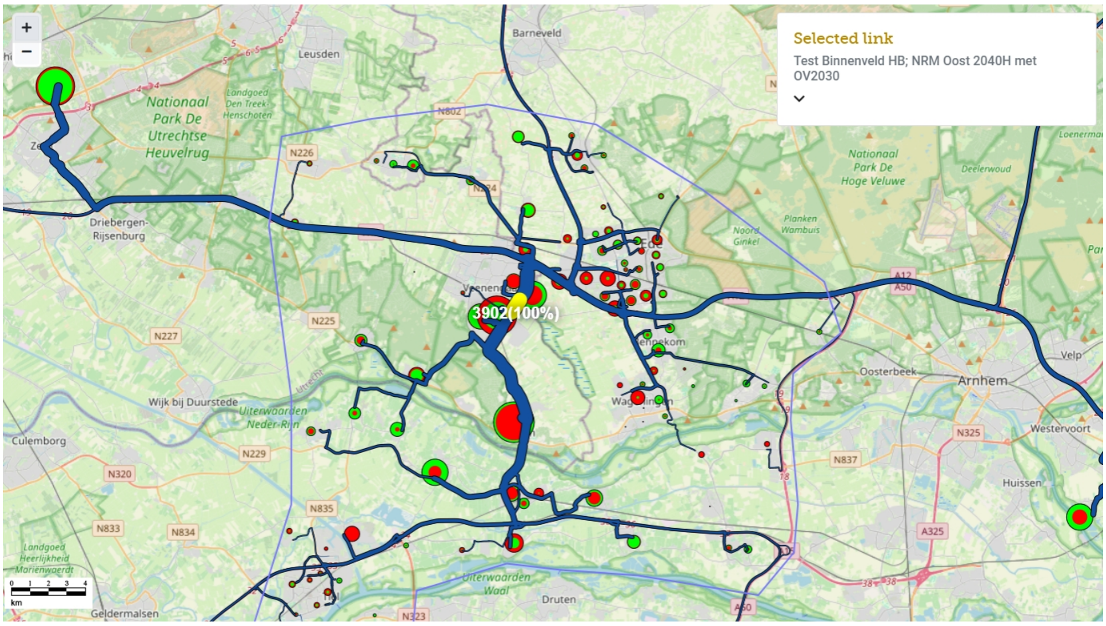

Figure 3.10: Selected link analysis near the Binnenveld area in the base scenario

3.6. Cost of measures

This section introduces the methods of comparing the costs in this research, which will be done later when the results for nitrogen deposition reduction are known as well. The monetary cost of each mobility measure will be ranked to compare expenses of the differing solutions. The ranking will be visualized in Figure 4.8. However, the costs are given in bandwidth since each case comes with a different figure. They are estimations of the cost of the measure. This implies that the ranking will be visualized in four quadrants: high and low cost as well as high and low effectiveness in reduction of nitrogen deposition. These high and low indications are thus relative to each other and relate to the bandwidth in cost, while the reduction is the relative value found in this research. The comparison in cost-effectiveness is mostly aimed at policymakers in the consideration of measures. Operational costs of measures and vehicle-loss-hours will not be taken into account within this research. Operational costs are difficult to entangle as there are not many comparable situations and the duration of each measure is unknown or different from the others. Additionally, the differences in operational/maintenance cost are not very significant when they are put on top of the policy implementation of each measure. Implementation consists of infrastructure, policy, rewarding and technology investments. Examples of implementation cost are the placement of smart traffic lights or constructing a cycle path with asphalt.

Vehicle-loss-hours is the sum of all the time gained and lost multiplied by the amount of vehicles and value of time, indicating the cost of cumulative delays and time gains. It is too complex to add the monetized cost of vehicle-loss-hours because of two factors in the estimation. The main issue is the absence of a timeline and horizon for the measures and the other issue is the vast amount of roads with various lengths and travel time differences. Each measure has a different amount of roads subject to a change in travel time and vehicles, resulting in very rough estimations for vehicle-loss-hours. For certain measures the loss or gain is negligible on top of the implementation costs. A basic cost comparison without those 'operational' components can assist in prioritizing measures in the first place. Policymakers also work with limited budget and the implementation cost provides this first view of what might be possible to execute.

The costs are estimated using expert judgment and various sources, including existing research. These will be mentioned when it applies to the measure. Expert judgment is also based on multiple online sources who do not provide numbers but a description of cost components instead (CROW, 2025). A best estimate is given since the cost of measures shows a wide range, depending on the scope and complexity of it. Explicit and substantiated cost-effectiveness scores can only be provided with more exact values for the cost of the measure.

4

Analysis and results

4.1. Mobility measures

Each measure has their own section in this chapter, where the measure will be discussed and the results will be presented. After all the individual presentations, an overview of the results is given for both emissions and deposition, as well as verification of the Conceptual Model. At the end of the chapter, section 4.3 shows and explains how the measures compare in cost-effectiveness.

4.1.1. Intelligent traffic light systems

Changes in peak-hour and free flow travel speed by 5% lead to a considerable amount of intensity changes elsewhere. The improvement in traffic flow through intelligent traffic light systems has been implemented into the model within five kilometers of the Natura2000 area. Results show that it is not uncommon for the subjected roads to receive higher intensities because the roads got more attractive in terms of travel time. There are also emission reductions from the improved speeds through emission factors, aside from the roads that do see lower vehicle intensities from rerouting. It is mostly the trips longer than ten kilometers that change their route, while short trips will still pick the original road. For both study areas, the cumulative amount of kilometers driven increases slightly, while emissions decrease. The nitrogen deposition, however, does not decrease with a significant amount at the desired roads near N2000. Instead, they decreased near a couple roads elsewhere, close to other N2000 areas, were intensities decreased. The decrease in emissions and minimal change in deposition are affected by the changing emission factors from the speed adjustments in the traffic modelling, which will be a more common theme among the measures in this research. This minimal decrease in nitrogen emissions means -0.1 to -0.6%, with the deposition balancing around 0. The differences between the low and high economic scenarios stem from the extra amount of traffic volume in the high scenarios and applies to both study areas.

The costs for this measure are relatively low, but heavily depend on the amount of intersections. Aside from the physical infrastructure needed for the iVRI, it also needs software and system engineering. Cost per iVRI installation vary between 30,000 and 150,000 euros. For the scope and implementation in this research, the costs quickly add up between 1.5 and 5 million euros.

4.1.2. Road downgrading

In the MOVE Meter tool, roads with a free flow or peak-hour travel speed above 60 km/h have been adjusted to this value. This applies to all roads within 10 kilometers of the N2000 area. Results suggest that the downgrading of roads to lower speed limits does not reduce nitrogen emissions throughout the whole network for vehicles. As a result of slightly longer travel times, vehicles pick a different route which is in most cases longer than their original route. This leads to more vehicle kilometers cumulatively in the study area. The deposition of nitrogen however did decrease at the hexagons closest to some subjective roads. A significant amount of hexagons in the Bruuk & Sint Jansberg study area did show an increase in deposition from the extra vehicle kilometers though. Even more interesting is the larger increase in deposition at the other study area of the Binnenveld. Table 4.5 shows a smaller increase of emissions from the extra vehicle kilometers, but the extra mole deposition per hectare per year is greater than in the other study area. This can be explained by a recurring modelling issue in this research. Lowering the travel speed on road sections leads to an increase in emissions. This may seem somewhat logical from the theory provided earlier on the relation between speed and nitrogen emissions, but happens because the road is subject to another emission factor instead. Stepping over a threshold speed provides the results with a contradicting effect: lowering the vehicle speed increases the emissions in some cases, while increasing the speed can decrease them.

This issue with the emission factors is also visible in the differing results between the two study areas. Table 4.5 shows a higher increase in emissions for the Bruuk & Sint Jansberg area compared to the Binnenveld, while the deposition results in Table 4.6 show worse values in the Binnenveld. Roads subject to the decrease in speed limit were extremely close to the latter one in combination with the modelling constraint, hence the significant increase in nitrogen deposition. For the Bruuk & Sint Jansberg area there were no subjected roads nearby and the increase in deposition is better explained by the extra vehicle kilometers on the network. It is difficult to entangle to what extent the deposition rise because of the extra vehicle kilometers or from the modelling constraint. It is theoretically possible that the nitrogen deposition would decrease for both areas, and the Binnenveld especially, if the modelling constraint with the vehicle speed was not there.

The monetary cost of this measure is surprisingly high with a bandwidth of 20 to 50 million euros. The reason for this is that it is not really simple to downgrade subjected roads and there are multiple variables. The cost per kilometer varies between 300,000 and 3 million based on the extent of redesign, greening, lane separation and new signs. For the implementation of the road downgrading in this research there is quite the amount of kilometer road to be adjusted, hence the high total cost. These costs are comparable to the construction of new bicycle paths and also vary with the complexity of the route.

4.1.3. Driving behaviour campaign

Improved traffic flow from more efficient driving in the study area. The measure is aimed at the difference between free flow and peak-hour speeds on the roads in the study area. Goal is to reduce the difference between the two through a campaign aimed at the drivers and their driving behaviour. Roads with the highest differential between the two speeds have been chosen for the measure, based on the data from the base-scenario in the model. For the measure, the peak-hour speed has been raised with 40% towards the free-flow speed where possible. If this adjustment is not possible because the gap is smaller than this percentage, the two speeds have been set to equal.

The emission and deposition results for this measure are twofold. This has also been documented in Table 4.4. One caveat is the the difficulty in modelling the emission factors with the changes in travel speed for the vehicles. The increase in actual speed puts some roads into a different class and thereby half the emissions for those roads, even though they host more vehicles than in the base-scenario. This influenced the effects on the nitrogen emissions in the study area. The results show a reduction ranging from 0.7% to 1.7%, which is what seems to be an overestimation. One of the main takeaways from this measure is however that the traffic volume increases as the roads get more attractive from the increased travel speed. The decrease in emissions from the emission factors is stronger though, hence the cumulative decrease in nitrogen. The different values through emission factors in the model are in line with the theory provided in Figure 2.4. The measure also shows that the reduced travel time over local and regional roads pulls traffic volume away from the highways. This pulling effect is not in the advantage of the Natura2000 areas. The nitrogen deposition reduction is very significant according to the model. A visual example of this measures can be found in chapter 5.

Setting up a campaign is one of the cheaper measures in this research. The costs depend on the geographical extent of the campaign and reach of the resources. Fitting with the task-setting implementation, a broader campaign for each study area is envisioned and the costs are between 400,000 and 1 million euros. This is comparable to historic campaigns aimed at drivers (NOS Nieuws, 2011). The campaign is using television, social media and local activities to impact driving behaviour.

4.1.4. No-entry zones passenger vehicles

For both study areas, closure of roads inside and adjacent to the Natura2000 area leads to an increase in cumulative nitrogen emissions. More vehicle kilometers are driven in the whole system because of the closures, leading to more emissions overall. Less kilometers are driven directly next to the sensitive N2000 area however. This has an impact on the nitrogen deposition in the area. An example of this can be seen in Figure 4.1, where the decrease in deposition at the closed road is significant, but more nitrogen can be found near other (detour) roads. Green hexagons notify a decrease in deposition while the red hexagons are an increase. It has to be said that for almost all Dutch roads, it is impossible to block all of the traffic, as vehicles with their destination on the road are still allowed. A similar case stands for roads that are dependent on certain roads for accessibility. It also applies to trucks who are more reliant on the main road network and won't take local roads that easily in case of disruptions. This measure is thus mostly a no-entry zone for through traffic and still allows non-elastic cargo traffic and a small amount of passenger vehicles. The possibility of closing specific roads and the effectiveness has been shown elsewhere (NOS, 2023).

The magnitude of the reduction in nitrogen deposition is much stronger for the Binnenveld study area compared to the Bruuk & Sint Jansberg combination. This pinpoints how important regional variances are for a measure like this. Around the Binnenveld, there are possible detours closeby and logical for the traffic to use, while those options are limited for the other study area. Not all relevant roads can be closed for through-traffic as detours would be unacceptable and lead to much more traffic or the detours lead to much more nitrogen emission at other edges of the natural area. Results also show that the area of effect is smaller for the study area in Figure 4.1, whereas the area of effect of the no-entry measure in the Binnenveld area is very large, even stretching out to the southwestern quarter of the Veluwe Natura2000 area. A darker green hexagon indicates a stronger reduction in nitrogen deposition compared to lighter green, while white hexagons see no change at all compared to the base scenario. Red hexagons indicate an increase in nitrogen deposition.

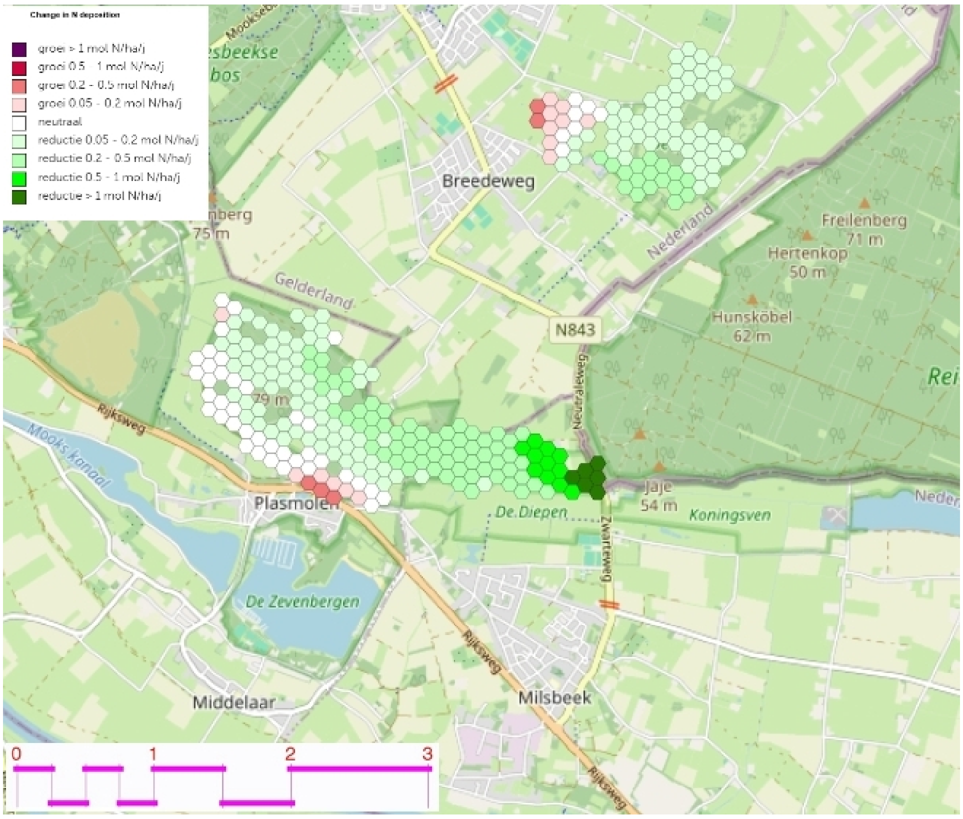

Figure 4.1: Nitrogen deposition for the no-entry measure at Bruuk/Sint Jansberg. The N843 road section between the red stripes is closed for non-destination traffic.

The cost of this measure can vary greatly for each road section, as in some cases a few simple adjustments are enough while for some others more detailed changes are needed. Total costs in relation to the implementation in this research are between 1 and 5 million, depending on the complexity in planning, communication, surveillance and signs. Communication towards the users is necessary and it includes the translation into navigation systems as well. The costs are still relatively low compared to other mobility measures. The costs are lower for a single location but installing a no-entry zones or road closure requires multiple locations with said infrastructure.

4.1.5. Bypasses

This measure is both different in implementation and results for the two study areas. In addition to this new link and in accordance with (Mangones et al., 2020), a 10% increase in demand has been applied to the zones that are related to this new bypass and came forth in the selected link analysis. The increase in demand from new routing options heavily affects this measure.

The bypass for the Binnenveld study area is located southeast of Wageningen and resembles a new bridge over the Rhine river. This new connection should relieve the whole north-south oriented N233 of some traffic, as this surfaced from the selected link analysis. The N233 is the only option for traffic between the A15 and A12 in the region and apart from the Rijnbrug is the only bridge, the road is positioned directly against the N2000 area in Veenendaal. The bypass is thus aimed to reduce the amount of traffic on this north-south connection. MOVE Meter shows that 700 vehicles in each direction would use this new bypass, but the reduction from the Rijnbrug is not that extreme. This bypass does not eliminate traffic from the desires roads near Veenendaal. Other bypass options are very limited, especially closer to the protected natural area. The results for nitrogen deposition are similar to those of the emissions. There are some slight favourable decreases, but not at the desired locations and for some hexagons there is a slight increase in harmfull deposition. Effects are best seen near the A50 and A12 highways, softening emissions and deposition in the Veluwe N2000 area. Reason for this is that the beforementioned amount of traffic using the new bypass, doesn't drive over the highway connection crossing the Rhine in the east. Origin and destination of the traffic is related to the city of Wageningen.

The bypass in the Bruuk & St.Jansberg area is located north of the N2000 area. This link between Malden and Groesbeek acts as a continuation to the east from the highway exit and N271. The calculation of the model shows that 1200 plus 500 vehicles would use this link in the morning commute. These vehicles are drawn away from the roads to the south, closer to the protected natural area. This new road was chosen because the selected link analysis showed demand in all directions to and from Groesbeek and the link also invited traffic to use the highway, whereas some traffic would go east of the Maas river, causing emissions north of Milsbeek. Figure 4.2 illustrates it, with green being lower emissions and red for higher emissions compared to the base scenario. Results for the nitrogen deposition analysis show that, even though the emissions in the study area increased, there is a decrease in deposition for the hexagons closest to the roads. The decrease is very marginal compared to the total mole deposition in each hexagon.

However, caution is needed with the addition of roads such as these, as they traverse through other natural areas, which are just not assigned as Natura2000. New and increasing emissions could lead to issues in these other forests and meadows. Other than that, the effects of this measure are dependent on the context and differ for each area and region. Causalities between emissions and deposition also differ for this type of measure. Where this bypass measure has more positive results for the Binnenveld in Table 4.5, the deposition from vehicles is lower in the other study area. This can be explained by the vehicles traveling less kilometers in one study area and more in the other, the so-called shortcuts and detours.

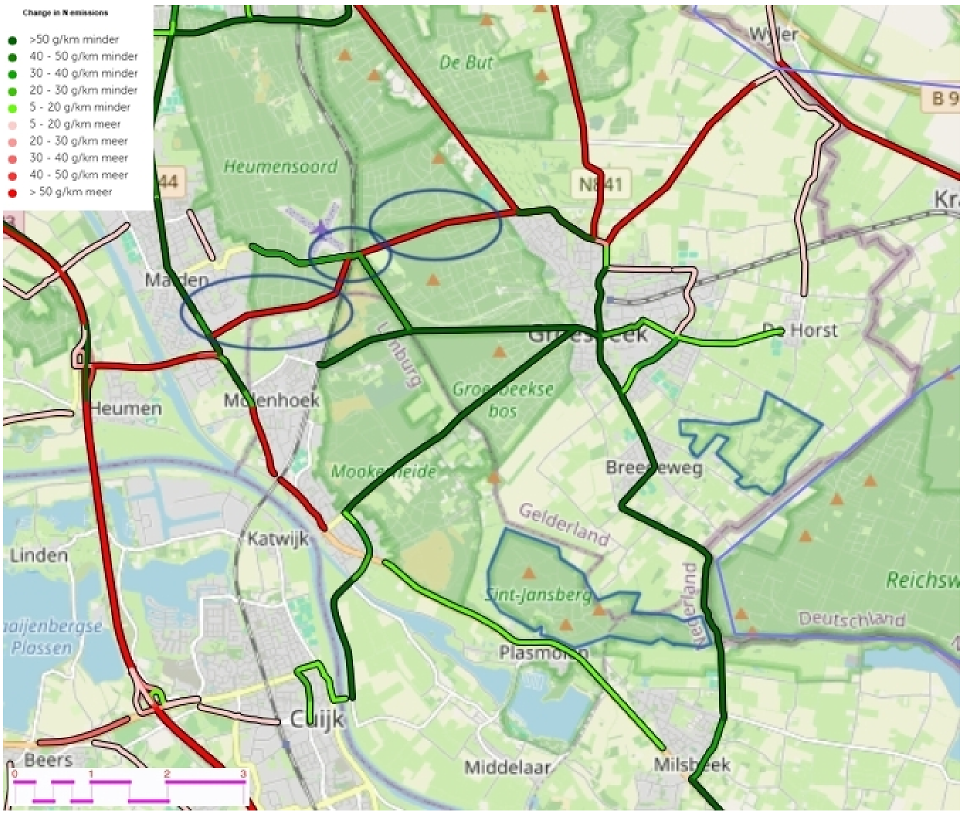

Figure 4.2: Visual of the bypass measure near the Bruuk & Sint Jansberg area. The road in subject is circled in blue.

The monetary cost of constructing bypasses and new roads can add up quickly due to complexity. They are estimated to be between 5 and 100 million euros for the bypasses in this research. Constructing bypasses is not expensive from the addition of new asphalt but the addition of civil works and traffic control systems instead. The longer the road section, the more it will cost and possibility there is for additional complexity.

4.1.6. Electrification passenger vehicles

Results for this electrification measure are comparable for both study areas. In this measure, the traffic generation has been decreased by 8% over all distance classes. There were roughly 120 zones on which this was applied, on the basis of broader regional cooperations. For the Binnenveld area this was Gelderland and Foodvalley together while it was Gelderland and Limburg for the other study area of the Bruuk & Sint Jansberg. The reduction in traffic generation is an alternative to changing the emission factors. The task-setting reduction is lower than the aim of a 10% electric vehicle gain, as electric vehicles will still contribute to traffic jams and influence emissions from other vehicles in that way. More elaboration can be found in Appendix A.

Results indicate that most of the reduction in emissions take place at high-intensity roads, such as highways and important regional connectors. The cumulative reduction in emissions for the study area is among the highest for all mobility measures in this research. Alas, the reduction in deposition is not at the same level because of the location of the reductions and the non-locality of this measure. This measure on a much broader scale has high potential, as it is only focused on a local boost in electric vehicles for this measure. Inter-regional traffic also plays a part in this potential. On a positive note, the results for each low and high scenario provides a visible relationship between emissions and deposition for most of it. A factor two emission reduction did not translate to a doubling in deposition reduction, as this only went up to a 0.1 mole/ha/y reduction from 0.06. The reduction even toned down for the high economic scenario at the Bruuk & St.Jansberg.

A large scale boost to the electrification of passenger vehicles is one of the more expensive measures. For smaller regions the cost can already add up to 50 million and the estimation is that the bandwidth for this specific implementation with the study areas is between 50 and 200 million euros. The costs are for grants, partnerships, communication and charging infrastructure for example. The switch to electric car usage requires the enabling from provinces and municipalities through the charging stations and space in the electrical grid.

4.1.7. Carpooling

The aim of 12.5% volume decrease in the morning commute is spread out over the eight distance classes in the MOVE Meter, but not evenly. The average distance of a carpool journey is estimated between 15 and 30 kilometers (PBL, 020a; MuConsult, 2021). The percentage spread will be focused around this distance class, shown in Table 4.1. This measure applies to all zones within the study area to represent cooperation between larger campaigns and employer packages.

Distance class (km)	Reduction
0-3	6%
3-7	6%
7-10	7%
10-15	7%
15-30	32%
30-60	16%
60-100	23%
100+	20%

Table 4.1: Carpooling distance classes in the MOVE Meter

Effects on nitrogen emissions and deposition are uniform. A decrease in traffic and the subsequent effects can be found all over the study area. The model shows a more significant decrease in emissions and deposition on and near the roads with the highest intensities. Figure 4.3 illustrates this as well, as the darker green roads show a higher intensity and thus with it a stronger decrease in intensity and emissions from the measure. The decrease in traffic volume has a softer effect on roads where intensities weren't high in the first place. The positive effects of this measure sure are in the upper half of all the measures calculated in this research. However, the traffic volume has to be reduced even stronger to notice better effects compared to the 1 to 2% decrease in emissions and on average 0.15 mole decrease per hexagon. The gap between the low and high scenarios is not as pronounced like it is in the electrification measure.

The cost for this measure is a combination of physical infrastructure and encouraging the carpooling through advertisement and employer-packages. Depending on the size of the region and the amount of new facilities for carpooling, the cost ranges from 1 to 3 million euro for the measure in this research. It is one of the lower priced measures.

4.1.8. Flexible office times (peak-hour avoidance)

Peak-hour avoidance has been modelled for all distance classes with a focus on slightly longer trips, who have a bigger chance of encountering higher traffic intensities. The distribution can be found in Table 4.2. The zones are chosen through regional alliances and the possibilities to

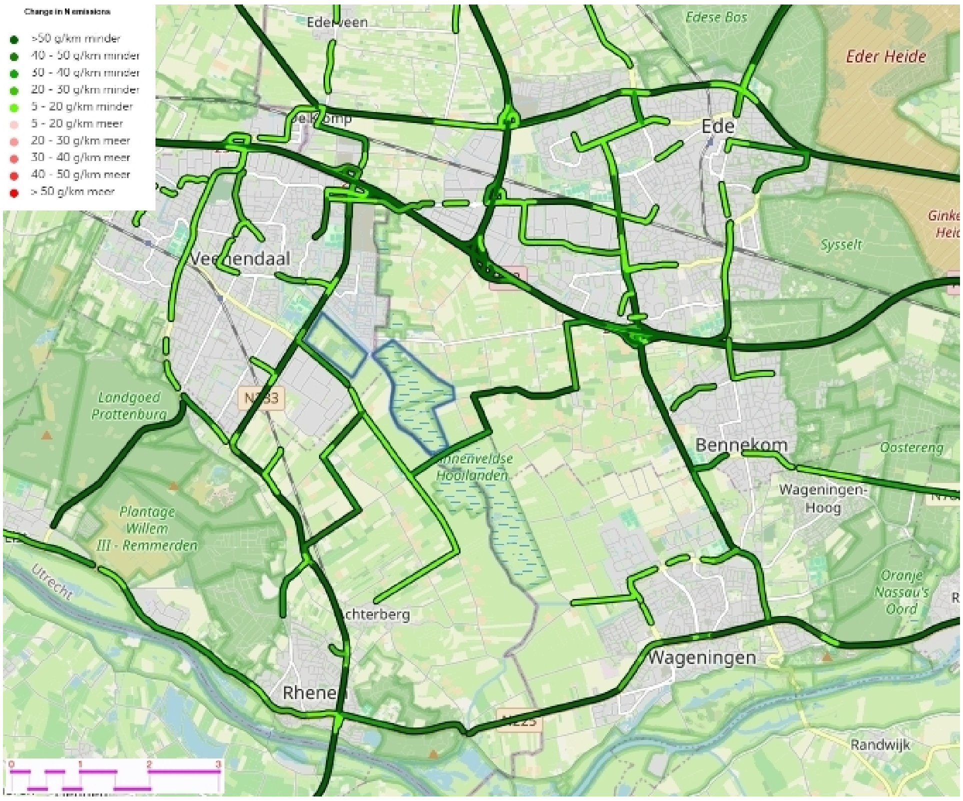

Figure 4.3: Results for the carpooling measure emissions in the Binnenveld area.

stimulate employers and employees to implement flexible office times. Goal of the measure is to shift traffic generation and lower intensities and with it the emissions of traffic jams by delaying trips or bringing them forward. For the Binnenveld study area the chosen zones are then the municipalities in the Foodvalley alliance, which can also partly be seen in Figure 3.8. For the other study area of Bruuk/St.Jansberg it applies to Nijmegen and surrounding municipalities with the addition of Land van Cuijk and Gennep in Limburg. It did not make enough sense to apply it to the Green Metropole Region of Arnhem & Nijmegen because of it's shear size, most of of which is to the northeast with negligible amounts of traffic generation in the vicinity of the study area.

The measure has a relatively good impact on lowering the nitrogen emissions. One aspect in favour of this measure is the applicability to all distance classes, resulting in all types of roads having lower traffic intensities for passenger vehicles. Importantly, the reduction in nitrogen emissions can also be found on roads in or near the N2000 areas. This has its effect on the nitrogen deposition as well, which slightly decreases. Results are similar to the electrification measure. Which is not surprising, given the fact that it was entered into the tool with somewhat similar task-setting values. This peak-hour avoidance measure shows reductions of traffic volume on all types of roads in the study area. Nitrogen deposition reduction is stronger for the hexagons with the best proximity to subjected roads. One note for this measure is that it shows a reduction during the morning commute from shifting departure times. This implicitly means that the vehicle trips can or will still occur and add towards the emissions and deposition. This aspect needs to be considered when it is compared to, for example, the electrification measure.

Distance class (km)	Reduction
0-3	3%
3-7	4%
7-10	7%
10-15	15%
15-30	15%
30-60	17%
60-100	32%
100+	25%

Table 4.2: Peak-hour avoidance distance classes in the MOVE Meter

The promoting of flexible office times can be done by employers and regional cooperation. These tracks have a slight variance in their cost, but more importantly, there are a lot of tracks to encourage flexible office times for a traffic decrease in this research. The bandwidth in monetary cost is between 10 and 50 million for the whole province of Gelderland. It is on the higher side in cost of measures. These tracks focus on both the communication and encouraging measures.

4.1.9. Stricter emission standards ecological zones

The stricter emission zones have been put in with some workarounds for the task-setting nature of the model. Aside from a 2% decrease in vehicle intensity at specific roads, the speed and capacity have been lowered by 10% for those. The decrease in vehicle intensity accounts for all distance classes in relevant zones. These relevant zones are the five municipalities at the Binnenveld and a large rectangle of zones east of the river Maas for the other study area of Bruuk & St.Jansberg. Modelling results illustrate that the measure succeeds in the reduction of emissions and deposition at a very local scale, such as directly next to N2000 hexagons. Reason for this is a relatively strong decrease in traffic volume. However, the modelling restrictions with the emission factor changes from the adjustments in travel speed make it difficult to interpret all of the results and provide slightly skewed numbers. In three of the four measure-scenarios, the cumulative amount of emissions increases (Table 4.5). In theory, the reduction in total vehicle kilometers driven on the network leads to a decrease in pressure on the natural areas, but it is hard to tell from these results. The confusion is visible in Figure 4.4. The figure shows both a decrease and significant addition in nitrogen deposition. It perfectly shows which roads are subject to the change in emission factors from the change in speed, such is the case near the town of Plasmolen.

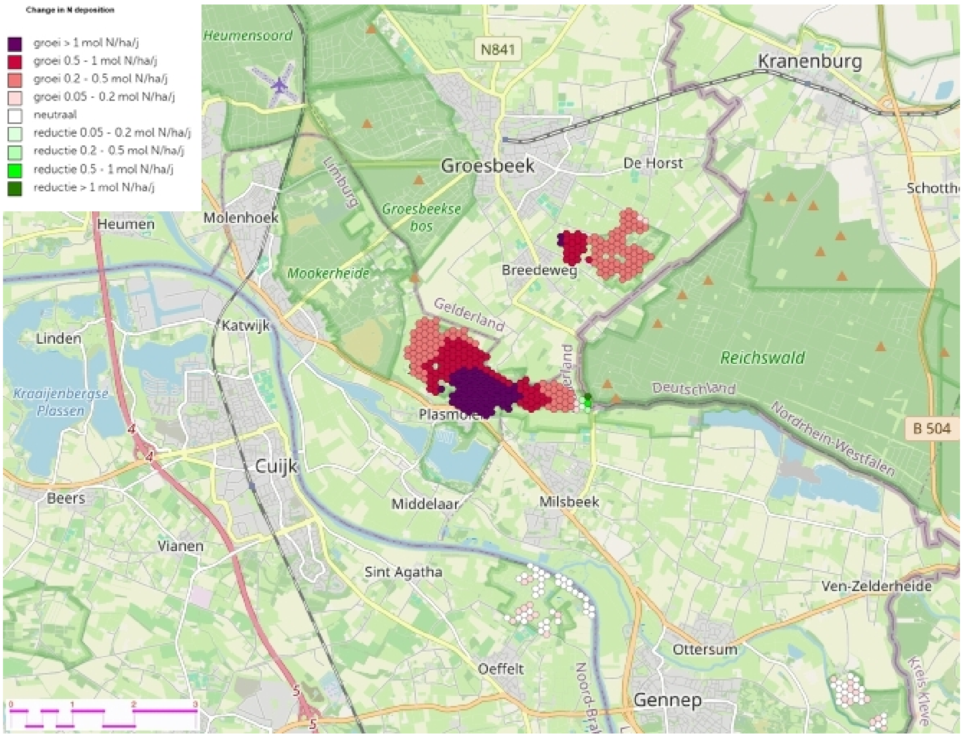

Figure 4.4: The two different effects of changing the speed on specific road sections. From deep green as reduction to purple for addition.

The cost of implementing stricter emission zones is build up from four steps: research, planning, implementation and enforcement. The total cost for a stricter emission zone in a study area is roughly between 1 and 10 million euros (Buck-Consultants and RHDHV, 2019). Aside from the implementation costs there is a yearly operational fee to enforce the zone. This maintenance cost is not taken into account as explained earlier. Implementation can get more expensive if the zones are more complex, such as many entry points.

4.1.10. Park & ride, hubs and shared mobility

The reduction in vehicle trips from P&R, hubs and shared mobility facilities has not been implemented with a percentage reduction but with a decrease in absolute numbers, known from previous research and data. It is a mixture of three or five less car trips for each zone, where the larger urban zones are given this larger decrease. Main reason for this is the option of shared bicycle and scooter system. The reduction applies to all zones in the study area as a cooperative local policy and the distance classes reflect these shorter trips and average commute distance (PBL, 020a).

The reduction in traffic volume from this measure is almost negligible, with very limited decrease in vehicle kilometers and emissions compared to the base scenario. Only two road sections have a decrease in volume significant enough to even show up. These are the roads were multiple routes conjoint, such as a bridge. The small reduction in traffic generation together with the fact that the measure is not focusing locally, is holding this mobility measure back from reducing nitrogen deposition.

The cost of shared mobility adds up quickly because it works better in a proper network instead of adding a singular location. The bandwidth of the total cost 3 to 40 million, if the aim is a network in multiple cities and towns in a region. It is dependent on the amount of users and scale of the facilities. Physical space is needed for parking and storing vehicles whereas there is also a digital component in communication and some advertising. The measure also requires planning and research before the implementation.

4.1.11. Cycling incentives for modal shift

For the cycling incentives, a municipal approach has been taken into account. Employers are pushed by the municipality or regional alliances to aid in the sustainable transport of their employees. Examples are financial advantages for the purchase of e-bikes or kilometer allowance. In the tool this is translated to the inclusion of zones within complete municipalities that lie within 5 kilometer of the N2000 area and not just zones within 5 kilometers. Subsequently, fitting for cycling incentives, the percentage in vehicle reduction towards cycling will be applied to relatively short distance classes, except the shortest of 0-3 kilometer since the share of cycling is already very high. An 8% reduction will be used for all three classes: 3-7, 7-10 and 10-15 kilometer with the assumption that distance resistances are relatively similar.

Results for nitrogen emissions show a barely noticeable change compared to the base scenario across all four measure scenarios. The decrease in vehicle traffic and accompanied kilometers on the network is too small for significant differences. A similar thing can be said about the reduction in nitrogen deposition. The minimal change in traffic volume implies that it has to be in very short proximity to N2000 hexagons to have any significant effect. However, this measure could have more effect for N2000 areas in more urban settings. It needs more short trips than in the two study areas of this research. A higher population value means that there is more possible gain in avoiding vehicle trips.

This measures has a relatively low monetary cost between 1 and 10 million euros. The exact cost depends on the scale of the project and the geographical extent. The values include regional projects which include grants and allowances for employees that can range from 50 to 500 euros per person. These are used to encourage them to use the bike for the commute instead of the car.

4.1.12. PT incentives for modal shift

Through the task-setting nature of the model, this measure sees a 6% modal shift from cars to public transport from incentives. The modal shift applies to full municipalities within 5 kilometers of the N2000 area, similar to the cycling incentive measure. However, the shift applies to all distance classes for this measure. Again, incentives can be anything to stimulate public transport such as discounts, employer-packages, campaigns and rewards.

The measure results in a slight reduction in emissions and deposition. Most roads with a reduction in traffic do so with a 4% or 5% decrease, in contrast to the 6% modal shift. Not all of the traffic generation from a zone picks the same route and the vehicles become more spread out over the network, hence the lower reduction. The cumulative reduction in the study area is similar to the comparable measure of cycling incentives. Reduction of the emissions in the overall study area ranges from .2 to .5 percent. The reduction is surprisingly limited on short distances and more pronounced on middle- and long distance trips. This does result in a slightly better reduction in nitrogen deposition, but still the values are close to zero with -0.03 and -0.05 in the Binnenveld area for example.

Costs for this measure are based on one project with a regional scale to stimulate travel by public transport. The content is grants and discounts for PT subscriptions, organized by the employers. The cost is roughly 50 to 200 euros for each employee and the bandwidth for the whole measure adds up to 4 to 15 million euros. It just falls in the higher cost category with the setup of a larger regional approach.

4.1.13. Parking regulations in/for Natura2000

The decrease in trip generation is not high enough to result in any significant changes of the nitrogen emissions. The decrease in trips due to parking regulations only applies to four zones for both study areas. Modelling results show the decrease in traffic intensity at and near the N2000 areas. The decrease in trip generation has been calculated to reflect a 15% decrease, unevenly spread over he distance classes. The three shortest classes, up to 10 kilometers, have been modelled with a 17% decrease, while the next two are a 3% decrease, originating from lower demand due to less willingness to drive the longer distance when other natural areas are closer by. The decrease in emissions and deposition is very small and somewhat negligible, with deposition values of -0.01 and -0.02. The reduction in relevant trips by vehicles in the commute is too small for significant reduction at the N2000 areas. The reduction in vehicles is only one or two dozen and not even on all of the desired roads because the measure applies to a small amount of zones. Lack of theory and modelling restrictions did not make this a satisfying implementation of the measure. However, proper calculation through the parking policies would likely still result in minimal decreases in trips, especially in the weekday commute. Results may vary a bit for the weekends and 24-hour numbers. A similar note can be laid out for deposition modelling inside the natural area instead of intensities of nearby roads and zones, since visitor parking brings the emission source very close to vulnerable species.

This measure has a low implementation cost. The bandwidth is 200,000 to 3 million euros for infrastructure and communication. Total cost is not only variable to the number of regulated parking facilities for a natural area, but the cost also increases significantly if you take enforcement and maintenance into account. The costs are dependent on the scale of the facilities as well. Larger facilities bring a higher cost which includes payment machines, parking spots and signs.

4.1.14. New bicycle through-routes

This measure has been modelled through a 14% modal shift for carefully selected zones. The modal shift has been applied to the four shortest distance classes, thus up to a 15 kilometer travel distance. For the Binnenveld area this applies to zones in Rhenen, Ede and Bennekom. For the other study area of Bruuk/St.Jansberg, twenty zones are relevant and will be explained hereafter.

The most important factor for the reduction in nitrogen emissions is the improved attractiveness of picking the bicycle instead of the car, the pull-factor of the new bicycle routes. The modal shift is the direct cause for

Figure 4.5: Location of (possible) new bicycle routes and their effect on the nitrogen emissions.

the decrease in emissions with the bicycle paths as a catalyzer. The positioning of new bicycle paths does matter, along with the other regional characteristics. The modelling results show this as well, as there is a difference between the two study areas. The positioning of the bicycle paths regulates, in this case, which zones will see a change in their mode choice, which then affects some roads or not. Figure 4.5 shows this for the Bruuk & Sint Jansberg study area for example. Crossing a barrier like the Maas river with two new bridges results in more zones being affected by the modal shift in comparison to just connecting three zones together. Commuting by bicycle from Groesbeek to Cuijk is shortened by two kilometers and eight minutes for example. Just connecting zones smoother was the case for the Binnenveld area in this research. A lack of options for new bicycle through-routes led to the modelling of a connection from Rhenen to Bennekom as an alternative to the car in the morning commute. This results in a small decrease of 20 to 50 vehicles on relevant roads. The other study area has slightly lower absolute values, but because there is less traffic there overall, the percentages are more beneficial. Still, the resulting decrease in emissions and deposition is actually very small, because the change in traffic volume is not high enough. The difference between the two study areas is smaller for the deposition than it is for the reduction in emissions. This, once again, is the result of the implementation and location of the new bicycle routes and how they relate to the roads that need a relieve in nitrogen deposition. Where the reduction in emissions was six times stronger for the Bruuk & St.Jansberg area, the reduction in deposition is almost similar with values of -0.02 and -0.03 mole N/ha/y. With the task-setting nature of the research, these values depend on the potential for cycling and how the modal shift towards cycling turns out in combination with the zones selected.

The total costs for the infrastructure of new bicycle routes is expensive and also varies, depending on the complexity and length of the route. On average the cost is 500,000 to 1.5 million euros per kilometer and can increase rapidly if bridges, tunnels or intersections are needed. The bandwidth for the scale of this measure is 10 to 100 million euros. The level of urbanisation is also a factor in the cost of bicycle routes: the route for the Binnenveld study area is more rural and less expensive than the route in the other study area, where a bridge is needed as well. The bridge over the Maas river alone is already 14 million euros (Fietsersbond, 2020).

4.1.15. Mandatory cycling on short distances

Of all the vehicles on the road during the morning commute, half of them are driving for work-related purposes (Boer, 2023). Enforcing a measure where car trips within 15 kilometers of commuting are replaced by bicycle trips results in this 50% modal shift from car to bicycle. This percentage will be put at the same value in the MOVE Meter tool since it accounts for all working days. The measure is also meant for a nationwide policy level to stimulate all employers and employees. The 50% decrease is applied to the four distance classes evenly. However, this research will not dive into the effects on all other Natura2000 areas in the Netherlands, outside of the study areas mentioned before. Results for the emissions show a widespread and noticeable decrease, which also leads to a slightly better result compared to other measures for the nitrogen deposition. The widespread effects, shown in Figure 4.6, apply to a further extent than just the study area and within the area, the reduction adds up to 30% on some roads. Because the measure only applies to short distances for zones within the study area, effects do run out after 15 kilometers outside the study area in most directions. The reach of the measure is easy to understand, as it originates from the strong modal shift that has been applied to short distances.

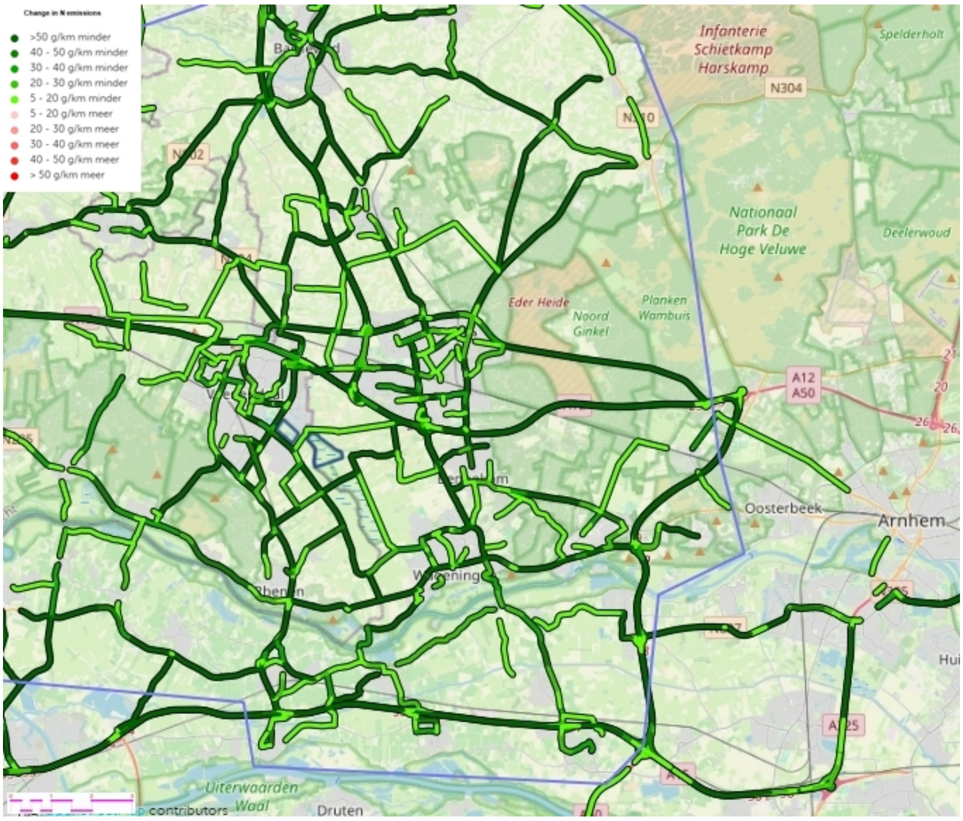

Figure 4.6: The widespread effects of a mandatory cycling on short distances policy. The Binnenveld study area is located in the middle-left of the figure.

This measure has a very high cost, which is mainly due to the scale it is used in for this research. A cost of 1 to 10 million euros is accounted for each region to facilitate a day of mandatory cycling to work. That brings the total cost for this measure to 10 to 100 million, as it is set as a nationwide measure to reduce vehicle traffic. The investments are used for bicycles, campaigns, legislative changes and physical cycling infrastructure.

4.1.16. Teleworking

Teleworking or (partial) work-from-home has the goal to reduce the peak hour intensity from passenger vehicles. Such incentives can be initiated at the employer' side for example. 10% less generation of traffic is taken for this measure, which resembles an extra telework day on average for example. This 10% decrease thus applies to all vehicle trips. Largest part of the reduction in O-D generation is for trips longer than 30 kilometers and a quarter is less than 7.5 (MuConsult, 023c). The implementation of percentages is shown in Table 4.3, accumulating to the desired percentage decrease in car trips. It's implemented into the MOVE Meter tool for zones up to 5 kilometer from the N2000 area. 43% of working citizens in the Netherlands works one or more days from home currently. A measure such as extra teleworking needs the support of employers and companies.

The percentage emission reduction and mole deposition once again similar to electrification and carpooling. The differences between the deposition reduction is smaller for the different low and high scenarios in this measure. The heavy reduction in traffic volume for trips between 30 and 60 kilometer realizes a significant reduction of trips on main roads: highways and regional connections. This implies that specific cases could benefit better from this measure, such as N2000 areas next to these regional connectors.

Distance class (km)	Reduction
0-3	0%
3-7	7%
7-10	10%
10-15	10%
15-30	22%
30-60	40%
60-100	10%
100+	0%

Table 4.3: Teleworking distance classes in the MOVE Meter

The cost of teleworking withholds the arrangement of boosts at employers and a campaign to encourage working from home. The costs vary between 1 and 4 million, fully dependent on the amount of employers the measure is aimed at. Various regions an partnerships have a mobility broker to arrange the contents of this measure. The average cost for each employer is 100,000. The yearly expenses to continue this measure are not taken into account. The geographical scale of the teleworking measure is smaller than the one from flexible office times and leads to fewer 'tracks', hence the lower cost.

4.1.17. Mandatory work-from-home day

This has been added as a self-conceived mobility measure and is a rigorous option. It entails a mandatory day in the workweek of employers enforcing the employees to work-from-home and don't travel. Goal is to spread this out nicely over the five working days and thus the mobility measure uses a 20% decrease in trip generation for a given morning peak hour. As the aim is to have this as a national rule, all of the Dutch zones in the model will see this decrease in trip generation. This measure also acts to put other measures into perspective and reduction in nitrogen deposition of other Dutch Natura2000 areas will not be taken into account for this research. For the distribution over the eight distance classes, the most attention is given to 7 to 60 kilometers. These have been given a 35% decrease while the other four distance classes shorter and longer than this range get a 12% decrease. This has been done based on Dutch research about the average distance driven for the work commute, which was 19 kilometers in 2020 (PBL, 020a). These percentages add up to the desired 20% overall decrease through weights.

Considering that this measure hold a pretty vast change in trip generation, the percentage decrease in trip generation for the study areas is rather disappointing. The most significant changes in intensities are visible on the main network of national highways and large regional roads. Because most changes are on the main network and the measure happens to be less applicable to local traffic, the amount of change in emissions inside the study area is small. On a positive note, the measure does result in less emissions. The decrease on the main road network is visible in Figure 4.7 as well. Around the highways in the region, the reduction is a couple mole on average for each hectare. The reduction is also visible at regional roads with a slightly paler green colour. Nonetheless, the reduction is very small at the Binnenveld study area itself with not even a 0.5 reduction in nitrogen deposition per hectare and that is disappointing with a measure of this scale. The dark green hexagons dotted around the Veluwe indicate a decrease of exactly one mole N/ha/y originating from modelling issues with AERIUS as a result of agricultural activities.

Similar to the other 'mandatory' measure that was aimed at a national geographical extent, the cost of this one is very high. The range is between 50 and 200 million euros. Aside from facilitating in the work-from-home possibilities, the investments are contributing to changes in policies and communication with employers. A large portion of the budget is also available as a compensation for the employee and his working from home.

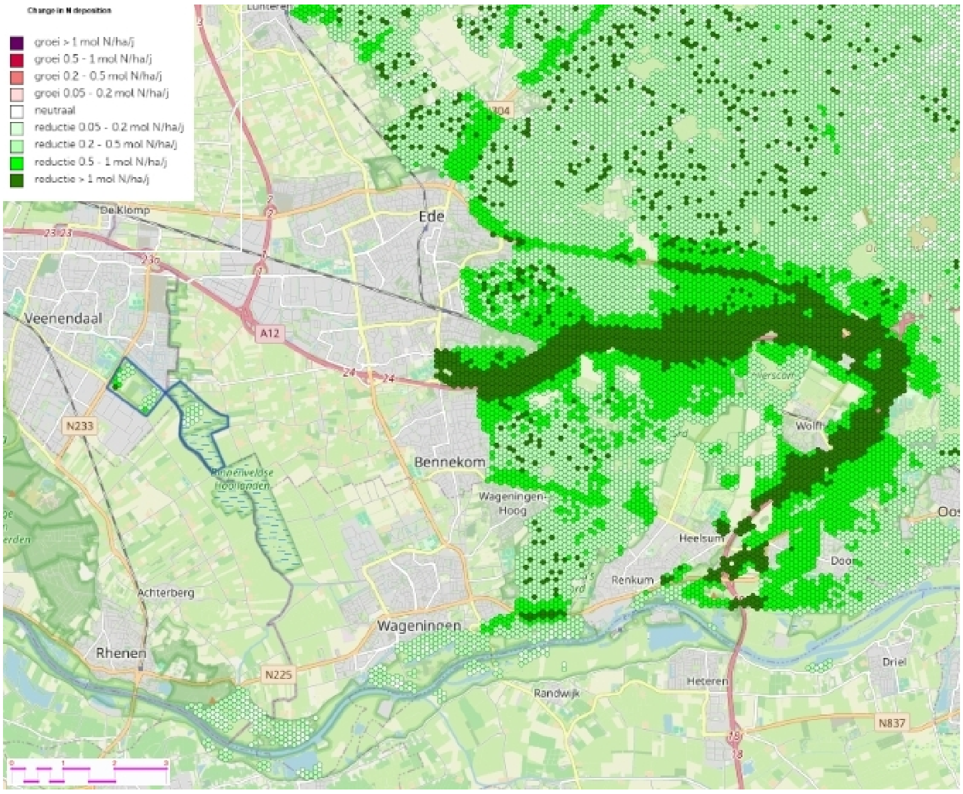

Figure 4.7: The decrease in nitrogen deposition from mandatory work-from-home in the center of Gelderland. A darker green resembles more reduction than lighter green.

4.2. Quantitative analysis overview

The values in Table 4.5 shows the percentage change in nitrogen-oxides emissions, based on values of kilograms per day. In the MOVE Meter tool, emission factors of calculation year 2025 have been used. Simply because this is the closest year with the current knowledge on the composition of the (future) vehicle fleet. The table before that, Table 4.4, illustrates the effects on traffic from the measures and relates to the causes from the Conceptual Model. This table is then also used to verify if the relationships from Figure 2.7 happen in the modelling. A short reflection on this topic is given in their own paragraph for each measure. An overall reflection on the additions in Table 4.4 is the missing link between 'routes' and 'volume' in the Conceptual Model. This came up multiple times and illustrates the feedback loop between the route choice and traffic volume. For both Table 4.5 and Table 4.6, measures that have been affected by the modelling constraint have been marked with gray to show that these are not completely verified. Conclusions on these modelling results will also follow in chapter 6.

Measure	Traffic effects	Expected from CM?
Intelligent traffic light systems (iVRI)	Slightly more kilometers driven on the network, but a better traffic flow leads to fewer emissions.	Yes
Road downgrading	Different route choice and lower vehicle intensities on subjected roads, but higher intensities elsewhere. Cumulative traffic volume is slightly lower. Lower speeds lead to more emissions on some roads	No, in some cases a lower speed results in different emission factor categories. The effect is then contradicting on the emissions.
Driving behaviour campaign	Improved traffic flow, but also higher vehicle volumes, from behavioural changes. The improved flow and speed does decrease emissions.	Yes, although improved flow affects volume negatively.
No-entry zones passenger vehicles	Large local emission reduction, but there is a cumulative increase of kilometers driven on the network. The increase of volume is a result of vehicles picking longer routes to reach their destination.	No, the measure also negatively affects the volume on other routes for more emissions.
Bypasses	More demand for car traffic and more kilometers driven, depending on the region and the location of the bypass. This results in higher emissions for some cases.	No, routing also affects volume positively and negatively. It relocates positive emission effects to negative effects elsewhere.
Electrification passenger vehicles	Decrease in trips and emissions on most roads with more significant results on higher intensity roads.	Yes
Carpooling	Reduced traffic volume on most roads in the study area, but not for short vehicle trips.	Yes
Flexible office times (peak-hour avoidance)	Reduced traffic volume in peak hours due to spread out office times, noticeable on almost all roads	Yes
Stricter emission standards ecological zones	A decrease in total kilometers driven on the network, but slight increase in cumulative emissions. Mostly because of adjusted emission factors from a change in speed.	Yes, but modelling restrictions made it so there are also changes in speed, volume and emission factors and not just restrictive traffic composition.
Park & ride, hubs and shared mobility	Very limited volume decrease and only visible on two roads. Basically no effect on emissions.	Yes
Cycling incentives for modal shift	Modal shift towards cycling leads to a minimal decrease in traffic volume and short trips.	Yes
PT incentives for modal shift	Small decrease in trips from modal shift and limited effects on short trips	Yes
Parking regulations in/for Natura2000	Modal shift with a minimal decrease in traffic volume as a result.	Yes
New bicycle through-routes	Slight reduction in emissions, carried by the small modal shift initiated by the new cycling routes.	No, the CM did not show a relation between routes and volume or O-D generation. It is however logical that some commuters switch to the bike.
Mandatory cycling on short distances	Large decrease in volume and vehicle kilometers, resulting in less emissions and deposition in he whole study area.	Yes
Teleworking	Slight decrease in traffic volume, which is also noticeable on main roads around the study area.	Yes
Mandatory work-from-home day	Very significant decrease in emissions from lower traffic volume in all of the Netherlands.	Yes

Table 4.4: Traffic related effects from implementation in the model

Measure	2040L Binnenveld	2040H Binnenveld	2040L Bruuk/St.Jansberg	2040H Bruuk/St.Jansberg
Intelligent traffic light systems (iVRI)	-0.5%	-0.1%	-0.6%	-0.4%
Road downgrading	+0.6%	+0.2%	+1.8%	+1.9%
Driving behaviour campaign	-1.2%	-1.7%	-0.8%	-0.7%
No-entry zones passenger vehicles	+0.1%	0%	+3.1%	+2.5%
Bypasses	0.0%	-0.2%	+0.6%	+0.7%
Electrification passenger vehicles	-0.8%	-1.5%	-0.7%	-1.5%
Carpooling	-1.0%	-2.1%	-1.2%	-2.4%
Flexible office times (peak-hour avoidance)	-0.9%	-1.6%	-1.0%	-2.1%
Stricter emission standards ecological zones	+0.1%	-0.1%	+0.2%	+0.2%
Park & ride, hubs and shared mobility	-0.0%	-0.0%	-0.0%	-0.0%
Cycling incentives for modal shift	-0.2%	-0.1%	-0.3%	-0.2%
PT incentives for modal shift	-0.3%	-0.4%	-0.2%	-0.5%
Parking regulations in/for Natura2000	-0.0%	-0.1%	-0.0%	-0.0%
New bicycle through-routes	-0.1%	-0.1%	-0.6%	-0.6%
Mandatory cycling on short distances	-0.6%	-0.9%	-0.9%	-1.5%
Teleworking	-0.5%	-1.0%	-0.4%	-0.9%
Mandatory work-from-home day	-2.2%	-4.5%	-1.8%	-4.1%

Table 4.5: Quantitative results percentage roadside nitrogen-oxide emission for each calculated mobility measure in MOVE Meter

Table 4.6 shows the reduction in mole between the base scenario and the measure. It is the average over all hexagons in the area and their respective change. The values for deposition in the Natura2000 areas show a wide variety, visible in Table 4.6. This table shows the average of all hexagons with the unit mole nitrogen per hectare per year. The average is chosen over the total sum of deposition reduction because it provides

Measure	2040L Binnenveld	2040H Binnenveld	2040L Bruuk/St.Jansberg	2040H Bruuk/St.Jansberg
Intelligent traffic light systems (iVRI)	-0.01	+0.02	-0.01	+0.01
Road downgrading	+2.93	+3.39	+0.03	+0.04
Driving behaviour campaign	-54.40	-28.72	-1.62	-4.36
No-entry zones passenger vehicles	-46.76	-35.32	-0.23	-0.98
Bypasses	+0.01	+0.02	-0.01	-0.01
Electrification passenger vehicles	-0.06	-0.10	-0.06	-0.05
Carpooling	-0.14	-0.15	-0.08	-0.09
Flexible office times (peak-hour avoidance)	-0.08	-0.10	-0.08	-0.08
Stricter emission standards ecological zones	+2.36	+1.20	+1.05	+0.97
Park & ride, hubs and shared mobility	+0.00	+0.00	+0.00	+0.00
Cycling incentives for modal shift	-0.02	-0.02	-0.01	-0.01
PT incentives for modal shift	-0.03	-0.05	-0.04	-0.05
Parking regulations in/for Natura2000	-0.01	-0.01	-0.02	-0.02
New bicycle through-routes	-0.02	-0.02	-0.03	-0.03
Mandatory cycling on short distances	-0.14	-0.17	-0.14	-0.15
Teleworking	-0.07	-0.08	-0.06	-0.05
Mandatory work-from-home day	-0.26	-0.34	-0.30	-0.20

Table 4.6: Quantitative results average change mole nitrogen deposition on a hexagon for each calculated mobility measure through AERIUS calculations in the MOVE Meter tool (mole N/ha/y)

an easier comparison to values given earlier in this research. The average reduction from the measure gives a uniform benchmark to compare between them and the current share from traffic. Most of the local measures provide a reduction between 0 and 0.15 mole N/ha/y based on the morning commute. The more rigorous and large scale measures of mandatory cycling and working from home result in a 0.14 to 0.34 mole N/ha/y reduction of nitrogen deposition at the N2000 areas in the study area. The no-entry zone measure provides significantly larger reductions, especially in the urbanized Binnenveld study area. For the other study area of De Bruuk & Sint Jansberg, a reduction of 0.23 to 0.98 mole is still a noticeable reduction. Main reason for the reductions too be this deficient is that nitrogen emissions and deposition can still carry over from other places and sources outside the study area and that the background levels of nitrogen deposition outside of these mobility measures hold it back.

The AERIUS Monitor was updated to provide some more context to the values in Table 4.6. The AERIUS Monitor now displays the nitrogen deposition from road traffic in mole per hectare per year (AERIUS, 2023). The most recent confirmed data for this is the year 2022. For the hexagons in the Binnenveld Natura2000 area the values of nitrogen deposition by traffic ranges from 71 to 157. For the Bruuk and Sint Jansberg combination the values are between 51 and 136. The most important note to be added when these values are presented is the fact that these are not just originating from the morning commute like the results in Table 4.6. What it does tell is that the reduction in deposition is very significant for the no-entry and driving behaviour campaign measures. However, certain results in this research pointed out that the values found for the campaign measure are stained by the modelling constraint of changes in speed. This was not the case for the road closure in the no-entry measure, which did not even include a full closure and did not remove all traffic from the road sections. That means that the results can even improve while it is already the most effective measure in absolute numbers. The values from the AERIUS Monitor also show that the other measures result in very low reductions on the N2000 hexagons. Even if the results were adjusted to 24-hour values instead of the morning commute, the *average* reduction is minimal. As mentioned earlier, the distance between the subjected road sections and hexagons is very important and a decrease in traffic that is further away, does not significantly reduce deposition at N2000. This is also visible within the studied N2000 areas, with the hexagons closest to roads in the modelled network receiving the most noticeable changes and the effects fading out over the distance.

4.3. Cost-effectiveness

The cost-effectiveness of the measures is displayed in Figure 4.8. Measures of which it is known that they show incorrect deposition results from the modelling constraint, have been left out, with thus 13 measures remaining. Some of the measures have been excluded so that no explicit conclusions can be taken in combination with their cost. Costs are split up between relatively low and relatively high, based on their given bandwidth. These are estimations and are based on expert judgment from somewhat similar cases and a another on a recent report. Estimations are also compiled using indications by CROW (2025) with examples in different fields such as infrastructure. Differences in the cost of infrastructure measures arises from the amount of kilometers and complexity with bridges for example. Since these situations and contexts differ for each real-life implementation, only an estimation of the average cost can be given. The costs for this CEA light version are only the implementation costs of policies, resources, infrastructure and communication. As explained in section 3.6, other costs such as vehicle-loss-hours and maintenance have not been taken into account for complexity and time-horizon reasons. The cost-effectiveness is an indication for policymakers.

The best cost-effectiveness can be found at the top-left quadrant where the costs are relatively low, while the reduction in nitrogen deposition is relatively good. The best cost-effectiveness within this corner can be seen at the no-entry zones measure. With low costs between 1 and 5 million euros, an outstanding amount of reduction in nitrogen deposition can be accomplished at Natura2000. Overall, the lower cost category ranges from 200,000 to 10 million while the higher cost category has a range of 3 to

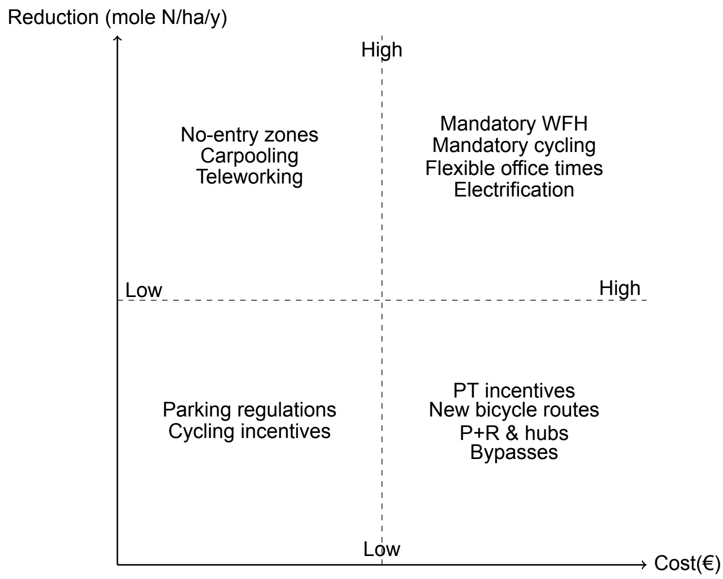

Figure 4.8: Diagram showing quadrants with the measures, sorted by costs and reductions. Invalidly calculated measures have been left out.

200 million euros. Moreover, two other measures were found to have a good cost-effectiveness: carpooling and teleworking. On the other end of the spectrum, four measures are relatively expensive compared to their contribution in the reduction of nitrogen deposition. Partly because their effect found in this research was minimal, but it also arises from expensive infrastructural costs. Other measures that score well and can be considered, less rigorously than Figure 4.8 suggests, are parking regulations and flexible office times. The bandwidth of the costs plays a large part in this, along with specific implementations of measures. Another side factor should be taken into account for the two 'mandatory' measures for example: their cost is based on a nationwide approach and thus higher than it would be for a local approach and in this case, the reduction on all other Natura2000 areas has not been taken into account for the effectiveness. The best cost-effective measures show both proximity and traffic volume as important factors.

5
Discussion

This chapter critically reflects on the obtained results and the points given in this discussion chapter reflect back on the methodology and literature but do not necessarily conclude on the results. There will be critical reflections on the specific data used in the tool, effects that have not been taken into account, combining mobility measures and overall on the methods used in this research. This last paragraph consists of the validation and measure-implementation, modelling constraints and the Conceptual Model too.

5.1. Forecasting and bandwidths

The first note on the results of this research is that it is based on forecasting and potential values for the future. These forecasts for future years, such as 2040 in this research, are based on the best current knowledge but do come with uncertainty. Similarly, the expected autonomous decrease in nitrogen deposition from LNV (2022) is also a projected forecast and can change with new developments for example. This expected autonomous decrease of 127 mole N/ha/y till 2030 is a lot larger than the values found in this research anyhow. To combat these uncertainties, bandwidths are given. The results for the emissions illustrate these as well (Table 4.5). The outcomes in the 'high' economic scenario can be double the outcomes of the 'low' economic scenario. Since a lot of the measures worked with a task-setting decrease in traffic generation in percentages, it is more pronounced in the scenario where there is more traffic to begin with. The values in Table 4.5 and Table 4.6 do provide good boundaries and indicate the bandwidth of the result, even though these are still predictions.

5.2. Static or dynamic traffic assignment

The advantages and disadvantages of the type of traffic modelling used came to surface during the research. It seemed that for some of the mobility measures the dynamic traffic modelling method is an interesting option, as advocated earlier in section 3.2. The measures that deal with flow and congestion would benefit the most from dynamic modelling, as well as measures with new routes or rerouting. For non-operational measures, the static traffic modelling in the MOVE Meter works sufficiently. However, the implementation of the bypass and bicycle route measures also worked fine without the dynamic traffic modelling. The traffic was reassigned over the (new) network with the implementation and new values were obtained smoothly. This type of modelling is sufficient for these long term predictions.

5.3. Indirect and longterm effects

There are a couple effects that are not taken into account in this research. The results for the mobility measures only contain the direct, standalone effects and not the indirect effects. Potential long-term effects are likewise omitted. Measures could indirectly influence general travel patterns and behaviour, leading to even fewer nitrogen emissions (Rodrigue, 2020) than directly calculated in the tool. The same can be said about long-term effects of hub measures and spatial planning for example. It is well established that measures can trigger changes through feedback loops in the 4-step-model. Similarly, the Conceptual Model also works with causalities (Figure 2.7).

5.4. Combining mobility measures

An option that has not been carried out in this research is the ability to combine different measures. This is possible in the MOVE Meter tool. Similarly, cumulative effects of singular measures can also be analysed. Judging by the results in the tables of chapter 4, some combinations can be of critical help in the reduction of nitrogen deposition through local solutions. Combinations where both the trip generation on a road decreases and traffic routing is altered show potential for example. Modal shift showed its advantages and so did improved flow or closure of a road. These combinations are likely to produce better effects than combining measures who are both aimed at less vehicle trip generation. A cap that has also been discussed in Mangones et al. (2020). And similar to that note, even the rigorous, and more nationally implemented, measure of a mandatory work-from-home day in the week with a significant trip generation decrease 'only' resulted in 1.8 to 4.5 percent less emissions in the study areas. This translates to less than one mole N/ha/year reduction in the morning commute.

5.5. Methods, models and validation

Validation of the research methods and the calculation of the measures is an important aspect. Especially with the deterministic, task-setting nature of the tools that have been used. Existing documents provide an excellent way to validate the calculations: satellite, field and on-road measurements of nitrogen (LNV, 2020; KNMI, 2022; Dai et al., 2024). These measurements could validate if the bandwidths of modelled values are possible. One aspect of the datasets used that cannot be changed is also put to discussion: the level of detail in the traffic modelling. Thankfully not all roads are included into the NRM data, otherwise the computation times increase significantly. However, including certain roads could be vital for the research, given their proximity to N2000 areas. Users of the NRM dataset of Dutch roads do not have any influence on which roads are included though. In some cases the user may need a specific road added or removed, for example with measures that require re-balancing of the traffic load on the network. In this research this was mostly noticeable in urban environments, were some urban centers had too many or too few NRM roads. An alternative would be to use more local or regional traffic models that include more and smaller roads.

A recurring issue in this research was the modelling constraint with emission factors through automatic assigning of road types after adjusting the travel speed. As Figure 5.1 shows, the emissions and deposition of ammonia behave normally in the traffic model with an increase as a result of the measure. This was expected, as the traffic volume increased on the Rondweg-Oost from the reduced travel times. For the same road, the nitrogen emissions were more than halved, resulting in the green hexagons of Figure 5.2 with the vast reduction. This was not as expected and the occurrence stems from a shift in roadtype after the speed was increased. The constraint was in this case working with emission factors in the traffic modelling. Main reason of this coming to the surface was the task-setting nature of the tools in combination with the speed on road sections. The sudden change in emissions from a small increase or decrease in speed heavily influenced the resulting effects of some mobility measures. The emission factors are included in the dataset for traffic modelling. The task-setting implementation and conceptualizing measures with deterministic percentages for example was a faltering part of the research. It could be advantageous to have some sort of safety slot and be able to manually correct emission factors. This would help research these measures with speed adjustments.

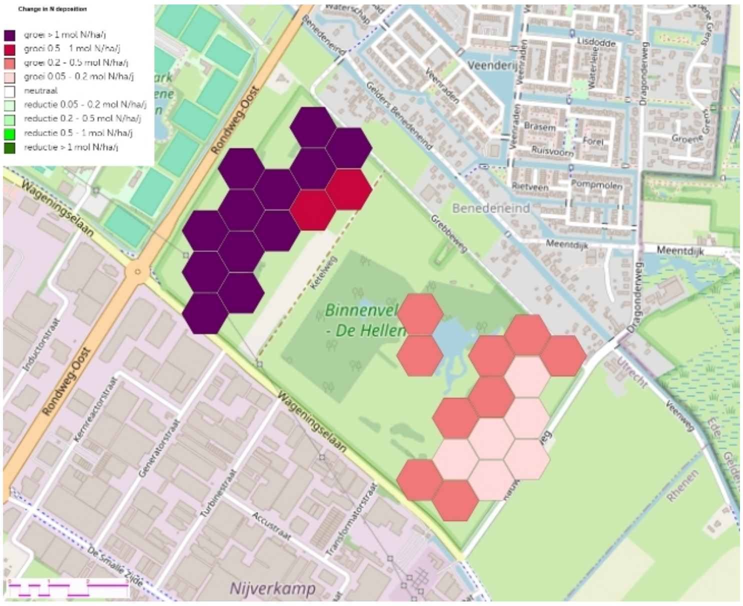

Figure 5.1: Resulting deposition of NH3 from the driving behavior measure, showing an increase which is stronger near the road west of the N2000 hexagons.

It's not visible in the Conceptual Model (Figure 2.7), but the effects of proximity for the measures can be significant. The relationship shown between emissions and deposition is affected by the scale at which the mobility measures are applied. As seen in the results that have been discussed in chapter 4, the cumulative amount of emissions on the traffic network can increase, while the deposition in the Natura2000 areas decreases. A prime example of this are the measures of downgrading roads to lower speeds and the closure of specific roads. More kilometers are driven, leading to more nitrogen emissions. However, since these are not concentrated at the 'most vulnerable' roads or close to the N2000 areas, nitrogen deposition decreases. This suggests that more deposition occurs elsewhere and that further research is needed towards the modelled ranges of 5 and 25 kilometers aerial transport distances of nitrogen emissions (section 3.3) to gain a clearer view of the net gains. Addressing further upon the proximity of measures was the research by Donovan et al. (2022) and the consequential measure of parking regulations and no-entry zones in this research. The task-setting approach was not the best way to model the effects of parking since it used a modal shift and the proximity is neglected in a large-scale data model and tool. The effects of proximity did show for the no-entry measure as this was a much larger scale of a decrease in traffic volumes. This does show that the results of Donovan et al. (2022) are striking and should be investigated upon further in more refined models and tools with possibilities of

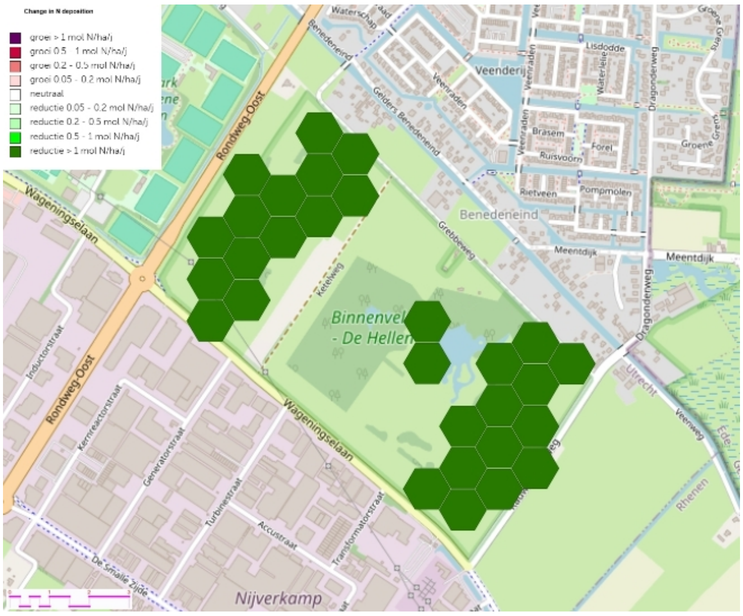

Figure 5.2: Resulting deposition of NOx from the driving behaviour measure. The wrongful reduction is more significant near the road west of the N2000 area.

modelling parking regulations and effects. This includes the use of 24-hour data and not just the morning commute, since the demand to park at natural areas is at its lowest then while it is at its peak in the weekends.

Another point of concern is the task-setting implementation of mobility measures into the MOVE Meter tool. The simplicity of this implementation, where the measure is applied using straightforward figures, offers convenience as a positive aspect. There are also drawbacks. Measures are mainly becoming best guesses and approximations when implemented in the model for example. One case of this is the new bicycle routes, where results show that it is just the modal shift and that introducing new routes does not lead to new computations. Another limitation is that percentages for modal shift and trip generation cannot be expressed in decimals. This not only reduces precision but also hampers an even distribution of the decrease in other cases. In realistic situations, the importance of local characteristics is much bigger as the implementation is deterministic now in terms of values and percentages. For the comparison between the study areas, keeping the operationalisation the same is convenient. Some flexibility in the interpretation of a measure is a choice in line with the theoretical assumptions of the research. In reality, every situation is much more complex than the modelled scenarios. The way the measures are implemented in this research are very 'what-if' and depend on assumptions and key figures from previous evaluations. Alternative real-world conditions could lead to different outcomes. The implementation fits the lack of exact data and the use of a quickscan tool, but more detailed research requires specific implementations focused on the local context.

One part of the results that caught attention is the lack of a decrease in short vehicle trips from the modelled mobility measures. This is relatively concerning as previous research indicated that the focus has to be laid on emissions from local traffic (Huang et al., 2022). For most of the measures in this research, the share of short trips even went up instead. An exception to this result are the measures where rerouting of traffic occurs, such as bypasses and changes in travel speed. The decrease in short trips from measures that are focused on cycling are more logical. These are targeted at the shortest distance classes. Foremost reason is the way of modelling the traffic generation and zones in the MOVE Meter with the study area demarcation. A good share of short trips is possible within the study area, but there will be few short trips leading in and out of it because of the aggregation of zones and the distance to these centroids. For a better modelling of these important short trips, it may be necessary to configure the study area much larger, but this will increase computation times.

Throughout this research, the figures for truck emission and thus their deposition has been the same. Being able to model and calculate the cargo traffic as well would highly benefit the precision in the measures. The importance of modelling the trucks has been underpinned in existing theory, mentioned in section 2.5. Badshah et al. (2019) explained that diesel trucks emit as much as 100 private vehicles in urban settings, hence the possibility to reduce nitrogen deposition greatly near urban environments. This would apply better to the Binnenveld study area compared to the area of the Bruuk & Sint Jansberg, as there was a lot of through- and regional traffic next to the Binnenveld, causing higher truck intensities as well. One lingering issue with mobility measures is the addition of nitrogen deposition on some hexagons. Measures that alter the routing or increase traffic volume on other road sections can increase deposition. Figure 4.1 is an example. Hexagons near roads with increased volume due to detouring showed up red because the nitrogen deposition slightly increased. This can introduce an issue since the Netherlands states that there can never be an increase in deposition of more than 0.005 mole N/ha/y if someone applies for a permit, even though the measure is overall very good for the reduction. Such permits are used in different cases, including building permits. If there is an addition of more than this value, approval is needed with mitigating measures (VRO, 2020).

6

Conclusions and recommendations

This chapter answers the research questions from the obtained results and sets recommendations for future research and policymakers. The conclusions address the Conceptual Model, traffic modelling aspect and effectiveness of measures.

6.1. Effectiveness

Quantitative results for nitrogen emissions and deposition demonstrate that some measures outperform others and that different geographical and spatial contexts also influences effects. Closing one or more roads to private vehicles emerges as the most effective measure for reducing nitrogen deposition. However, it does not achieve the greatest reduction in nitrogen oxide emissions and in fact ranks among the least effective in terms of cumulative emissions. This underpinned the importance of proximity. Existing theory and tools, such as Figure 2.2, illustrate that a short distance between a road and a Natura2000 hexagon strongly correlates with a decrease in deposition, even when total emissions from other roads in the study area increase.

The results show that the measures can be divided into two groups as well. The measures that are aimed at a change in traffic volume such as a modal shift work best if they are set up at a larger, non-local scale. These measures had the best effects on high-intensity roads like the highway network. The two self-identified measures that applied to many more zones, and resembled a slightly more nationwide approach, also scored well because of this. However, the effects of the more national policies for example, are not that much better compared to the local measures and should not be focused on. Especially with their much higher cost then the others. The effects of measures with an aim at traffic volume were low on local roads where there are less vehicles to reduce in the first place. There were measures that worked relatively better as local measures, even though the results do not directly show it. Closing roads for passenger vehicles decreases the nitrogen deposition significantly with 0.23 to 46.76 mole N/ha/y in the morning hours. The same accounts for the bypass measure and a potential strong relief in local traffic volume. Both these measures strongly depend on geographical context though. This context also defines the effects these measures can have on other sensitive areas due to an increase in nitrogen emissions elsewhere. In general, a lot of the researched measures do not decrease the nitrogen deposition at the N2000 areas by a significant amount based on the traffic volumes of the morning commute. Most values of the reduction are between 0 and 0.17 mole N/ha/y.

Effective measures on a local scale to reduce nitrogen deposition are either aimed at short proximity to natural areas or induce strong reductions in traffic volume with a focus on specific traffic demand for roads next to N2000 areas. One measure scored exceptionally well in the reduction of nitrogen deposition, but increases the total amount of emissions. This was the no-entry zone measure, also known as a road closure. Taking away almost all of the direct vehicle emissions in or next to N2000 areas reducing the deposition at a very local scale. The detours from traffic result in more emissions, and thus deposition, elsewhere though. Meaning that the implementation of such no-entry measure differs for each context and works less well in some other cases. The results were good, but significantly lower for the deposition reduction in the Bruuk & St.Jansberg study area for example. This also reflects on one of the research questions if measures and results can be generalized. Some of them can be implemented straightforward to other regions while most implementations require specific adjustments. The urbanization level of the local area also plays a role in this in combination with the traffic volumes. The recommendation for most of the mobility measures is thus to use a quickscan tool for different geographical contexts, but overall the measures should see comparable results as in this research. The measures aimed at a reduction in traffic generation, such as carpooling and flexible office times are easier to generalize.

The results point out that traffic and mobility do not seem to be the best way to reduce nitrogen deposition on Natura2000. The reduction from mobility measures is limited in absolute values but also in the bigger picture after modelling these measures. Closing a road gives a lot of reduction in theory and according to the results in this research, but in reality the emissions and deposition get blown into the N2000 from other places and sources anyway. These are not picked up by the modelling of the mobility measures because they are either outside the study area. The same accounts for other sources, from which the deposition descends down at the natural areas in unknown intensities due to meteorological conditions. That said, in combination with the presented distribution in Figure 2.3, it would be beneficial to look at other sectors as well for an efficient reduction in nitrogen deposition. Reductions from mobility measures in the bandwidth of 0.01 to 0.98 mole N/ha/y in the morning commute do not exactly stack up to the reduction from measures of the agricultural sector for example. In other context, these mobility measures provide enough reduction in nitrogen deposition to free up space for licenses and permits, but will not help enough in the preservation of nature and species.

6.2. Conceptual Model and theory

A starting point in the theory was the lingering issue of the effects of longterm exposure to excessive nitrogen deposition. Basic sources and literature on nitrogen showed that the extra amounts of nitrogen boost the growth of certain plant species and poisons the ground. Consequences of exceeding Critical Deposition Values of the habitats involves two issues. The main issue is this destruction of habitats and species, while a second issue is the legislative discussion that followed from it. The research did show the importance of proximity for nitrogen issues and how differences between emissions and deposition can be interpreted. Theory already pointed out that most of the deposition takes place within 200 meters of the source. This was visible in the results, as areas closer to (busy) roads showed more pronounced figures. This is an aspect of the modelling in research that needs to continue to develop. The conceptual model presented in this research (Figure 2.7) contained a couple of components on vehicles and traffic that followed from existing theory. Table 4.4 reflected on the performance of the conceptual model. Results mostly stroked with the relationships that originated from theory, but there are some exceptions. The modelling restrictions with the use of speed and emission factors derailed some of the thought processes around vehicle and traffic components. One example was the measure of new bicycle through-routes. The theoretical model did not show a relationship between routes and volume or O-D generation because the blocks are aimed at a different transport mode. A small feedback loop from routes to modal split would solve this small confusion. Additionally, the issues with the emission factors were somewhat in line with theory on vehicle speed and resulting emissions. The optimal vehicle speed for the lowest nitrogen emission is between 60 and 80 kilometer per hour. Very low speeds and higher speeds such as highway speed limits produce more emissions from vehicle engines. Hence why the emission factors are correct, the issue is just the way it is implemented in traffic modelling. At least for the quickscan tool used in this research. Results also confirm what a part of the presented theory showed and the proximity of measures is important, hence why parking regulations and no-entry zones are effective measures.

6.3. Traffic modelling

The results in this research are based on modelling and computation, whereas it is recommended to also validate and research the nitrogen deposition on location itself. There are many advantages of working with traffic modelling and technological systems, especially in light of future years and measures that could drastically change output. Disadvantage is the uncertainties and differences on a microscopic level. Most calculations are still based on average values and effects on a very local scale can differ, such as the harm on specific flora species. Hence why measurements on location are important and further research needs to incorporate these differences in the future, as every bit of nitrogen relief helps in some cases.

One recommendation stemming from this research is the further development of tools and modelling to investigate emissions and measures. This does not only apply to nitrogen (deposition) but also for other emissions such as carbon-dioxide. The choice between different projection years for datasets is sufficient, but the refining process to pick and exclude specific roads in traffic modelling could be better. The main focus should be on the aspect of local scale and ability to zoom in, as was the case for the aim at N2000 areas. Now not only does this further development apply to the traffic modelling, but also the calculation of the spreading of emissions, which in the research was aided by the AERIUS model. Producing a well-grounded and transparent model for the aerial spreading originating from nitrogen sources is necessary to improve research. A conclusion is that nitrogen deposition is difficult to model, assess and evaluate with the current instruments. It is not well suited yet to perform local-scale research on nitrogen yet, especially with the spreading of emissions from other areas and other sources. A general recommendation would be to perform similar local research but with local traffic models to better investigate results for proximity in nitrogen deposition from mobility measures. A second general recommendation is researching mobility measures without task-setting, deterministic input options. Measures such as the electrification of vehicles are difficult to model. Even though it fits a quickscan tool with the ease of use from task-setting, more detailed research and other ways of initiating the measures is needed.

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A

Appendix A: Operationalisation of measures

This overview relates to section 3.1 and chapter 4. The list gives a brief description of the mobility measures and goes hand in hand with the operationalisation. The description is connected to Table 3.2. This first list gives a brief look at the delimitation and reach of the measures, including some of their sources. Further description of each measure will be given in their respective paragraphs along with an analysis of the results from the MOVE Meter tool.

- **Intelligent traffic light systems (iVRI):** Better capacity utilisation and improved traffic flow because the traffic light knows how much and what kind of traffic is approaching and which routes will be taken. From previous research and policies it is known to reduce emissions (MuConsult, 2021). Efficiency in resolving traffic and improved flow of certain target groups such as freight traffic contribute in this measure, including 10% less travel time on a road section and fewer stop-and-go movements (BeMobile and MuConsult, 2021). This is translated into the MOVE Meter tool by increasing the free flow and peak hour travel speeds by 5% on road sections within 5 kilometers of the Natura2000 area. This measure has also been mentioned in section 2.5.
- **Road downgrading:** The effects of downgrading roads can be found on a very local level. Effects are more severe with longer road sections and drastic speed reductions. This measure does influence travel time and accessibility. The optimal speed has been set at 60 km/h based on various sources in section 2.5 (Zachariadis, 2008; Smithers et al., 2016). The speed has only been decreased on road sections where the current speed was above 65 km/h and only within 25 kilometers of the N2000 area. It is not applicable to highways since that is a different spatial level.
- **Driving behaviour campaign:** Improved behaviour behind the wheel through educational messages and infrastructure interventions. A 16% more efficient car park based on earlier research with more constant speeds and less stops (MuConsult, 2021; ECOdrive, 2012). This is translated to

40% better traffic flow in MOVE Meter (Voogt et al., 2011). This implies that the gap between the speed and free flow speed will be reduced by 40%, or less if they are already the same speed in the traffic model. This accounts for all of the road sections within 5 kilometers of the N2000 area.

- **No-entry zones passenger vehicles:** Closing roads in or closely nearby Natura2000 as a very local mobility measure. The news article of NOS (2023) showed that such measures are possible by municipalities or provinces as long as other routing possibilities are in place. However, closing one or multiple roads could lead to higher traffic intensities elsewhere. This relates to the 'routes' block in the Conceptual Model and especially through- and destination traffic. It has to be said that for almost all Dutch roads, it is impossible to block all of the traffic, as vehicles with their destination on the road are still allowed. A similar case stands for roads that are dependent on certain roads for accessibility. It also applies to trucks who are more reliant on the NRM network and won't take local roads that easily in case of disruptions.
- **Bypasses:** The addition of new roads to relieve roads in or near N2000 of traffic volume. These will be drawn in based on the O-D data and larger demands. Along with these bypasses there will be an increase in travel demand for specific, pre-analysed zones in the study area by 10% similar to capacity increasements effects on private cars (Mangones et al., 2020; van Maarseveen and Romijn, 2015). This measure is bound to routing and volumes and directly influences emissions.
- **Electrification passenger vehicles:** A more rapid transition towards electric vehicles than forecasted for in 2040. Instead of the values in the integrated traffic model, incentives to stimulate electric vehicle usage lower the use of conventional cars even more. In the model, a 10% change is translated to 8% less vehicle demand as electric vehicles do not have operational emissions (Bellin et al., 2022; PBL et al., 2022). The difference in percentage is due to the workaround of modelling restrictions and the fact that electric vehicles are not equal to avoided car trips and changed intensities. They are still present on the network and contribute to traffic intensities and thus traffic jams. This measure correlates with the traffic composition of the Conceptual Model. This conversion from 10% to 8% has been underpinned in Kosmidis et al. (2023) as well, stating that the convenience of cars and lower operational costs of electric vehicles can increase car usage by travellers, compared to anti car-traffic measures. The decrease in volume accounts for zones included in greater regional cooperations.
- **Carpooling:** Facilitating in car-sharing to reduce vehicle kilometers with a focus on the commute to and from work. Traffic volume will reduce. Instead of the current average of 5% usage rate on a national level, a boosted 15% usage rate will be used for this measure (MuConsult, 023c; Jorritsma et al., 2021). Different percentages of volume reduction are applied for the distance classes and it applies to all zones in the study area.
- **Flexible office times (peak-hour avoidance):** A decrease in car trips during peak hours to avoid traffic jams, supported by the employer. The percentage found for fewer car trips is 10% in the rush-hour (MuConsult, 2021; Tertoolen and Ruijs, 2015). Car trips can be swapped for public transit, bicycle, teleworking or altered departure times. Effects on the modal

split, O-D generation and volume blocks of the Conceptual Model. This measure is implemented into the tool with a somewhat linear decrease over all distance classes to represent all types of employees, but with a focus on longer distances. These longer trips hold the most resistance to travel to work during peak-hours. The zones are picked through regional alliances.

- **Stricter emission standards ecological zones:** Earlier research pointed out that there is not only a reduction in nitrogen emissions due to better technological requirements, but also a decrease in through-traffic for the zone (Voogt et al., 2011). The Belgian research stipulated this at a 2% reduction in traffic intensity as an average of both introducing and tightening the zones. This means that there is also a change in traffic volume from emission factors in the Conceptual Model. This measure has also been mentioned in section 2.5. The speed and capacity on roads within 2 kilometers of the N2000 areas have been lowered by 10%, while the 2% decrease volume decrease applies to a handful of zones at the protected area.
- **Park & ride, hubs and shared mobility:** Park and Ride, hubs and shared mobility solutions are used to reduce the amount of passenger vehicle trips and substitute them with other options with the thought of usership instead of ownership. A trip generation of 3 less vehicles in the commute will be used as an average value of solutions in Free Floating Cars, regional hubs and shared bikes and scooters (MuConsult, 2021; VerkeersNet, 2022). A value of 5 will be used for a couple larger urban zones in the study area. The decreased vehicle demand applies to all zones in the study area, as the emphasis is on urban solution and willingness to use. This measure correlates with volume, modal split and O-D generation from the Conceptual Model. There is slightly more focus on shorter distances stemming from shared bikes and scooters in this measure.
- **Cycling incentives for modal shift:** The promotion of cycling and employer incentives have the most effect on short trips, under 15 kilometers. Mileage allowance for cyclists is one of those incentives for example. The addition of cycling fastlanes and through-routes invites longer distance trips for the bicycle. This is especially the case for speedpedelecs and e-bikes. With these cycling-through routes, the measure gets interesting outside the cities as well. Employer incentives, campaigns aimed at travel behaviour and infrastructure improvements for more bicycle usage are at the expense of other transport modes, constructing a modal shift of 8% at the three shortest distance classes and for zones within 5 kilometers, since it is also dependent on the current incentives of employers (MuConsult, 2019).
- **PT incentives for modal shift:** Incentives and (employer-)packages to reduce passenger vehicle kilometers and promote the use of public transport to and from work. The share of vehicle trips saved is approximated on 6% (based on different measures) and these commuters take any form of public transit as a replacement after promotion and incentives (van Essen et al., 2018; MuConsult, 2021). This percentage is evenly distributed over the distance-classes and complete municipalities within 5 kilometers of the Natura2000 area.
- **Parking regulations in/for Natura2000:** A decrease in vehicles arriving in or

near the N2000 area from parking regulations. Regulations lead to different mode choices and fewer drivers searching for a spot. The installment of parking regulations leads to a 15% decrease in destinations for the zones inside Natura2000 and on the edges for visitors (MuConsult, 2021). Most of the avoided trips are shorter than 10 kilometers. From the Conceptual Model, this mobility measure relates mostly too modal split and volume.

- **New bicycle through-routes:** Addition of one or more new bicycle paths to relieve roads in or near N2000 from vehicle traffic through a modal shift. Thus accompanied with a 14% change in modal split from personal vehicle volume during peak-hours to bicycle usage, applied up to 10 kilometers of the new route which upholds specifically targeted cities (TourDeForce, 2023).
- **Mandatory cycling on short distances:** An extreme modal shift from vehicles to cycling within 15 kilometers. This measure entails the mandatory cycling day for those employees who live close enough to their workplace. It also accounts as a more national policy and thus applies to all Dutch zones. The modal shift is 50% for the four shortest distance classes at all Dutch zones.
- **Teleworking:** Incentives to promote working from home and thus reducing vehicle usage. Such incentives can be initiated at the employer' side for example. 10% less generation of traffic is taken for this measure, which resembles an extra telework day on average for example. Half of the reduction in O-D generation is for trips longer than 30 kilometers and a quarter is less than 7.5 (MuConsult, 023c). This allocation will also be implemented into the MOVE Meter tool for zones up to 5 kilometer from the N2000 area. 43% of working citizens in the Netherlands works one or more days from home currently. The change in O-D generation (Conceptual Model) affects the traffic volume.
- **Mandatory work-from-home:** A large decrease in trip generation from a mandatory day of not traveling in rush hour to work. This decrease has been set to 20% and is thus theoretically spread out over the working week. A focus in the decrease has been put on the distance classes between 7 and 60 kilometers as the average Dutch commute is 19 kilometers (PBL, 020a). The measure applies to all Dutch zones.