The impact of urban speed limit reduction policy on public transport

Using a simulation model to study the impact of urban speed limit reduction policy on public transport in a case study of The Hague

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by

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Cover: GTL8 tram from HTM driving in Delft, by Rio-fotografie (adjusted)

Preface

This thesis represents a significant milestone, marking the transition from student life to professional endeavours. Luckily, this thesis provided me the opportunity to explore two incredible companies. Despite their differences in culture and settings, both organizations shared a common thread: supportive, authentic colleagues who demonstrated that professionalism and individuality can coexist. The inspiring projects and gezelligheid in the office have made me excited for the next chapter of life.

I would like to extend my heartfelt thanks to my committee members for their invaluable guidance, helping me navigate the challenges—both anticipated and unexpected—of this project while fostering my personal and professional growth. First, I would like to thank my company supervisors. Monica and Thomas, thank you for making me feel more than welcome at Goudappel and HTM. You reminded me to place things into perspective, helped me to reach the right people, and showed that frequent small check ins are of great value.

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To my friends and family, I am immensely grateful for your encouragement, patience, and support throughout this journey. On the one hand they gave me welcome distraction helping me to forget the pressure of the thesis during the evenings and weekends. Furthermore, they gave me the stimulation, motivation and energy for the next push in my thesis, providing me the perspective and a finish in sight.

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Laurens, despite a year filled with intense personal events and the demands of a thesis, know that your proud-to-be fiancée is fully yours again!

Timo Koster
Delft, December 2024

Summary

Introduction

Over the last years, Urban Speed Limit Reduction (USLR) policy gained more attention of road authorities and municipalities as a tool to improve the livability and safety of cities. USLR policy is a set of road interventions dictated by the city council, aimed at reduced vehicle speeds. The proposed decrease of vehicle speeds worries public transport operators. They worry that lowering public transport speeds will result in longer travel times for both public transport drivers and passengers, resulting in a less attractive service. This might lead to decreased ridership while operating costs increase.

The impact of USLR policy on public transport speeds, travel times, modal share and passenger volumes due to USLR policy has not yet gained attention in scientific literature. Therefore, this study will answer the following research question:

> How will Urban Speed Limit Reduction (USLR) policy impact public transport operators in terms of public transport speeds, travel times, modal share and passenger volumes?

Case study methodology

A USLR policy scenario is formulated for the case study city of The Hague. In line with the cities' ambitions, streets planned for redesign until 2030 and under the attention of authorities are included in the scenario. This scenario was modelled in the V-MRDH model, a multi-modal gravity simulation model that simultaneously calculates the trip distribution and modal split. The modes public transport (bus, tram, metro, train), private car and bike (e-bike and regular) are included, for which both the car and public transport speed limits are reduced. The USLR policy scenario was compared to an existing reference scenario of The Hague in 2030 to estimate the impact of USLR policy on mobility in The Hague, and PT specifically.

We formulated a USLR policy scenario consisting of 99km of streets where the speed limit will be reduced and enforcement measures are assumed to take place. These streets were identified based on existing proposals from the city council of The Hague. This list was adapted based on (reports of) discussions with stakeholders, including municipality representatives, emergency services and transit authorities. Google streetview is used to determine the current speed limit, the current street type, and the alternative street design options based on current layout. Outcome of this step is a list of selected streets explaining the change of the speed limit and the change of the road category.

Car speed limits in the model occasionally deviate from legal speed limits, as they are calibrated to make sure modelled car volumes match measured car volumes on each street. The offset in modelled speeds in comparison to the lawful speeds makes implementing the policy more difficult. For example, a street with 50km/h by law that is instead modelled as 40km/h cannot simply be changed to 30km/h. After all the calibration of the model would be erased. To solve this modelmatic problem, discussions with six model experts are held. Finally, the choice is made to reduce the speed by 40% instead of by 20km/h. This allows the calibration effects to be less disturbed. When the street category changes from a flow street to a local street, we applied a 60% speed reduction and a change of the streets BPR parameters.

No PT driving speeds are available in the simulation model. Instead, per PT line the travel time is included for each stop from the previous stop per time period. Therefore, based on the timetable times and link length, for each link the minimum, maximum and average timetable speeds are calculated. However, this travel time consists of dwell time, time to accelerate/decelerate, driving time, and time lost to disturbances. Therefore, the assumption is made that the calculated speed derived from the timetable lies 5km/h lower than the real driving speed. This means the USLR policy speed limit of 30 km/h is instead applied to PT speeds as 25 km/h. All links with speeds between 42 and 51km/h had

their speed reduced by 40%. Links already in the range of 25-42km/h are set to a flat 25km/h, meaning a speed reduction of less than 40%.

Using this methodology a USLR policy scenario of the Hague was created reflecting the expected changes in 2030, following implementation of the USLR policy scenario. Around 7% of the total street network length in The Hague is included in the USLR policy scenario.

Case study results

Incorporating the speed limit of the formulated USLR policy onto PT lines shows that half of PT lines driving over a USLR-affected street are hardly affected in their travel times. Speeds vary per line, location, and time of the day. While some lines had no effect, other lines experience an reduction of the average speed up to 7,7%. On average, travel times of PT lines travelling over USLR-affected streets increase with 1,2% during morning rush hour. The limited overall impact on PT travel time is likely the result of only small parts of PT route being affected. Also, PT travel times is expected to have less impact than cars because PT operates wider vehicles and has to brake and accelerate for each stop, leaving for less time travelling at the speed limit.

When considering all public transport lines using USLR-affected streets, the total daily timetable hours are estimated to increase by 0.9% The absolute effect on timetable hours is dominated by the non-rush hour period, due to its long duration. Meanwhile, the relative effect on timetable hours is quite even for the time periods. The effect on timetable hours is projected per street as well, but the uncertainty about speed estimations requires a prudent approach. Despite these estimations limitations, we can conclude that the main underlying cause for the timetable increase depends on the location of the street in the city. In the city centre, high frequencies contribute to large increases of needed timetable hours per street, despite small changes in speed. Outside the city centre the major changes in travel speeds cause large increases of needed timetable hours per street, despite low frequencies.

Table 1: Change of TTH per year due to USLR policy. Hours are rounded to the nearest hundred.
Yearly change of TTH is split up between three time periods of the day, and split between tram and bus.

	TTH morning rush period			TTH non-rush period			TTH evening rush period			total TTH		
	tram and bus	*tram*	*bus*	tram and bus	*tram*	*bus*	tram and bus	*tram*	*bus*	tram and bus	*tram*	*bus*
Reference scenario	131.300	*72.300*	*59.000*	419.200	*269.200*	*150.000*	134.800	*70.500*	*64.300*	685.300	*412.000*	*273.300*
USLR policy scenario	132.800	*72.800*	*59.900*	422.900	*270.900*	*152.000*	135.900	*71.000*	*65.000*	691.600	*414.700*	*276.900*
TTH change (absolute)	1.400	*500*	*900*	3.700	*1.700*	*2.000*	1.100	*500*	*600*	6.300	*2.700*	*3.600*
TTH change (relative)	1,1%	*0,7%*	*1,5%*	0,9%	*0,6%*	*1,3%*	0,8%	*0,7%*	*1,1%*	0,9%	*0,7%*	*1,3%*

This study shows the modal shift resulting from urban speed reduction in The Hague will be limited, with no decrease in public transport modal share. On a city level, the modal share of bikes increases with 0,2% while the modal share of cars decreases with 0,2%. The absence of a strong modal shift following USLR policy is at first glance surprising given that depending on the street, modelled car speed limits were reduced up to 60%. Still, multiple factors can explain this result. Firstly, the USLR policy speed reduction has had a limited effect on total travel times. Secondly, in-vehicle travel time is only a part of total travel resistance. For PT access and egress are equally important for route utility, but remain constant. Also pre-boarding waiting time and any transfer times contribute to the total travel time of PT. Thirdly, the relative attractiveness between cars and public transport modes decreases less than the individual attractiveness of both modes. This also explains why cycling sees a positive modal shift, as its attractiveness was not decreased by USLR policy.

Our simulation results show differences in trip destination choice following USLR policy in The Hague. The increase in travel time due to USLR policy inflicts a travel resistance upon The Hague, resulting in a more local trip choice. Consequently, the average PT passenger trip length decreases with -0.7% for bus and tram lines in The Hague. Interestingly, the three districts (Loosduinen, Segbroek and Scheveningen) sandwiched between the sea and the rest of The Hague have fewer external trips, which are replaced with trips to more nearby locations. This is the result of these districts having to travel through the city to reach any non-local destination. Therefore, all destinations become harder to reach following USLR policy in the city, making local destinations more favourable.

For districts in the south-east adjacent to other municipalities (Laak, Haagse Hout and Leidschenveen) the speed reductions are instead avoided by shifting the trip destination choice. To circumvent the USLR policy, less trips are made within the city and the trips are shorter. Meanwhile, there is an increase in external trips as other municipalities have no USLR policy in our study.

Finally, the results suggest a small modal shift on longer distances from cars to PT, benefitting regional (heavy) rail services. At the same time, on shorter distances a small modal shift occurs from PT to cycling. Since there is no effect on the modal share of public transport on a network level, revenue from public transport ticket sales is expected to stay stable. On one hand, the USLR policy could advantage inter-regional public transport operators, but on the other, it might reduce the earnings of local operators due to shorter and potentially fewer local trips.

However, the increased travel times result in additional transport operator expenses on timetable hours and increased costs per trip. On top of that, if current levels of service are to be maintained, PT operators will need additional vehicles to accommodate for the higher timetable hours, leading to high one-time investments on top of increased operating costs. Therefore, the overall impact of USLR policy on public transport operators is negative, harming passenger service and financial position.

Because The Hague region has a comparable public transport and road network to most major Dutch cities, these results can likely be generalised. This means public operators across The Netherlands will be facing increased costs for the same share of travellers as the urban speed limit change gets implemented.

Where is mitigation needed for PT?

Planned USLR policy for The Hague will have an unintended negative impact on the operations and financials of public transport, as seen in the above case study. However, by implementing mitigating adaptations, the negative results can be reduced, while maintaining the positive consequences of USLR policy, such as those on public health.

Our case study showed the focus on which streets to mitigate negative USLR-policy effects depends on three things. Firstly looking at the severity of a streets speed reduction provides the streets where travel times will increase the most. We observed these are generally streets with bus lines. Secondly, the severity of affected costs for PT operators should be considered. This can be determined by looking at streets which have the highest number of time table hours running through them. Our case study showed these are generally streets with multiple tram lines as these have the higher PT frequencies. Finally, the affected streets with the highest passenger volumes should be considered, as even a small delay in these streets will have a large societal effect due to the many passengers. All in all, when looking at overall costs to society, policymakers should focus their USLR policy mitigation efforts on streets with a high PT frequency and passenger volumes (generally tram lines) but on streets where vehicles consistently achieve speeds above the target USLR policy speed. However, this does bring the risk that large increases in travel times for small passenger groups will not be mitigated. Therefore, which cost to focus on is in the end a political decision, between the maximum benefit to overall society versus equity.

The societal consequences of USLR policy

The case study confirmed USLR policy increases travel time for both cars and PT. This was observed most strongly for the seaside districts of The Hague, due to these districts having to travel through The Hague for any destination, and therefore always having increased travel time. The question is if a more local orientation is a problem, for any point along a route, vehicles cause pollution to their surroundings, bring a safety hazard to street users and cost time for the person who makes the trip. Therefore, shorter trips by default improve pollution and safety and thus contribute to the goals of USLR policy. However, municipalities should ensure basic needs can be reached within acceptable times, and if needed more amenities should be created nearby (in particular relevant for the seaside districts).

The effect in shifting destinations and thereby shifting external costs of mobility depends on the USLR policy scale and other complementary policies. When USLR policy is extended to more streets, travel times would further increase strengthening the effect on trip length as well as shifting societal mobility costs. Meanwhile, complementary policy that prevents an increase of PT travel time would dampen the effect on trip length, and simultaneously reduce the societal mobility costs. Societal mobility costs could reduce through mitigating the negative effect on travel costs in terms of travel time (internal mobility costs for traveller) and by further pushing a modal shift away from cars, leading to fewer external costs on society.

Which policies could go well with USLR policy?

Multiple mitigation measures can be considered to reduce the negative impact of USLR policy on PT operators, passengers and other stakeholders. Since the speed limit was not always reached by PT, we recommend to focus on accelerating elsewhere and ensuring a reliable and undisturbed PT route.

Talks with HTM personnel and our PT speed estimations revealed that crossing traffic is a major cause of speed reductions. Therefore, reducing traffic crossings is an effective way of increasing smooth traffic flow and speeding up PT. Multiple mitigation measures can be employed to achieve this. One way to reduce traffic crossings is by specifically removing left turning traffic crossings. We think this is a suitable policy at intersections where emergency services and PT do not need the left turn, and when alternative intersections are close by. Another solution is to introduce more one way streets. One way streets could even be the solution to maintain 50km/h if desired, as it would allow dedicated bicycle paths in narrow streets. On intersections with traffic lights, PT priority is already used often in The Hague to prioritize PT. This could be expanded further, or should at least be maintained to optimize PT speeds. Another way of accelerating PT is by improving the traffic flow on streets important to PT. For example by changing the street category from ETW30 to GOW30. This can reduce intersection delays, as GOW30 allows priority at intersections where ETW30 (and ETW50) must yield.

Besides optimizing traffic crossings, modal filters can be applied to block passenger cars from certain streets. Emergency services and PT could benefit, as fewer traffic means fewer disturbances. This also increases reliability of PT, as the speed profile becomes less varied. Freight and logistics benefits from these points as well, and this measure could be combined with hubs for city logistics (Huisman et al., 2022, p. 34).

Applying speed segregation would set a higher speed limit to PT than to cars, allowing PT to still go 50km/h (or in theory even faster if safety allows). The travel time by PT would therefore no longer increase. Speed segregation mitigates increased costs for PT operators and thereby prevent increased subsidy (for the case study this is MRDH who regulates PT concession). PT passengers would also benefit, as their travel time increase is mitigated. Furthermore, the relative attractiveness of PT compared to the car improves, stimulating a modal shift from car to PT. Speed segregation is a costly measure, so it should be kept in mind for planned street restructuring work, and not as the first go-to mitigation measure.

We believe a combination of the mentioned measures can mitigate the negative impact of USLR policy on PT, companies, and emergency services. The implementation of USLR policy will give policy makers the chance to rethink how public space is divided, and should utilize this opportunity not only to mitigate USLR policy negative impacts, but also to achieve other aims in improving the public space.

Strengths and limitations of the case study

We chose The Hague as our case study because the city is in the process of formulating a USLR policy. This allows our research to still contribute in the discussion. However, the lack of a definitively defined USLR policy also proved a limitation in our study. e chose to formulate a realistic USLR policy fitting with the current aims of The Hague, so that the results could also by used by the municipality. The main advantage is that it gave a realistic view on the impact this USLR policy would have on various stakeholders, the ongoing discussions, and the resulting trade-offs. For future studies, we recommend opting for a more generic USLR policy, to allow more academic transparency during the formulation. Such a ”strict” policy scenario could explore the impact of a speed limit reduction applied to the entire city centre. In this city wide policy, 30km/h is the norm. hough this is more ambitious than the (expected) proposed USLR policy by the current city council, it can help to understand the impact on modal share and provide an alternative to current policy scenario of the city council in the case study. Future studies could also research scenarios with additional mitigating measures in place, favouring PT. This allows examination if financial compensation for PT operators is still needed, or that a modal shift can truly be achieved in favour of PT.

The V-MRDH model, used in this study, has a strong theoretical basis backed up by literature, with extensive fitting to revealed behaviour on both destination choice, mode choice and route choice. The high complexity and detail of the model allowed us to identify behaviour changes that would not have been captured in simpler simulation models. Furthermore, because the regional transport network was also simulated we could observe changes in trip destination choice, mode choice, and route choice from outside The Hague as well. However, the extensive set of input parameters and functions also made it complex to draw conclusions of what parameters were truly driving the changes in output we were seeing. This led to a lack of transparency in mechanisms that caused our observations. Furthermore, as the model is optimised for a macro-level, it was hard to reflect on the results when zooming in. While the complexity of the model provided some difficulties, particularly on the micro-level, it was also an important strength of the model for our research. Namely, it made for a very strong macro-analyses, with the many intricate consequences of the USLR policy reflected on a citywide scale.

For this study, we formulated a standardized methodology for USLR policy implementation into a simulation model. This standardized methodology provides transparency, is easy to reproduce and easy to adjust during a sensitivity analysis or when renewed insights are gained on speed. The method relies on timetable times, which is based on the median travel time per segment. Using median times does mean that for half of the trips the effect of a speed reduction is underestimated. Discussions with two HTM drivers indeed indicated this problem occurs. Therefore, we chose a relatively major 40% speed reduction to include possible cascading effects. Still, this does not reflect differences at a street level in the severity of this speed impact. This further emphasizes how the results of the study should mainly be interpreted at a macro-level. The impact on public transport travel speeds, timetable hours and passenger volumes seen in our study is less severe than earlier (grey) research by Bigalke et al. (2023). This can be explained by the different methodologies used. Bigalke et al. (2023) used an elasticity model with fixed demand between each OD pair and the modal share is variable. The latter is more often used in (both academic and grey) literature (Farahani et al., 2013), but relies on the assumption that there are no effects on car speeds and flows. Because USLR policy does cause such changes on cars, elasticity is not reliable. Therefore, a model was needed that includes impedances/resistance so the modal split is more realistic.

General discussion and conclusion

The primary goal of this thesis is to assess the impact of Urban Speed Limit Reduction (USLR) policy on public transport (PT) operators, using The Hague as a case study. The results show that USLR policy does not significantly affect modal share and thus PT income, but does increase travel times, and thereby overall costs for PT operators. USLR policy has multiple effects on both transportation systems and society. The first-order impacts, such as small increases in travel time for public transport, do not result in a notable modal shift away from public transport. However, the increased travel times lead to additional operational costs. The case study shows that income from ticket sales remains unchanged, but operational costs rise, creating a financial strain on PT operators. This is contrary to a major goal of USLR policy, which is to stimulate a modal shift away from private cars, as lower PT speeds increase travel time and operating costs. Without financial compensation this inevitability leads to service cuts. From a financial point of view, it makes most sense to have those service cuts take place on services with already low ridership and further passenger volume decline. After all, to balance costs and income it makes most sense to cut a few services with a large (financial) net loss, instead of having to cut many services each with a small net loss. A potential risk is that equity-oriented PT services are hit in particular, causing mobility equity decline as undesired side-effect of USLR policy.

Beyond these immediate effects, there are second-order impacts based on existing literature. USLR policy is linked to lower CO_2 emissions, although no consensus is yet reached on the policy effect on pollutants like NO_x and PM. Safety improves with lower speed limits, especially for vulnerable road users like cyclists and pedestrians, making this policy an important tool for urban safety. However, we argue the safety effects of USLR policy depend on how the policy is implemented. If car traffic remains constant and cyclists are moved into shared lanes with cars, USLR would actually increase exposure to hazards, potentially undermining the desired safety benefits.

Governments should consider how to respond on the increased PT timetable hours needed. If not mitigated, USLR policy causes as undesired side effect either increased fares or forced service cuts resulting in reduced PT service levels. To reduce the cost impact on PT operators, alternative solutions should be explored, such as financial compensation or infrastructure investments to minimize the increase in PT travel times. Strategic solutions, such as mitigating measures on streets with high passenger volumes or with significant increases in required timetable hours, could improve public transport attractiveness while reducing operational costs. Potential solutions to prevent further delays include modal filters, dedicated lanes, intersection priority, and restricting turning movements at intersections. These options align well with the goals of USLR policy —improving liveability and safety— by reducing conflict points and promoting a modal shift. Further research on the effectiveness of mitigating options is recommended.

The findings from The Hague are largely generalizable to other Dutch cities with similar public transport networks. However, caution is needed when applying these results to cities with a different modal split or transport infrastructure. For example, cities that rely more on metros or trains will need to consider different factors. The results are most applicable to mid-sized European cities with bus and tram networks similar to The Hague's.

Further research should focus on refining the model and exploring indirect effects of USLR policy. If this study were to be repeated, improvements in modelling traveller behaviour and regional differences would be beneficial. Introducing more detail around the behavioural responses to speed limit changes, especially around habitual vs. elastic responses, could improve model accuracy.

In conclusion, this study demonstrates that while USLR policy increases operational costs for public transport operators, it does not significantly alter modal share or ridership. The model, while a simplification, offers a robust estimate of the financial impact of USLR policy on PT operations. Policymakers must balance these increased costs against the broader benefits of USLR policy, such as improved safety, reduced pollution, and enhanced urban liveability. Furthermore, policymakers should focus their USLR policy mitigation efforts on streets with a high PT frequency and passenger volumes and where vehicles consistently achieve speeds above the target USLR policy speed. These findings provide a foundation for urban policymakers and public transport operators to plan for the financial and operational impacts of USLR policy.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
MRDH	Metropoolregio Rotterdam Den Haag
OD-matrix	Origin-Destination matrix
PT	Public Transport
TTH	timetable hours
V-MRDH	Verkeersmodel - Metropoolregio Rotterdam Den Haag (gravity based traffic simulator via software program OmniTRANS)

Terminology

Term	Explanation
OmniTRANS	software program
Vision Zero	long-term strategic goal to get close to zero deaths and zero serious injuries on EU roads by 2050 (Kountoura & Committee on Transport and Tourism, 2021, p. 5)
V-MRDH	Verkeersmodel - Metropoolregio Rotterdam Den Haag (gravity based traffic simulator via software program OmniTRANS)

Terminology of public transport

Term	Explanation
Deadhead time	non-passenger service time (eg. travel time to/from/between depots)
Layover time	time set aside in a schedule without driving (eg. slack time between two round trips)
Dwell time	station/stop service time for boarding passengers
Unplanned stopping time	time spend on waiting (else other than dwelling) such as at traffic lights.
Holding points	stops with additional waiting time to allow corrections for schedule deviations in order to prevent late departures or departures ahead of time.
Operating trip time	scheduled travel time between vehicle departure from one terminal and vehicle arrival at another terminal
Mohring effect	welfare/productivity increases when frequency increases. Operational costs and demand grow with same speed (assumed linear), but existing demand has fewer waiting time and thus lower time costs.

1 Introduction

1.1. Problem context

1.1.1. Incentive for urban speed limit reduction policy

All over the world, cities struggle with the impact of mobility on the livability of cities. Infrastructure causes space scarcity, congestion causes delays, and vehicles cause pollution and accidents (Gressai et al., 2021).

To tackle these socio-economic costs, policies around the world are formulated focusing on the livability of cities. In 2021 the European Parliament adopted a resolution recommending ”to apply 30km/h speed limits in residential areas and areas where there are high numbers of cyclists and pedestrians”, as step towards getting close to zero deaths and zero serious injuries on EU roads by 2050 (Gressai et al., 2021; Kountoura & Committee on Transport and Tourism, 2021; Vilkas, 2021). In response, the Dutch House of Representatives (*tweede kamer*) adopted a motion to make 30km/h the default speed limit in urban areas (*bebouwde kom*) (NOS, 2021). Deviation from the new norm is still possible for individual roads, but needs to be well reasoned and safe.

1.1.2. Implementation of urban speed limit reduction policy

Urban Speed Limit Reduction (USLR) policy is a set of road interventions dictated by the city council, aiming to reduce vehicle speeds. Over the past years, various European cities have already reduced the urban speed limit, such as Brussels, Zurich and Amsterdam (Elvik et al., 2023; Manning, 2023). USLR policy can be implemented through many different means and as a result lacks a clear definition or method of implementation. Commonly, the maximum speed is reduced from 50km/h to 30km/h. This speed limit reduction can be applied on a selection of roads, a city zone, or at a citywide level. Furthermore, reduction of the speed limit can happen with or without physical measures to enforce the new speed limit. For example, the Dutch ”*woonerf*” principle establishes a 15 km/h zone in residential neighborhoods and applies the speed limit to all of the zone’s streets. To enforce the lower speed limit, physical measures are implemented, such as speed bumps, lane narrowing and special road paving (Rietveld et al., 1998; Vis et al., 1992).

1.1.3. Current knowledge on urban speed limit reduction

The effects of urban speed limit reduction (USLR) policy are an emerging topic in scientific literature. Studies on the effects of USLR policies focus mostly on the motivations for the policy, namely the livability and safety of cities.

There is common acceptance that the policy will improve safety (Archer et al., 2008; Cairns et al., 2015; Gressai et al., 2021; Rossi et al., 2020), reduce noise pollution (Borowska-Stefańska et al., 2023; Cleland et al., 2021; Gressai et al., 2021; Rossi et al., 2020), and reduce CO2 emissions (Cairns et al., 2015; Gressai et al., 2021; Rossi et al., 2020; Tang et al., 2019). However, studies provide different conclusions to which extend other air pollutants will change.

While the positive consequences on the livability and safety of cities has been established, research has not yet adequately addressed how USLR policy affects traffic and accessibility in general.

Based on the current literature and ongoing debate, a knowledge gap has been identified in the effects USLR policy on modal share, travel times and traffic assignment on the road network. Changes in these values can have dramatic changes in how people travel through the urban environment. Particularly, public transport (PT) operators are worried the impact of urban speed limit reduction policy will be negative for PT operators (NOS, 2021; van Vliet, 2022). However, the perspective of public transport operators has not yet gained attention in scientific literature.

1.1.4. Problem statement

The impact of urban speed limit reduction policy on public transport (PT) is feared to be negative by PT operators (NOS, 2021; van Vliet, 2022). Lower operating speeds can result in higher operational costs with reduced passenger volumes. For the PT operator in Rotterdam (RET) lower operating speeds due to proposed urban speed limit reduction policy is expected to result in an annual additional 16.000 timetable hours, increasing the operational costs by €2.3 million annually (Gemeente Rotterdam et al., 2023). In Amsterdam the policy can cause up to 66.000 additional timetable hours annually (Royal HaskoningDHV Nederland B.V., 2022).

These alarming prognoses suggest the PT operators worries are justified. Unfortunately, academic studies on the effects of urban speed limit reduction policy do not quantify the effect on modal share and travel time, or how to mitigate such effects. By quantifying these differences, a more accurate calculation of the financial consequences can be made.

Therefore, this research aims to quantify the impact urban speed limit reduction policy has on public transport in terms of travel time, timetable hours and passenger volumes. The conclusions in this study are most relevant for European cities relying on buses and/or trams as public transport modes. However, the study results can not directly be used outside Europe or applied to cities relying on metros and/or trains without critical reflection, because the PT and road network layouts and modal split can not directly be compared.

1.2. Research objective and research questions

1.2.1. Research objective

The main goal of this research is to quantify the impact on public transport operators when policy on lowered urban speed limits is implemented. To determine the impact on public transport operators, both the operational costs and income are considered. The effect on operational costs is estimated by quantifying the increase of travel time and resulting additional required timetable hours. To determine the effect on income, the modal share and passenger volumes are quantified.

1.2.2. Research questions

Main research question:

> How will Urban Speed Limit Reduction (USLR) policy impact public transport operators in terms of modal share, travel times, and travel volumes?

Five sub-questions are formulated to break-up the main research question:

1. What is the current state of knowledge about urban policies on speed limit reduction and its impact on public transport?
2. How can the impact of USLR policy on public transport be estimated in terms of modal share, travel times, and travel volumes?
3. What is the impact of USLR policy for public transport operators on *timetable hours*?
    - KPI's: PT speed, travel times, and timetable hours
4. What is the impact of USLR policy for public transport operators on *ridership*?
    - KPI's: modal share (main mode per trip), travel volumes, and travel behaviour
5. Where in the road network are mitigating adaptations for public transport needed?

The first sub-research question is used to point out the research gap. The second sub-research question helps to select formulate a suitable methodology. In order to answer sub-research question 3, we first estimate the effect on speed, which is then used to calculate the resulting effect on travel time. The latter is the input for calculating the effect on timetable hours. Travel times are also used to calculate the effect on PT ridership. As part of this, also the modal share, travel volumes, and travel behaviour are researched.

1.3. Scope

Cars, buses and trams are the only modes that are assumed to be directly affected by USLR policy. This means that pedestrians, bikes, metros, boats and trains have no change of speed. After all, these modes of transport do not use the public road network, or are already travelling below 30 km/h. The unaffected transport modes thus also have an unaffected absolute attractiveness, while the absolute attractiveness for the modes cars, buses and trams will change.

The USLR policy reduces the maximum speed on the selected roads. The maximum speed affects the travel time between two points, which is a major factor for trip distribution, mode choice and trip assignment. It is assumed that people will reconsider their travel behaviour when travel times change. This assumption is likely true when the change of travel time is noticeable, as habits do not directly change. However, some people are limited in their mode choice. For example, not everyone can cycle or afford a car. The car ownership per neighbourhood is included in this research, but people relying on public transport is excluded. Therefore, effects on people who rely on public transport can be misinterpreted.

USLR policy can affect the needed timetable-hours for PT operators or PT service levels via the frequencies (or a combination). In this study, the public transport service level remains the same, meaning that public transport frequencies, locations of stops, line network, etc. are not affected. Instead the timetable-hours (dienstregelinguren) will increase when travel time increases. It is thus assumed that PT fleet size and personnel are no constraint. This allows us to calculate the resulting change in timetable-hours, and thus costs for PT operators.
Since the minimum service levels (frequencies) are constrained by tender requirements, keeping timetable-hours constant - instead of frequencies - would cause a complicated timetable redesign where every line and time period in the tender needs to be compared with the frequencies. Furthermore, this would result in less generalizable conclusions.

Furthermore, disruptions are not included in the research, meaning that the results reflect a day without noticeable disruptions. As disruptions usually cause rerouting and travel time delays, the relative effect of the policy on total travel times might be smaller than estimated. On the other hand, detours will cost more travel time non-relatively. The amount of disruptions might also change if the USLR policy causes less accidents. Disruptions due to unloading trucks are likely not expected to change.

Finally, USLR policy is not compared or combined with other policies. There are various types of mobility policies available to improve the livability, which are described in Subsection 2.1.2 (Cairns et al., 2015; Cleland et al., 2020; Gressai et al., 2021; Vis et al., 1992). To confine the scope, only changes in the road network itself are considered in terms of speed limits and road category.

2
Implementation of urban speed limit reduction policy

During this chapter we will establish the context in which our research operates. First, an overview of current knowledge on USLR policy is provided based on a literature review. This overview allows the identification of research gaps and provides context. Second, the general impact of USLR policy in the context of this research is explained, through which relevant KPIs are identified and the research scope is refined. Thirdly, potential research methods are identified and compared to choose the most suitable method. Finally, different implementations of the selected research method are detailed to help choose one or a combination of implementations.

2.1. Literature review

This chapter aims to answer the first research sub-question: What is the current state of knowledge about urban policies on speed limit reduction and its impact on public transport? For this, a literature review was performed to investigate the different impacts speed limit reduction policy has on urban environments. Unless specified, the findings from papers concern 50 to 30 km/u (or 30 to 20 mph) within cities in Europe (including the United Kingdom). The goal of this literature review is to find the knowledge gap(s) on the impact of urban speed limit reduction policy and provide an overview of the knowledge on urban policy to place this research into context.

2.1.1. Literature review method

To identify relevant starting papers, keywords were formulated and inserted in search engine Google Scholar. Google Scholar is useful for a first orientation, as it contains both academic and non-academic ”gray” literature sources. When possible we started with general literature review papers to gain an overview of current knowledge. Hereafter, individual topics were further investigated to gain a more nuanced and complete picture. In addition employees from Goudappel and HTM were asked for relevant sources, which resulted in various grey sources.
Afterwards the search engines Scopus and Science Direct were used. Findings from the first orientation were used to enhance the initial keywords. Relevant articles were fully scanned or read, and both forward and backward snowballing was applied to find further articles. This iterative process was applied both in Scopus and Science Direct. An example of used keywords for this study in Science Direct can be found in Table 2.1. Papers on speed limits in a non-urban context were excluded.

Limitations

A major limitation is literature not being concise on the USLR policy being evaluated, or not adequately mentioning confounders. Also, differences in context and study design makes comparing literature less straightforward. Furhtermore, little case studies on PT in USLR setting were identified. This may be the result of gray sources, such as policy documents, being non-public or confidential. This limits the literature research on case studies, and prevents us from quantifying concrete policy executions.

Table 2.1: Example of used search engine input

Search input (Science Direct)	Search constraints (optional)	Number of search results:
"speed limit" "public transport" cities travel time		1,795
"speed limit" "modal split" reduction intervention	first page only	108
"speed limit" "modal share" reduction intervention		79
"speed limit" "modal share" speed reduction	article type: review articles (6), case reports (1), and research articles (176, but only first page checked)	173
4 step simulation traffic transport modal split		112
public transport operator perspective	first page only	35,175
service level public transport pyramid		4,897
public transport operator perspective overview review		1,867

2.1.2. Types of USLR policy

USLR policy can be implemented in various ways and timescales. This can depend on political choices, financial constraints and policy motivations. The type of USLR policy can be categorized on scale, scope, and time:

- Streets adapted to enforce new speed limit or not
- Instant implementation versus slow implementation
- City/district wide versus street specific

While some papers papers investigate policy types on micro level (Borowska-Stefańska et al., 2023; Cairns et al., 2015; Gressai et al., 2021), other papers evaluate policy on a network level (Archer et al., 2008; Cleland et al., 2020; Nightingale et al., 2021; Rossi et al., 2020).

Many motivations have been given for using USLR policy. For instance, USLR policy has been used to reduce traffic congestion or as traffic calming interventions (Cairns et al., 2015; Cleland et al., 2020). USLR policy can be used in combination with other policies, such as parking regulations, restricting traffic movement or giving public transport priority. (Gressai et al., 2021).

A meta-narrative systematic review by Cleland et al. (2020) categorized 20 mph (32km/h) policy interventions into 'speed limits' and 'speed zones'. 'Speed limits' only utilize signage and lines. This way, drivers are only alerted but not actively slowed down. Enforcement, awareness and education campaigns should ensure reduced speeds (Cleland et al., 2020). Speed limits can also be named "advisory systems" (Archer et al., 2008). 'Speed zones' utilize physical traffic calming measures designed to slow down vehicles. This ensures the reduced speed limit is adhered to. Such interventions include road narrowing, speed bumps, central islands, or a combination thereof (Cleland et al., 2020). To avoid confusion with area zoning (e.g. residential zoning, "woonerf"), such physical traffic calming measures are sometimes referred to as "traffic interventions" in other literature (Cairns et al., 2015; Gressai et al., 2021; Vis et al., 1992) or "mandatory systems" (Archer et al., 2008).

USLR policy is more effective in reducing speeds when physical traffic calming measures are included than USLR policy without (Cairns et al., 2015).

Physical traffic calming measures are effective in reducing the number and severity of collisions and casualties, but there is insufficient evidence to conclude that physical measures are effective on other public health outcomes such as livability and pollution (Cairns et al., 2015; Cleland et al., 2020). However, research suggests a negative effect on air quality and noise levels due to vehicles braking and accelerating more frequently (Atkins et al., 2018, p. 60).

Rossi et al. (2020) analysed the effects on health of different sets of policy scenarios, instead of individual types of policies. This study revealed that the extend to which a policy is implemented, matters significantly. For this, the authors used a reference scenario - without any 30 km/h speed limits -, a current scenario - with partial speed limits - and additional scenarios with further implementation of 30 km/h speed limits, including a whole city scenario. However, the effects on modal share is not included in this research, and thus requires further investigation.

Nitzsche and Tscharaktschiew (2013) assessed the effects on general welfare based on a macro simulation using different scales of USLR policy. Their results suggest that implementing a general speed limit uniformly in the entire urban area, thus paying no attention to the spatial shape of the city and its road network, is likely to be an inadequate measure to enhance social welfare. However, USLR policy restricting speed limits locally, thus focusing on the design of a 'slow zone', is much more promising to enhance social welfare [1].

Overall, current literature on USLR policy either focuses on the type of USLR measures (e.g. physical measures versus speed limit only), or on the quantity (e.g. selection of streets versus entire city zones). While literature on the type of USLR policy is available, not all papers describe the quantity and quality of policy packages, which hinders policy comparisons.

2.1.3. Known impacts of USLR policy

Reducing the inner city speed limit has wide consequences, which can be categorized into traffic flow (travel times, average speed, traffic capacity, and congestion), safety (risk of accidents and severity of accidents), and pollution (emissions, noise).

Traffic flow

The impact on travel time is debated in literature. A study by Archer et al. (2008, p. 45) concludes that "a minor impact on average travel time is likely", without making further distinction per road network, travel mode, travel motive, etc.. However, Gressai et al. (2021) found a major impact on travel time through a microscopic traffic simulation of Budapest, Hungary. Depending on the type of road conditions (free-flow, under-saturated, saturated, over-saturated), the average vehicle speed could drop up to 20%. In general, the average travel time and the number of stops is suggested to increase, while the road capacity is not fundamentally effected. Finally, the capacity of the road network in Budapest is estimated to not be affected by changes in speed limits. This is explained by the macroscopic fundamental theorem of road traffic: $Q = \rho * V$. Where traffic volume Q (veh/h) is the product of the vehicle density ρ (veh/km) and the spatial average speed V (km/h) (Gressai et al., 2021). The pre-post observational evaluation by Nightingale et al. (2021, p. 10) confirmed that the correlation between traffic speed and volume remains unchanged when the speed limit reduces.
Gressai et al. (2021) conclude further research is needed on the effect on modal shift, for who and where the impact on travel time differs, and the reconfiguration of traffic management (e.g. intersections, road marking and public transport timetable).

Based on their literature review, Rossi et al. (2020) expect an improved traffic flow, due to less stop and go traffic. This is in line with Nitzsche and Tscharaktschiew (2013) and Cleland et al. (2020), who both found in three different papers that a more uniform speed or a reduced speed leads to a smoother traffic flow.

Borowska-Stefańska et al. (2023) assessed the impact of speed limit reductions on traffic flow and on road noise. Their results show a marginal impact on the level of congestion and modal split. However, the study only limited speeds on major roads, allowing for alternative routing. Wider implemented speed limit reductions could lead to different results. For instance, policy applied on a neighbourhood level, such as the dutch 'woonerf', can cause local decline of traffic volumes by 5% to 30% (Vis et al., 1992).

Academic literature addressing the impact of speed policy on public transport is limited. Nonetheless, the topic has been addressed in grey literature.
A case study of Rotterdam by Gemeente Rotterdam et al. (2023) showed that a 30km/h policy will weaken the position of PT. In this study, 5 counts per direction per line are performed, where every 1-2

[1] The research quality is in our view is however questionable, as it uses for example a fixed speed for public transport of 18km/h for the whole case study simulation. Furthermore, the change of modal split is estimated instead of recalculated. Perhaps even more questionable is the high aggregation level. The theoretical city exists of 7 zones. In our opinion the effects of USLR policy can not be determined if the links are an aggregate illustration of a road system and only 7 nodes are used, corresponding to the 7 zone centroids.

seconds the vehicle driving speed is derived from GPS data. The resulting impact from counts of 10 lines are extrapolated to other lines, based on comparable infrastructural situation per line. Assuming that PT maintains 50km/h on dedicated lanes, the impact on travel times is much larger for PT lines with shared lanes. While tram lines -often on dedicated lanes- will not see a large effect on travel times (0-1 minute, or 0%-4% increase), the increase of travel time on bus lines is much larger (1-3 minutes increase). For the PT operator (RET in Rotterdam) this could result in an annual increase of €2.3 million in operating costs, caused by an annual increase of 16.000 timetable hours needed to fulfil the same services. Meanwhile, the amount of passengers is expected to decrease, though this is not quantified by Gemeente Rotterdam et al. (2023).

Safety

The umbrella review by Cairns et al. (2015) concludes that overall safety will increase due to 30km/h zones and limits. The paper suggests that the interventions are cost-effective and perceived positive by local residents. However, health inequality and cultural change is addressed as challenging when implementing traffic calming interventions. The literature study of Gressai et al. (2021) shows that there is a strong correlation between the value of speed reduction and the risk of accidents (12% decrease in accidents), as well as the severity of accidents (20% fewer persons were seriously injured after introducing the reduced speed limits.). Vulnerable road users (pedestrians and cyclists) are likely to benefit most from reduced vehicle speeds (Archer et al., 2008). Nitzsche and Tscharaktschiew (2013) shows that a more uniform speed and therewith a smoother traffic flow is associated with better traffic safety.

USLR policy affects not only a change of the speed limit, but also includes redesign of street characteristics that affect travel behaviour and patterns. The effects of USLR policy on road casualties in London are estimated by Li and Graham (2016) via doubly robust estimation[2]. Their results show USLR policy leads to a 10% reduction of slightly injured casualties, a 24% reduction of killed and seriously injured casualties, and a 21% reduction of pedestrian-related casualties (which is significant at the 99% level). On the other hand, the effect on motor-related casualties is not significant when estimated in percentage, only the absolute number of casualties is found to be significantly reduced by 1.5. Surprisingly, the study found no significant effects of USLR policy on cycling-related casualties.

Pollution

Noise pollution

Rossi et al. (2020) showed that the implementation of a 30 km/h speed limit in the city of Lausanne (Switserland) is expected to induce health benefits not only through a decrease in road traffic casualties, but quantitatively even more through a reduction in noise exposure. The prevention of morbidity and premature mortality (due to cardiovascular disease) caused by road traffic noise is a much more pronounced health benefit than the prevention of traffic crashes. For each of the three policy scenarios, health benefit from noise reduction is more relevant than safety benefits. Nonetheless, the study of Rossi et al. (2020) excluded health benefits due to active travel or emissions. Because literature was absent or conflicting, those benefits could not be accurately quantified and would make the conclusions less robust.

Noise pollution decreases when speeds are lower (Borowska-Stefańska et al., 2023; Cleland et al., 2021; Gressai et al., 2021; Rossi et al., 2020). The range of noise reductions varies, but most 50-30km/h studies show a noise reduction in the range of 1-5 dB (Borowska-Stefańska et al., 2023; Gressai et al., 2021; Rossi et al., 2020). Both Rossi et al. (2020) and Borowska-Stefańska et al. (2023) point out that below 50km/h noise is mainly from the car engine instead of tires. Policy promoting electric cars could therefore achieve more effect on noise than policy on speed limit reductions. Based on earlier studies, Borowska-Stefańska et al. (2023) points out that for new cars the tyre noise overrides engine noise already at speeds of 15.7km/h. This not only because new passenger cars have quieter engines, but also because new cars have a greater curb weight and wider tyres.

[2] Regression-based statistical models can be used to model the impact of USLR policy, such as before–after and time-series methods (used by Nightingale et al. (2021)). However, the validity of these methods relies on their ability to control for confounders. To properly address confounders and reduce bias in their findings, Li and Graham (2016) use a doubly robust estimator approach that combines outcome regression (OR) and propensity score (PS) models. The obtained estimator is consistent and asymptotically unbiased so long as at least one of the component models (i.e. OR or PS) is correctly specified, allowing for more consistent and asymptotically unbiased causal effect estimates. However, Li and Graham (2016) had no data available regarding actual traffic speeds and traffic volumes.

When the speed limit is reduced on only a limited set of roads, alternative routes without speed intervention might become more attractive for traffic, which could result in local noise increases (Borowska-Stefańska et al., 2023; Gressai et al., 2021). Still, Borowska-Stefańska et al. conclude that the overall noise pollution and severity decreases on network level.

Air pollution

The consensus in literature is that 30km/h policy lowers CO2 emissions (Cairns et al., 2015; Gressai et al., 2021; Rossi et al., 2020; Tang et al., 2019). The effect of speed policy on other air pollutants however are more nuanced. The emission of nitrogen oxides (NOx), CO and particulate matter (PM) increases due to speed limit reduction (Gressai et al., 2021; Tang et al., 2019). Both papers compared driving speeds. Because generally speaking car combustion engines are designed to function most efficient at 50 km/h, at lower speeds the degree of incomplete combustion increases. The effect of enforcement measures is not included, but would further increase emissions due to more frequent braking and acceleration resulting from the kangaroo effect[3]. However, the extent of the increase depends on network topology, and the characteristics of traffic. Furthermore, both papers assumed a constant modal share.

On the other hand, Rossi et al. (2020) and Gressai et al. (2021) concluded that emissions can change in both directions, depending on the state of traffic and type of vehicles. In an over-saturated traffic state the amount of stops increases, resulting in more breaking and vehicle accelerations. Nonetheless, speed limit reduction policy will more often result in an increase of emissions (Gressai et al., 2021).

However, Cleland et al. (2020) concluded that there is insufficient evidence to determine if speed limits or physical calming measure have an effect on air pollution.

Speed change

The effect of USLR policy on the actual travel speed is researched by Atkins et al. (2018), Cairns et al. (2015), Nightingale et al. (2021), Rietveld et al. (1998), and Vis et al. (1992).

One case study of the City of Edinburgh Council described the actual changes in traffic speed and volume by a 12 month pre- and post observation, where 30% of the streets have a speed limit reduction without any physical traffic calming measures. The mean speed reduced with 5,7% on average per targeted street. Interesting is that the largest speed reductions were observed for the third quartile speeds, and as a result the change in median speed was smaller than the change in mean speed. Simply said, the larger reductions in speed were observed in the upper tail of the distribution of speeds.

This study also showed that the absolute speed change is constant throughout the day (Nightingale et al., 2021). This observation is similar to (Atkins et al., 2018, pp. 31–32), who saw similar speed limit compliance for rush hour and non-rush hour after the influence of congestion was removed from the results. However, compliance did differ for roads in city centre areas compared to residential areas, as the average speed dropped by 0,7mph in residential areas and 0,9mph in city centre areas. More interesting is that evidence in the reports' case study suggests that the set-up of the road has a bigger influence on driver speed than the speed limit reduction itself. The effect of infrastructure adaptations is indeed observable. Grey literature of case studies using no calming measures reviewed by Nightingale et al. (2021) showed small reductions in observed average speeds: in Manchester (0,7mph reduction), Bristol (2,7mph reduction), Edinburgh (pilot scheme) (1,9mph reduction), and Portsmouth (1,3mph reduction). Meanwhile, 3 other case studies where traffic calming measures have been included show a 9mph speed reduction, according to the literature review by Cairns et al. (2015). Changing the road design and incorporating enforcement measures therefore results in higher levels of speed change.

Acceptance

Speed limit reduction policy is widely accepted by residents (Atkins et al., 2018; Cairns et al., 2015; Vis et al., 1992). In one study the reduced speed limit policy was accepted by drivers, though the advisory policies are generally preferred over mandatory policies (Archer et al., 2008, p. 23). Cleland et al. (2021) explored the perspectives among diverse focus groups, and concluded that while speed limit interventions are accepted in general, participants questioned the need for a reduced speed limit because traffic travels already slow during rush hour. An education campaign was therefore recommend

[3]The kangaroo effect describes driver behaviour where vehicles are braking before road humps, speed cushions or cameras and accelerate afterwards. Instead of speed compliance the enforcement measures could sometimes lead to kangaroo jumps. This results in emissions increasing and unpredictable speed profiles, which poses a negative effect on traffic flow and safety (De Ceunynck, 2017; Tang et al., 2019).

to increase acceptance and ”*in order to avoid the ripple effects of misconceptions or beliefs*” (Cleland et al., 2021, p. 8). Physical enforcement measures are perceived to improve compliance to the new speed limit, according to focus group participants, drivers interviewed, and respondents to the cyclists and motorcyclists surveys (Atkins et al., 2018, p. 57). However, at the same time USLR policy including enforcement measures are less popular than USLR policy without those measures. Reasoning includes:

- Concerned drivers about damaging their vehicles.
- Physical measures can encourage erratic or unpredictable driving. This includes the kangaroo effect, where vehicles are speeding between or after road humps / speed cushions or cameras. Another concern is swerving to avoid partial speed humps or chicanes, increasing the likelihood of conflict with other road users.
- Road humps and speed cushions can be slippery in wet weather and awkward for motorcyclists and cyclists to ride over, particularly for inexperienced riders.
- Road humps are perceived to increase noise and air pollution.

2.1.4. Knowledge gaps

The effect of USLR on modal split is barely known. Borowska-Stefańska et al. (2023) used a simulation model to simulate the effect on modal split and found a 0,38% increase of modal share for public transport, 0,57% increase of modal share for active modes, and 0,27% decrease of private car modal share. A simulation study by Nitzsche and Tscharaktschiew (2013) concluded that the modal share of public transport doubles from 9% to 18%. However, the simplifications used in this study are so severe that the results in our opinion can hardly be used. For example, public transport travel speed is modelled as a city wide flat speed of 18km/h and not impacted by USLR policy, while assuming a congestion free public transport network. The effects on modal share are ignored by Rossi et al. (2020), who argues that there is no convincing evidence on changes in modal share (only addressing active modes). Therefore, research on modal split is recommended by Gressai et al. (2021).

Although some literature briefly mentions the impact of speed reduction policy on modal split in general (city wide), no scientific articles analysed the modal split on a district and neighbourhood level. Therefore, a knowledge gap is identified on the modal split caused by speed reduction in semi-aggregated or agent based setting.

No scientific literature has been found that investigates the effect of speed limit reduction policy from the perspective of the public transport sector. Further research is recommended by Gressai et al. (2021) to quantify and mitigate the consequences for public transport in terms of travel time. Grey literature exists that estimates the increase of travel times due to speed reduction policy, and the initial findings encourage a scientific study to quantify the effect on travel time and modal share of public transport.

Another research gap is how to mitigate the effects on public transport in terms of travel time, travel volume and operational costs. Grey sources did analyse to which extend some (combinations of) mitigation options could limit operational costs (Royal HaskoningDHV Nederland B.V., 2022) or passenger volumes (Huisman et al., 2022). However, a (scientific) study testing the effectiveness of individual mitigation options is not known.

Furthermore, as Nightingale et al. (2021, p. 11) concluded before, there is *”little literature for comparison in terms of effects on traffic volume, or factors associated with the odds of reduction in average volume”*. A literature review comparing USLR policy implementation, enforcement, or its effects is missing.

2.1.5. Conclusion

This chapter aimed to answer the first research sub-question: What is the current state of knowledge about urban policies on speed limit reduction and its impact on public transport? The existing knowledge about the impact of urban speed limit reductions can be summarized and categorised into 5 groups: the impact on traffic flow, safety, air pollution, noise pollution, and acceptance. It can be concluded that there is common acceptance that the policy will improve safety, reduce noise pollution, and reduce CO_2 emissions. However, studies provide different conclusions to which extend other air pollutants will change.

Overall safety increases due to USLR policy (Archer et al., 2008; Cairns et al., 2015; Gressai et al., 2021). Lower maximum speeds particularly benefit vulnerable road users (pedestrians and cyclists) in terms of accident risk and severity Archer et al. (2008) and Gressai et al. (2021). Apart from a decrease in road traffic casualties, the wider health effects include the prevention of morbidity and premature mortality caused by road traffic noise, which is quantitatively even more important than road safety (Rossi et al., 2020).

Although some literature briefly mentions the impact of speed reduction policy on modal split in general (city wide) (Nightingale et al., 2021), no scientific articles analysed the modal split in more detail. Therefore, a knowledge gap is identified on the modal split caused by speed reduction in semi-aggregated or agent based setting.

No literature has been found that analyses the effect of speed limit reduction policy from the perspective of the public transport sector. Further research is recommended by Gressai et al. (2021) to quantify and mitigate the consequences for public transport in terms of travel time. Another research gap is how to mitigate the effects on public transport in terms of travel time, travel volume and operational costs.

3 Research methods

Chapter 2 showed that the impact of USLR policy on PT operators is largely unknown. This PT impact can be split into two components: the impact on the travel time and on ridership. This chapter explains the research methods used to investigate these components, in order to answer the second research sub-question:

> How can the impact of USLR policy on public transport be estimated in terms of modal share, travel times, and travel volumes?

In this chapter we first explain why we chose a simulation model as a method. Afterwards, the requirements for this model and its input are discussed. Next, we explain the components of this model step by step: how to model USLR policy scenarios, how to construct the transport model, and how to implement the USLR policy scenarios into the transport model.

3.1. Selecting a method to estimate USLR policy impact

Considered research methods are a literature study, a revealed case study or combination of multiple case studies, interviews and any form of transport simulation.

The main problem with a literature study or a revealed case study is that it contains a major research gap. Existing literature on USLR policy either lacked in sufficiently detailed methodology or detailed results on the impact of PT. Also, different assumptions used resulted in conflicting conclusions. Therefore, a literature study would not result in cohesive conclusions and is no suitable method for answering our main research question.

The main limitation of revealed case studies is the natural reason that such studies are mainly longitudinal. This makes it impossible to isolate the impact of USLR policy from parallel developments in policy, economics, and social behaviour. As data gathering is expensive, such (un)observed factors are not always accounted for, introducing biases in revealed case studies.

Furthermore, literature research on revealed case studies showed that the type, magnitude and effect of speed limit reduction policy varies greatly over the cases. However, often in papers it was not mentioned in sufficient detail what the policy implied, making it hard to quantify the effects and compare conclusions. For example, Nightingale et al. (2021) evaluated the effect of policy using a pre-post observational evaluation on traffic speed and volume. However, they did not mention the speed limit beforehand. This makes it hard to interpreted the effect on observed speeds when the change of speed limit itself is unknown. Instead of using speed limits, they grouped the streets into measured speeds.

Meanwhile, a simulated case study allows for a controlled setting where the impact of USLR policy on PT can be tested without interference from other factors.

Interviews are not used as methodology because they provide subjective, qualitative results, which is not suitable for the objective, quantitative analysis needed to assess the system-wide impact of urban speed limit reductions on public transport.

Prior to this study talks with supervisors were held as preparation for the research, as well as desk research reading through (news) articles. It already revealed dispersed opinions, with an observed strong bias. Some argued cars becomes notable less attractive relative to PT, causing PT ridership to increase. Others fear PT travel time increases and will result in less PT ridership instead. This was reason enough not to use interviews as main method to predict the effects.

Furthermore, the goal is to gain insights on modal share in semi-aggregated level (per district). It is questionable to which extend this can be predicted with human interpretation and opinions alone.

Since literature on the effect of USLR policy on PT operators is limited, and an interview approach was not deemed realistic, it was clear a simulation model was the best approach. This allowed for the generation of new data on the impact of USLR policy on public transport. In particular on the modal share of PT, to estimate changes in PT income, and on changes in the amount of required timetable hours, to estimate changes in PT costs.

3.1.1. Required complexity of the simulation model based on expected effects of USLR policy

In this section the qualifications for the simulation are listed which are required in order to solve the research questions. For this, we first need to explore the expected effects of USLR policy as these need to be captured in the simulation model.

The following effects of USLR policy are expected:

1. A decrease of the speed limit will cause longer travel times. So the model must be able to capture the effect on travel time. As the impact can differ per street and part of the street, the street network needs to be simulated as a set of small street segments.
2. During rush hour the driving speed of motorized vehicles is often limited by congestion rather than the speed limit. Subsequently, the model should include the effect of congestion. Additionally, the model should distinguish between rush hour and non-rush hour.
3. The travel time will increase more between certain origins and destinations than others. Therefore, it is expected that in the long term a person can decide to go shopping at a more nearby location as some destinations become less attractive. Consequently, the model should allow and capture changes in trip distribution. This means that people for example can change jobs, even when the trip generators itself are not changed (thus assuming construction / development of new offices, housing, etc. is not impacted by USLR policy and zonal data remains constant in this study).
4. People may reconsider their mode choice after a permanent change of travel time. When the travel time by car increases while the travel time by bike remains constant, for some people the most attractive mode switches from car to bike. Therefore, the mode choice must be included in the simulation.
5. Increased travel times on certain streets will make those streets less attractive. Therefore, it is expected that people will reroute to find the most attractive (fastest and most convenient) route. Consequently, the simulation model must include trip assignment.
6. As explained in Subsection 2.1.2, USLR policy often comes with a speed reduction in combination with enforcement measures. Such enforcement measures are meant to discourage people from speeding, but can give hindrance and can instigate congestion. As a result, the expected effect is a reduced (route choice) attractiveness of streets targeted by USLR policy due to both enforcement measures and a reduced maximum speed limit. Consequently, we expect on those targeted streets a decrease of car traffic volumes and to a lesser extend public transport volumes. The simulation model should capture:
   (a) Changes in route choice both by car and by public transport, due to people avoiding targeted street and taking detours.
   (b) Changes in mode choice due to the combined effect of targeted streets on overall mode attractiveness.
   (c) The effect of enforcement measures on link attractiveness. This includes the effects on link capacity, speed, congestion and congestion sensitivity. Those effects are particularly relevant for cars and to a lesser extend public transport.
   We also expect some effects on the subjective attractiveness such as comfort, safety perception and environmental perception. This subjective attractiveness mostly effects cycling, but

also public transport (comfort in particular). However, it is excluded in our simulation. Quantifying such parameters is challenging and not common practice in city wide multi-modal traffic simulation.

To conclude, to capture the expected effects of USLR policy on PT demand behaviour, the used simulation model will have to calculate step 2, 3 and 4 of the classic 4-step transport simulation model.

The used traffic simulation model will have to simulate both an approximation of the reference traffic network and the expected effects of USLR policy. For this reason, the choice is made to use a detailed transport network representation on street level, since USLR policy is per street. Furthermore, the simulation model needs to be multimodal and distinguish between rush hour and non-rush hour.

3.2. Methodology for formulating a USLR policy

Now that we have determined the characteristics needed for our simulation model, we will need to determine the scenarios we want to incorporate into our model. Two scenarios for 2030 are used, one excluding and one including an urban speed limit reduction policy.

Selecting the assessment year: 2030

A future USLR policy should be assessed using the conditions under which the policy will be active. This is because it takes years before policy is implemented, and some changes in the city are expected to have significant impact on mobility, such as the surge of the e-bike and city densification (Ministerie van Infrastructuur en Waterstaat, 2023; van de Werken, 2018). For example, the city densification results in higher travel demand and therefore the capacity on parts of the road network will be reached more often. Similarly, e-bikes makes cycling more attractive on longer distances (Jorritsma et al., 2021, p. 76). To account for the urban developments that will occur during the implementation of the USLR scenario, the year 2030 is used as assessment year. Subsequently, two policy scenarios for the year 2030 are formulated to feed the simulation model.

A disadvantage of performing and ex-ante study is that the uncertainty increases as one investigates deeper into the future. As we move further away from the known situation (current year), we have to both extrapolate existing parameters (e.g. predict housing supply in 2030 versus 2040) and predict additional parameters (e.g. will there be self-driving cars in 2040?).

In our opinion, the changes itself outweigh the uncertainty of changes and therefore the year 2030 is best suitable to be used for each policy scenario. Policy impact and street adaptations can still be compared, since different policy scenarios are compared for the same same year, justifying the choice not to include the year 2023.

Reference scenario

The first scenario is a reference scenario, where no speed limit policy is included. The reference scenario in the case study was already predefined before this research project and thus has not been part of the research process itself. Besides constructional developments, the reference scenario embraces policies, cultural, societal and economical changes for the year 2030 (see Schoorlemmer et al. (2023) for full explanation):

- It includes the current development plans on a neighbourhood, zonal or regional level. Implementation of these plans in the 2030 scenario is based on expert judgement in close collaboration with national, regional and local governments.
- Planned and ongoing infrastructural projects are included when expected to be finished before 2030, again based on expert judgement in close collaboration with national, regional and local governments.
- The reference scenario embraces policies, cultural, societal and economical changes for the year 2030. Based on expert judgement, policies that are likely to come into effect have been included. In addition, expected traveller behaviour change is included based on scientific and grey literature and expert judgement.

USLR scenario

The second scenario is a copy of the reference scenario, but it includes implementation of the urban speed limit reduction policy. This requires a method to determine which streets are affected by USLR policy and which street adaptations are expected. The method developed in this study is based on a method used in a previous case study by Nightingale et al. (2021) to determine which streets in the City of Edinburgh Council would be effected by USLR policy. Since the actual USLR policy of the city of interest in 2030 is still in the making, we need to formulate a close approximation of the expected USLR policy. The steps for this are described below.

The developed method consists of five steps:

1. Start with available lists of potential locations for USLR policy from the city council.
   Using existing proposals from the city council of the case study allows to give the results of this research both a scientific and practical value.
2. Adjust the list based on (written reports of) discussions by main stakeholders. Those stakeholders are municipality representatives, emergency services and transit authorities.
3. Personal judgement by the researcher.
   Google streetview is used to determine the current speed limit, the current street type, and the alternative street design options based on current layout and the assessment framework described by (van Oosterom & Swart, 2021) (Veilig50 principle, GOW30, ETW50 or ETW30). The width of the street limits the possibilities. To determine whether cycling lines are possible to implement, the removal of parking spaces, trees, lanes, or the narrowing of sidewalks and similar features was weighed against the interests of relevant stakeholders. To include the opinion of the local community, we searched for online (news) articles about the street and its neighbourhood via Google search engine. In some cases, the necessity for a 50 km/h speed limit is determined by emergency services, while in other areas, parking pressure, crowded sidewalks and expected commotion are decisive factors in determining the alternative street design options.
   Safety is a major factor, and around schools, it is the leading concern, guided by the city's ambitions and policies. Cycle suggestion lanes and shared space are not considered safe on 50km/h streets (Kennisplatform CROW, 2023). This means the maximum speed is reduced to 30km/h unless the street width allows separated cycle lanes.

   Outcome of this step is a list of selected streets explaining the change of the speed limit and the change of the street category. When relevant the resulting list includes the expected effect on vehicle speeds, and possible options to mitigate the effects on travel time for public transport.
4. Review the list via consultation.
   Whereas Nightingale et al. (2021) performed this step in group setting, for this research the choice is made to have small iterative individual feedback sessions. This allowed more flexibility in the review process. The discussions are held with one or more representatives from the city council, PT operator and relevant mobility consultants. Using open questions the person was asked to reflect on the locations. After answering, the view of the researcher and other representatives were explained, upon which the person was asked to reflect again. Furthermore, this step is iterated going back to the previous step.
5. Eliminate discrepancies.
   How Nightingale et al. (2021) performed this final step is not explained, so personal interpretation of this step is used.
   Because documents were not always concise or contained errors, personal judgement is used, where the chance of a street redesign before 2030 is estimated. We took a conservative approach when in doubt.

To summarise, two scenarios for 2030 are formulated. The first scenario is the reference scenario, where no speed limits are changed. The second scenario is in line with the current ambition of the city council when USLR policy is continued. It is based on policy documents and expert opinions, including a complete list of changes in speeds per street.

3.3. Methodology for simulating a USLR policy: a multi-modal traffic simulation model

This research uses a multi-modal traffic simulation model, based on the classic four-step transport model described by De Dios Ortúzar and Willumsen (2011) (see Chapter 2). An existing transport model tool is used to allow usage of a detailed model despite the limited available research time. Specifically, a macroscopic simultaneous multi-constraint multi-modal gravity model is used.

As seen in Figure 3.1, there are four basic steps (blue ovals). During the first step - the trip generation - the model computes the expected travel demand to and from each location. Parallel to the first step, the second step - skim generation - calculates the costs to travel for each possible trip. This gives generalized costs between each location and for each possible mode and motive, based on travel time, travel distance and other costs. In the third step - trip distribution & modal split - the number of trips between each location, and mode of transportation is calculated. For this, the demand and costs to travel calculated in the first steps is used. The lower the costs, the more likely a trip will be made. Finally, in the fourth step - trip assignment - trips are divided over possible routs based on route attractiveness. This results in the model output in the form of traffic flows per transport mode.

To simulate the reality, each street is represented as (multiple) links in the model and building blocks are represented as centroids. This model distinguishes per travel motive, time period of the day and transport mode. The model consists of 3 time periods for an average working day: morning rush hour (7-9am), afternoon rush hour (4-6pm) and the rest of the day. As mentioned earlier, there are four basic steps. The model goes through those basic steps for all three time periods separately. The following paragraphs will explain the steps of this model in more detail.

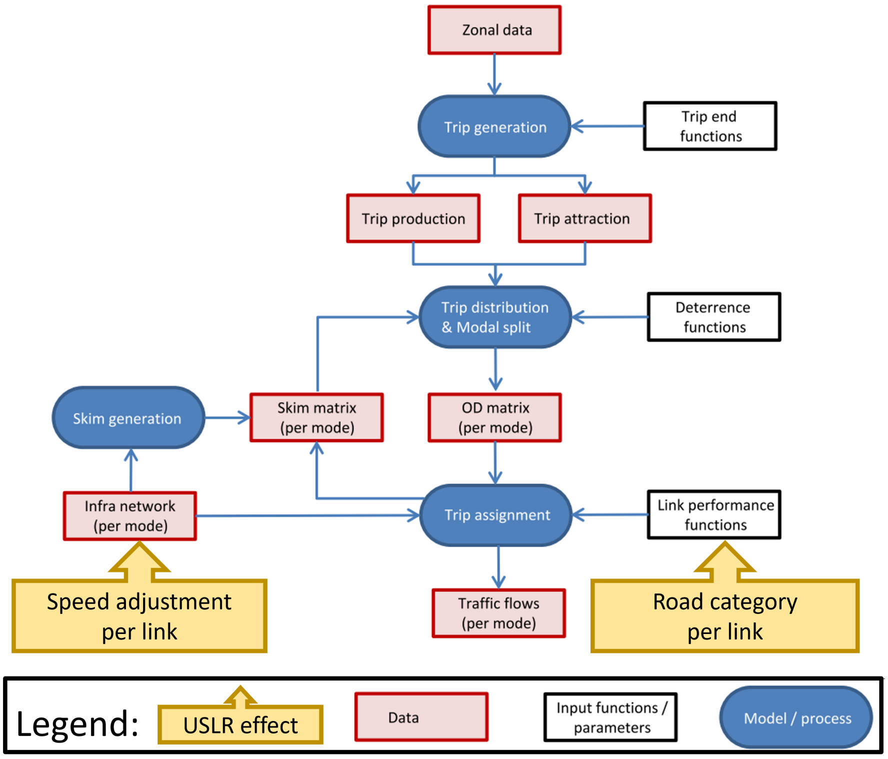

Figure 3.1: Transport simulation model with adjustments for policy implementation. The speed adjustment for public transport is not only per link, but per transport line as well. Modified, based on van Nes (2019, p. 64).

3.3.1. Basic principles of multi-modal traffic simulation model

1: Trip generation

The first step is **trip generation**. Based on socio-economic data the trip production and trip attraction per zone are calculated for each time period (Figure 3.2). The socio-economic input data does not differ between the policy scenarios, and therefore remains the same between the reference and USLR scenarios. This study uses a linear regression model at the zonal level.

Both the trip production and attraction are direction dependent. We distinguished the following motives (types of trips): home-work, work-home, home-business, business-home, home-education, education-home, home-commercial, commercial-home, and other-other.

Specific major utilities cause a deviating trip generation, such as hospitals, museums, amusement parks, concert halls, large shopping centers, etc. Those utilities are exogenously added into the trip generation and added to the category "other" (Schoorlemmer et al., 2023, p. 19). The different utilities have small corrections in for example the car occupancy and user group, based on expert judgement and a work-group.

The three time periods are simulated independently. As a result, the time periods have fixed shares during the trip generation. This means people can not choose to travel in a different time of the day.

The result of the trip generation is the amount of incoming and outgoing trips per centroid, given for each time period and for each travel motive.

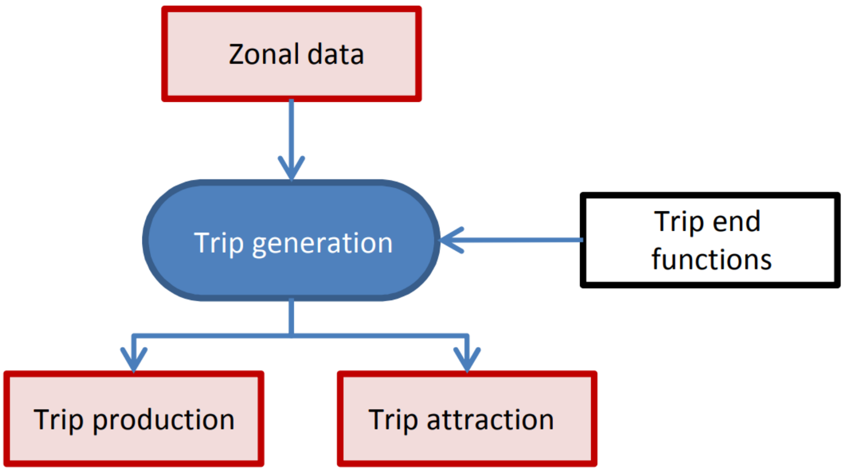

Figure 3.2: Input and output of the trip generation step (van Nes, 2019, p. 46)

2: Skim generation (impedance/resistance-matrices)
In the second step, the skim-matrices are calculated. A skim matrix is a matrix containing a representation of the impedance between an origin zone (rows) and a destination zone (columns). In other words, this impedance is the general costs of traveling between two points, expressing the accessibility. Each value in the skim-matrix is calculated using Equation 3.1, where distance and time are converted to general costs of traveling. Separate skim-matrices are formulated for each mode, motive and time period.

$$C_{mp} = L_m * VoD_{mp} + R_m * (VoTmp * IndexVOT_{msh}) + P_m \tag{3.1}$$

C_{mp} = generalized cost for mode ***m*** and motive ***p***
L_m = Distance (km) for mode ***m***
VoD_{mp} = Value of Distance for mode ***m*** and motive ***p***
R_m = Travel time (minutes) for mode ***m***
$VoTmp$ = Value of Time for mode ***m*** and motive ***p***
$IndexVOT_{msh}$ = Value of Time for mode ***m*** and degree of urbanisation (*stedelijkheidsgraad*) ***sh***
P_m = Penalty costs for mode ***m***

For each origin-destination pair the most attractive route is determined. A route algorithm determines for each mode the most attractive route using the predefined car/PT/bike networks. The used route algorithm is the shortest path algorithm of Dijkstra. The model builds shortest path trees using Dijkstra's algorithm with backlinks rather than backnodes in order to model banned turns and to prevent trees passing through the same node more than once. The shortest route is determined on the basis of general costs, with initial values based on the free-flow situation.

For (car) traffic the general costs are relatively simple to calculate, as it mainly depends on distance, travel time and some penalty costs. For public transit, more values play a role, like the number of changes, waiting time, stop- and/or transit-line specific penalties, fares, frequencies, etc. In the model, the availability and quality of public transport services play an important role when computing the impedance between pairs of zones (van Nes, 2019, p. 59). In a zone with a major train station public transport is far more attractive compared to a rural area where a bus passes only once every hour. The two used scenarios in this research have the same availability and quality of public transport services. This way only travel times are affected by the USLR-policy, allowing to see the isolated effect of travel times on modal split.

The travel time between each OD pair is initially assumed to be free flow traffic time. This means congestion is not included when performing the skim generation. The advantage is that ignoring congestion effects eases the simulation computation time. However, travel time depends on congestion and travel time is an important cost. Because congestion has a big impact during rush-hour, the skim generation is iterated three times for the rush hour periods to include the effect of congestion. This iteration happens after step 3: the simultaneous multi-modal multi-constrained gravity model.

3: Simultaneous multi-modal multi-constrained gravity model

During the third step, the trip distribution and modal split are calculated simultaneously. As input the trip production and attraction matrices from step 1 are used, as well as the skim matrices from step 2. The gravity model simulates the trade-off between the willingness to make a certain trip and the costs per mode needed to make that trip. Top-lognormal distribution functions translate the generalised costs per mode into a relative attractiveness of each mode. Different parameter values for the lognormal distribution functions are formulated per motive, time period, mode, and whether or not private cars are available.

In other words, a simultaneous gravity not only evaluates the relative attractiveness of different destinations, but also the relative attractiveness of different combinations of mode and destination. Each mode has its own deterrence function, reflecting the competition between the different modes for a given trip impedance. This results in matrices containing the amount of travellers per mode between each origin and destination, per time period. The number of trips from one zone to another zone using a certain mode is calculated using Equation 3.2:

$$T_{ijm} = a_i * b_j * P_i * A_j * f_m(c_{ijm}) \tag{3.2}$$

T_{ijm} = number of trips from zone ***i*** to zone ***j*** using mode ***m***,
a_i, b_j = scaling factors,
P_i = trip production of zone ***i***,
A_j = trip attraction of zone ***j***,
$f_m(*)$ = deterrence functions describing the incentive of travelling to zone ***j*** from zone ***i*** for each mode ***m***
c_{mp} = generalized cost (travel impedance including distance and travel time) for mode ***m*** from zone ***i*** to zone ***j***

4: Trip assignment

After the number of trips from one zone to another zone are calculated for each mode during the third step, in the fourth step the trip routes are calculated, thereby dividing trips over the transport network based on route attractiveness. To assign those transport flows to the network, different assignment methods or even a combination of methods are used for each mode. All assignment methods used are static (meaning demand per time period is uniformly distributed over time and traffic flows do not propagate over time in the network) and deterministic (meaning there is no randomness and therefore a re-simulation results in the same output).

Car routes in the trip assignment depend on overall route costs and is iterated. The attractiveness per route is the sum of the generalized travel costs of the used streets (represented as links) and intersections. The maximum speed is not necessary the driving speed, since the driving speed decreases when congestion increases. Due to congestion, a detour can be more attractive if the saved travel time outweighs the increase in distance (trade-off between the value of time and fuel costs).

The generalized costs are capacity dependent (see explainer box below) and therefore calculated in 20 iterations. Traffic assignment over the network is a combination of volume averaging and intersection modelling. Converges towards the user equilibrium using the Method of Successive Averages (MSA) algorithm (van Nes, 2019, p. 65). For an explanation of the method, see De Dios Ortúzar and Willumsen (2011, pp. 370–371).

Car trips can be made as a car driver or a car passenger. Therefore, it is necessary to convert personal trips to car trips before cars can be assigned to the network. For each travel motive the average car occupancy rate is determined (conform ODiN) (Schoorlemmer et al., 2023, p. 10).

How are travel costs on a link calculated?
Car traffic in the network is represented as link volumes, in vehicles per hour. The conventional approach to determine travel costs per link is the BPR-function developed by the American Bureau of Public Roads (De Dios Ortúzar & Willumsen, 2011, p. 353). The function, shown in Equation 3.3, includes delay caused by congestion. The ratio between link capacity and link load is used to estimate the delay due to congestion using two parameters (α_a and β_a). Each street type has different characteristics. Those street type characteristics can be represented by the parameters α_a and β_a in the BPR function, making the function usable for for each road in the network.
With a small α_a (e.g. 0.5) delays occur only when the link volume is getting near to full capacity (highways). On the contrary, for roads with a large α_a (e.g. 2) severe delays occur well before full capacity is reached (such as residential roads). Though the parameter β_a is usually set to 4.0, each street type can have its own set of empirically derived parameters (De Dios Ortúzar & Willumsen, 2011; Zhang et al., 2019).
The USLR policy has an effect on the maximum speed and -depending on whether the street category is changed- the street category specific parameters. This will be further elaborated in a later section (Section 3.4).

$$C_a(x_a) = \frac{L_a}{v_a^{max}}(1 + \alpha_a(\frac{x_a}{q_a})^\beta a) \tag{3.3}$$

$$\begin{aligned}
&Where\\
C_a(x_a) &= \text{travel cost on link } a \text{ with load } x_a\\
L_a &= \text{the length of link } a\\
v_a^{max} &= \text{the maximum speed on link } a\\
x_a &= \text{load on link a}\\
q_a &= \text{capacity of link a}\\
\alpha_a \text{ and } \beta_a &= \text{street type specific parameters}
\end{aligned}$$

A frequency based, multi-path algorithm without crowding is chosen as public transport trip assignment method
Various assignment algorithms exist for public transport assignment, as can be seen in Figure 3.3. We chose a frequency based, multi-path algorithm without crowding. This means that public transport service levels in terms of waiting times, transfer penalty's, comfort and crowding remain unaffected by USLR policy, while the service level in terms of in-vehicle time is effected by USLR policy. This algorithm is chosen since it is most suited for determining the effects a speed limit reduction has on modal share, caused by longer travel times. Below, we will explain this choice in further detail.

Schedule based versus frequency based assignment techniques
The difference in timetable usage between schedule based and frequency based assignment techniques is shown in Figure 3.4. While schedule based assignment techniques rely on *moments* in time, frequency based assignment techniques rely on the *duration* of time.

Schedule based assignment techniques require vehicle timetables as data input: charts showing the departure and arrival times of individual vehicles (e.g 09:15 AM arrival of bus vehicle 123 at Central Station). With vehicle timetables, a delay due to reduced speed propagates over all subsequent time points in the vehicle timetable. This delay propagation can even propagate into the next round-trip

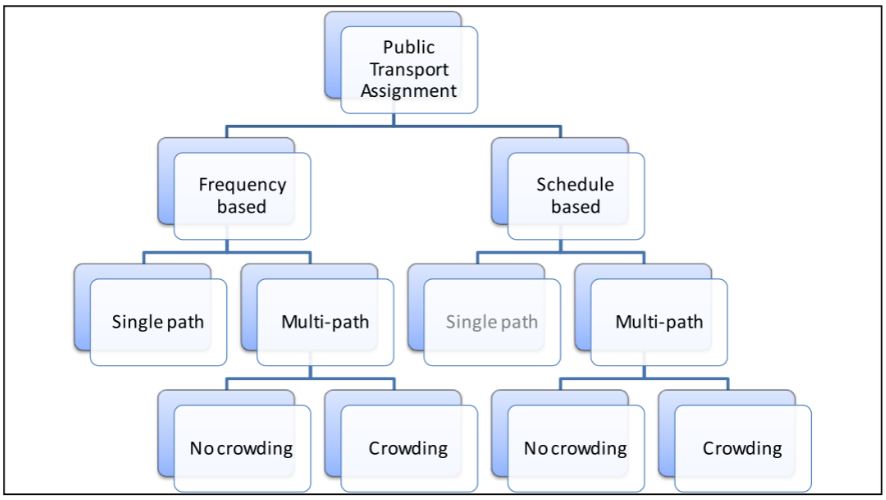

Figure 3.3: Classification of public transport assignment algorithms. Copied from van Nes (2019, p. 80)

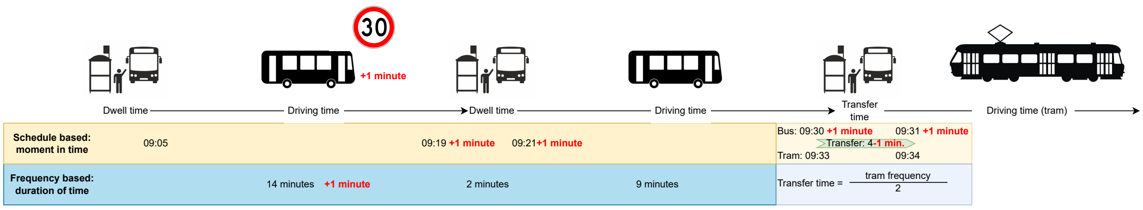

Figure 3.4: Difference in PT timetable usage between schedule based and frequency based assignment techniques. In this example, the driving time on the first part of the route changes with +1 minute. Shown is the impact on the data points of both techniques. In schedule based timetables, the effect propagates over all subsequent data points (arrival & departure times) and transfers. In frequency based timetables, only one data-point (travel time duration on the first part of the route) is affected.

if slack times are insufficient, disrupting the entire timetable as the day continues. Schedule based assignment techniques provide excellent insight on the impact on transfers, as the ”real” transfer time can be used. However, when making timetables the transfer times are often minimized to reduce passenger waiting times. Since transfers are optimized, travel time increases can cause passengers to miss the transfer connection when timetables are not readjusted and optimized for the new situation. Therefore, when travel times increase, a new timetable has to be made. This timetable optimization is a study on its own and thus not convenient for our research. In our opinion, schedule based assignment techniques are not suitable for studies on a tactical decision level.

Meanwhile, frequency based techniques require line timetables as data input: charts showing the travel times between two stops (e.g 2 minutes driving time of line 6 from Central Station to City Centre). One advantage is that travel time increases only affect one data point, which prevents delay propagation. For transfers, frequency based techniques usually rely on the ’rule of half’, where the half of headway time is used as a surrogate for public transport waiting times (Salonen & Toivonen, 2013). With a fixed frequency the waiting times and transfer penalty’s remain constant and the effect of USLR policy on timetable-hours can be estimated.

To conclude, for this research we decided to use a frequency based technique. However, this technique implies that resources are not finite: either additional driving can be compensated by slack time between trips, or additional vehicles can be deployed.

Single path versus multi-path algorithms

A path-based approach means that a set of path alternatives is constructed before the assignment step (van Eck et al., 2014). Single path algorithms only include one route between two locations, while multi-path algorithms allow inclusion of route alternatives. Public transport lines with operational speeds below the new speed limit or lines running over unaffected roads will have no increase of travel times. As a result, per line and/or part of the line the attractiveness will change and alternative routes should be considered. Therefore, this study uses a multi-path algorithm.

Finally, bicycle trips are assigned to the network according to the 'all-or-nothing' method. This means that bicycle congestion is excluded and therefore has no effect on bicycle attractiveness. One-third of the trips are assigned based on the shortest travel time, another third is assigned based on the shortest distance, and the remaining third is assigned using a combination of the shortest travel time and shortest distance. Additionally, access and egress trips to and from PT by bicycle are added to the bicycle allocation. E-bikes are integrated into the regular bike trips, and have a 0.8 travel time correction. The share of E-bikes depends on the distance (<2.5km, 2.5-7.5km, >7.5km), and is estimated for the reference year.

3.3.2. Required input data

Having chosen a model to simulate the policy scenarios, the right input data will need to be gathered:

- Reference scenario and a USLR policy scenario:
  The USLR policy scenario will have to be both location specific and type specific. "Which street will have which effect?" can be answered with the formulated USLR policy scenario. The methodology of constructing these scenarios is explained in Section 3.2.

  To evaluate the effects, of course a reference scenario is needed to compare with.
- Zonal data:
  Detailed simulation requires small zones and data on neighbourhood level or smaller. This data - such as inhabitants, jobs and facilities - is used for trip generation and trip attraction.
- Transport network:
  The transport network consists of a street network and a PT network. For each street, data is needed on street capacity, street type, vehicle allowance, speed limits and driving speed per mode and time period. However, revealed car driving speeds were not available for this study. Therefore, estimations are needed for each mode.

  Data on the PT network is a combination of information per line and per stop. Line data consists of the PT stop locations, timetable times, mode per line, frequencies per time period, and PT routes in terms of length, costs and direction. The data on stops includes stop accessibility per mode, line usage, transfer options, a attractiveness correction for high quality stops, and the location in the urban and traffic network.
- Input parameters:
  Trip End Functions: These estimate the total number of trips generated by and attracted to each zone in the study area. They consider factors like population, employment, and land use to predict trip productions (origins) and trip attractions (destinations).
  Deterrence Functions: These calculate how the "cost" of travel—measured in terms of time, distance, or monetary expense—reduces the likelihood of trips between two zones. They help distribute trips by modelling the effect of travel impedance on trip distribution.
  Link Performance Functions: These describe how the travel time or cost on a road link changes with traffic volume. They model congestion effects, showing that as traffic increases, travel time typically increases due to reduced speed or increased delays.
  Value of Time (VoT) per mode and per motive, because depending on the travel incentive people appreciate time-loss differently.
  Public transport parameters, such as mode specific fares, and factors to penalise waiting, transfers, specific modes, lines and stops.

3.4. Methodology for implementing a USLR policy into a traffic simulation model

As part of this research, a new methodology is developed to implement USLR policy in simulation models. This subsection describes the generalized methodology. The derivation of estimated public transport speeds is explained in the case study.

USLR policy is implemented only on the roads that will be redesigned and given a new maximum speed. We therefore focus on USLR policy incorporating physical traffic calming measures. The framework to select a set of streets is earlier described in Section 3.2. Those roads are represented as (multiple) links in the model.

Modelled impact on cars

Three characteristics of the links are changed:

1. The modelled maximum speed is reduced depending on the new speed limit and change in street type. The speed limit goes from 50km/h to 30km/h, which is a 40% decrease. In the used model the link speed can have deviations from the legal speed due to calibration effects. Therefore, we used a 40% speed reduction instead of legal speed limits to prevent interference with calibration. When the street category changed from arterial street to local street, instead a 60% speed reduction is used to reflect the additional usage of enforcement measures and resulting reduced street attractiveness.
2. The BPR-parameter values are set to the values of the new street category, if relevant.
3. The link is given a tag to allow easy selection of all links affected by the USLR policy, helping adjustments during the sensitivity analysis. This makes it possible to optimise the simulation model based on newly gained insights benefiting future research.

BPR-parameters considered for a new street type

Adjustment of the BPR-parameters α and β requires consideration, because a new street category will be implemented that does not officially exist yet in the Netherlands. However, already in the Netherlands cities adjust their streets to avoid delay of USLR policy. Guidelines for the new street design are being made. Meanwhile a provisional guideline is available to support road authorities (CROW, 2021; Kennisplatform CROW, 2023). The new street category is a high capacity flow street with a maximum of 30km/h (GOW30). Currently, 50km/h is the lowest speed limit for high capacity flow streets (GOW50). In the Netherlands the philosophy is to have recognizable street categories. This should help drivers to know how to behave (Kennisplatform CROW, 2023, p. 6).

One option is to stay as close to original (ie GOW50 or ETW50) road values for α and β. Advantage that solely the effect of speed on itself can be evaluated, but the downside is that the impact on road congestion is less realistic.

The second option is to have new α and β values, eg an average of GOW50, ETW50 and ETW30. However, it is not known what the capacity of the new street type will be, so guessing here would be unnecessary risky. It can blur the effect of the speeds, while the effect of a new street type is not known. On the other hand, the USLR policy does include changing the street type, so a sensitivity analysis of the street type parameters (with for example two sets for α and β) could provide new insights on the wider effect of the speed reduction policy and how to execute it.

The choice is made to use the same α and β values as GOW50 for the new street category GOW30. The new street category GOW30 has a focus on traffic flowing. This is in contrast to street categories ETW50 or ETW30 which function is to focus on access, parking, halting and stopping, meaning that many vehicles stand still or interact.

We assumed that the preliminary guidelines for GOW30 design are followed[1]. We estimated the effects of the new street type based on below guidelines, because the effects of this street type are not yet known or proven (Kennisplatform CROW, 2023, p. 4):

- Guiding principle for GOW30 is to have public transport stops on the street (Kennisplatform CROW, 2023, p. 15). For locations where currently an off-street bus stop is, the effect on travel times for buses could be less while the effect on car travel times would be more (as cars no longer can surpass a stopping bus). It also means that the bus frequency and dwell time constrain the street capacity for cars (since dwelling buses queue up traffic behind them). However, off-street

[1]There are preliminary guidelines at the moment for GOW30, because road administrators and municipalities already implement USLR policy while guidelines for low speed through streets were not available. While formulating the USLR policy, preliminary guidelines are already made available in the meantime(CROW, 2021; Kennisplatform CROW, 2023).

bus stops are preferred for stops with a long dwelling time and holding points because of its impact on emergency services (Kennisplatform CROW, 2023).

- Guiding principle for GOW30 intersecting with a dedicated public transport street is to give priority to public transport (Kennisplatform CROW, 2023, p. 20).
- In order to ensure the function of the street is on traffic flowing, parking is only allowed at parallel or backwards diagonal parking spots, but preferred to be avoided (Kennisplatform CROW, 2023, p. 15).

Furthermore, it is assumed that USLR policy will have no effect on intersection capacity and corresponding travel time delays to cross the intersection. This assumption is based on the macroscopic fundamental theorem of road traffic: $Q = \rho * V$. Where traffic volume Q (veh/h) is the product of the vehicle density ρ (veh/km) and the spatial average speed V (km/h). The assumption is made in other research as well (e.g. Gressai et al. (2021). The pre-post observational evaluation by Nightingale et al. (2021, p. 10) confirmed that the correlation between traffic speed and volume remains unchanged when the speed limit reduces.

Modelled impact on public transport speeds

Public transport speeds are derived from the timetable time and available speed maps of the case study, provided by the local public transport operator. On specific locations the driving speed was available, which have been compared with the timetable-based model speeds. An estimation of the free flow speed per street is made using Google streetview.

Furthermore, employees of the local public transport operator estimated whether the new speed limit would have consequences or not on a representative selection of links, based on individual mini interviews. Employees were asked for each street if the current driving speed exceeds 30km/h and/or reaches 50km/h. To compensate for dwell times and other non-driving related time, a penalty is subtracted from the timetable speeds to estimate the public transport driving speeds. The derivation of the speed penalty is elaborated in Chapter 4. With the penalty being implemented, the public transport driving speeds before and after USLR policy per link are calculated and used to determine the effect on travel time per link. The resulting effect is compared with existing estimations and research performed in grey literature (Bigalke et al., 2023; Gemeente Rotterdam et al., 2023; Huisman et al., 2022).

3.4.1. Calibration of the traffic simulation model

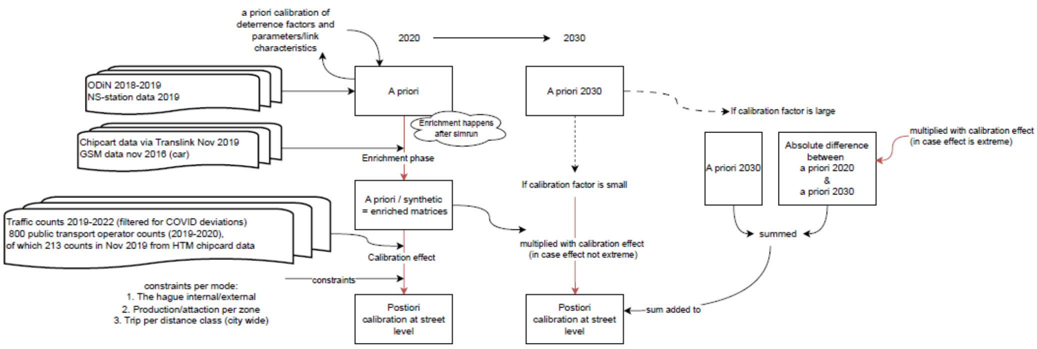

Figure 3.5: Model calibration steps

The traffic simulation model is calibrated in three phases (see Figure 3.5 for summary). The model calibration process existed before our research and we applied it without changes.

The first calibration phase is the model a priori calibration of deterrence factors and parameters/link characteristics. The second calibration phase is the ”enrichment” phase. The initial resulting matrices from the simultaneous multi-modal multi-constrained gravity model are enriched with revealed behaviour. Since it relies on revealed data, this step is only applied onto the model base year 2020. The Fratar technique (also known as Furness technique) is used for this iterative balancing process (Schoorlemmer et al., 2023, p. 44). It repeatedly calculates and applies row- and column balancing factors until convergence is achieved (van Nes, 2019, p. 53) (De Dios Ortúzar & Willumsen, 2011).

Thanks to this balancing step, the model can better predict OD-relationships and modal split on district level. The third calibration phase is the calibration at street level. Calibration is based on maximum entropy-optimisation and performed iteratively, using software package Sigkal (Schoorlemmer et al., 2023, pp. 12, 48). The calibration objective is the best fit on two types of conditions, namely counts and constraints.

Constraints:
The calibration uses multiple soft constraints which are formulated per mode. Soft constraints imply deviation from the constraint is possible though penalized. This means calibration of the simulation is not forced to result in the perfect fit of input conditions, but instead allows to stay closer to the uncalibrated results. The goal of the calibration is to have the model output as closely as possible to traffic counts, without major shifts between a priori matrices and a postiori matrices (Schoorlemmer et al., 2023, p. 47). Such constraints are OD volumes (both per time period and full day), production/attraction per zone (full day), trip length (both per time period and full day).

3.4.2. Summary of USLR policy implementation

The effects of speed limit reduction policy on public transport timetable speeds, travel times, and operating times will be estimated via comparative analysis of derived timetable speeds for public transport. For the car, a percentage reduction of the maximum speed (calibrated model speed derived from legal speed limits) is applied depending on enforcement measurements (a change in street category). When the street category changes, additionally the street becomes more sensitive to congestion via a change in street parameters. The car driving speed decreases when congestion increases.

The effects of speed limit reduction policy on modal share and travel volumes will be estimated using a macroscopic gravity-based transport simulation model. The choice behaviour of travelers is based on the gravity theory, with the quality of access between zones as resistance.

3.5. Method limitations

The methodology adopted in the study allows an ex-ante estimation of the effects of USLR policy on both the transport system as a whole and in more detail for public transport lines. As any assessment method, our study comes with limitations. Modelling is per definition an estimation of reality instead of the physical reality itself. Also, certain boundary conditions are assumed and generalisation is required. Social behaviour can differ per neighborhood, seasonal or daily weather fluctuations affect modal preference, events and disturbances cause daily deviations, etc.

The simulation model is optimised at simulating behavior of network traffic behaviour, but not individuals. This means that the results are more reliable for bigger volumes and less reliable for small passenger volumes.

3.5.1. Public transport speeds

Public transport speeds are estimated based on timetable times, giving the following limitations:

- The median of revealed travel times is used for timetable times per stop. Even if the speed estimation assumption is correct, still the travel time effect on the 50% fasted trips is underestimated. This means that the supplementary time margins at holding points will be consumed by longer driving times. Fewer time at such stops can become a problem when holding points are combined with dwell time or rest moments for public transport drivers.

  All trips above the average speed will therefore have a lager effect on travel times than estimated. It is debatable if this is a problem. If travelers and drivers assume to arrive at the time in the timetable, the reduction of early arrivals is no problem. However, when travelers and drivers assume to arrive (at least sometimes) earlier than the planned time in the timetable, the effect of USLR policy will be underestimated.
- Estimation via the timetable includes the current effect of congestion on driving speeds. However, any change in congestion severity is not included. Whether congestion will increase or decrease along public transport routes depends on how many and which streets are targeted by USLR policy.

3.5.2. Public transport crowding

Public transport assignment techniques including or excluding crowding levels

Public transport trip assignment algorithms can include or exclude the effects of crowding. Crowding is sometimes incorporated in public transport trip assignment methods. When crowding is included, a common approach is the usage of load factor bounds as constraints of the system (Ibarra-Rojas et al., 2015).

> **What is the effect of crowding on the effects of USLR policy?**
> The USLR policy could cause passengers to switch to a different line. When a line becomes more popular without frequency changes, crowding will occur. Crowding causes discomfort, as people have to search longer for free seating, have to stand or even squeeze in. In more extreme cases, it can be impossible to board and a service becomes unavailable. Crowding is part of a balancing feedback loop: more passengers lead to more crowding; more crowding leads to more discomfort; more discomfort leads to less attractive services; and less attractive services leads to less passengers.

There are two reasons to use a public transport assignment algorithms with no crowding.

1. First and foremost is model availability. We use an existing model, which already underwent fine-tuning not part of our research. To have the model working as intended and prevent unexpected model behaviour, we decided to stick to the algorithms that were used during set-up.
2. Second, we are in particular interested on the effects a speed limit reduction has on modal share, caused by increased travel times. Overcrowding can usually be prevented with assigning more or higher capacity vehicles to the bottleneck corridor. There are several ways to assign more vehicles to a corridor: increase line frequency with new vehicles, increase line frequency by reducing frequencies elsewhere, reroute additional lines onto the corridor, etc. Therefore, including crowding would require readjustment of the network and/or timetable, which consequently changes public transport attractiveness. The changed public transport attractiveness in return affects passengers volumes, thus crowding and thus adds a new feedback loop. This not only expands the research scope, but also makes it more complex to see the direct effect of travel time. For the same reason we chose a frequency based algorithm over a schedule based algorithm, we simplify.

To keep public transport service level constant for this study and only change travel times, the choice is made to use a public transport assignment algorithm with no crowding. Without accounting for crowding, overcrowding in the model is not effecting services which can cause extreme demand increases. In reality, those extreme demand increases would be less severe, because crowding reduces attractiveness and people would opt sooner for alternative routes. Therefore, the outcome of the simulation model may be incorrect for routes prone to crowding and alternative (parallel) routes. Passenger volumes on public transport routes with overcrowding will be overestimated, while passenger volumes on alternative routes will be (to a lesser extend) underestimated.

Crowding levels are closely related to timetable design, as the public transport line capacity depends on vehicle capacity and frequency. Since timetable optimization and fleet allocation are a study on its own, it is no part of this research scope. Therefore it makes sense to exclude crowding altogether. Instead, our study focuses on the effect of speed limit reduction on travel times.

Neglecting crowding effects has the advantage that it can help identify (parts of) routes that have the potential to grow in passenger volumes. Namely, when passenger volumes are not depending on crowding levels, the vehicle capacity is no longer a constraint revealing (induced) demand of passengers that would otherwise be scared of by the overcrowding levels.

Consequently, the public transport operator can accommodate this (induced) demand, by reallocating (double) articulated buses to lines where passenger volumes show a significant increase.

3.5.3. Car speeds

The maximum speeds for cars are reduced by 40%. It is assumed that traffic adheres to the speed limits. This means that speeding is not assumed to happen in the simulation model. In reality speeding of course occurs. Nonetheless, the assumption applies to both simulated scenarios. As long as the frequency of speeding does not change, we argue the assumption holds true. After all, including speeding in the USLR policy scenario while excluding speeding in the reference scenario would be to compare apples and oranges.

The proposed USLR policy combines the new speed limit with a street redesign to enforce the new speed. Changing the character of the street has a big influence on driving speeds, justifying our choice to use (calibrated) normative speed limits as maximum speed (Atkins et al., 2018; Vis et al., 1992).

When physical traffic calming measures are no part of USLR policy, the impact on car travel times and the derived attractiveness of cars will be less severe. Literature shows that speeding frequency does increase for USLR policy without enforcement measures (Atkins et al., 2018; Cairns et al., 2015; Goudappel, 2022; Nightingale et al., 2021). Still, the largest observed speed reductions occurred on streets with with the highest initial observed speeds (Atkins et al., 2018; Nightingale et al., 2021).

If traffic on USLR-affected streets does not fully adhere to the speed limit, this could also be the case for PT, in particular if vehicles are behind schedule. Therefore, the total effect of speeding on modal share would likely be limited and our conclusions remain the same.

3.5.4. Car spill over effect

In literature the spill over effect was addressed (for example Cleland et al. (2020), De Ceunynck (2017), and Röth (2022) or in grey literature Gemeente Amsterdam (2021) and Koster et al. (2023)). The idea is that as more streets have reduced speeds implemented, the more drivers are used to low speeds. As a result, drivers are more comfortable driving at low speeds and therefore have less incentive to drive 50km/h. This effect 'spills over' towards unchanged streets where 50km/h is allowed, causing a reduction of driving speeds on all streets. Because the extend of the spill over effect is not known and calibrations would be lost, the spill over effect is not included in this study by changing the speeds on nearby streets.

At first sight, the used method could potentially have a slightly higher driving speed on nearby streets than would be expected due to the spill over effect, as the infra network characteristics of nearby streets are not changed. However, because the speed limit on streets affected by USLR policy reduces, more drivers will take alternative routes. As a result, the nearby streets will have more traffic, leading to more congestion, and finally leading to a lower driving speed on nearby streets nonetheless. Our simulation model captures the effect on congestion via the link performance parameter function (BPR function). Therefore, the used method is still capable to capture the spill over effect to some extend, albeit indirectly as a confounding variable and only when link volumes change significant.

3.5.5. Street capacity

Besides the congestion sensitivity (captured in BPR-function) and speed limit, also the street capacity could decrease. However, we chose to keep street capacity constant because of three reasons:

- First, the impact of of USLR policy on street capacity is unknown. Gressai et al. (2021) argues that the link capacity experiences no impact at all. CROW (2021) gives a more nuanced explanation. Though the theoretical street capacity reduces with lower speeds, in urban area the street capacity is often no constraint.
- Second, and most importantly, in urban area the street network capacity is mostly constrained by its intersections rather than the streets themselves.
- Thirdly, the link capacity in the model is not standardized. Instead link capacities are frequently individually adjusted based on the amount of lanes, counts, street type, fitting during calibration, etc. A consistent approach that realistically captures the effect of enforcement measures on street capacity is therefore not realistic.

Instead, if the street category remains unchanged, the intersection capacity will also remain the same. If the street category does change, we have already included a penalty in the speed and congestion sensitivity. Therefore, a further correction for the intersection change is not necessary and street capacity needs no adjustment.

3.5.6. The (absolute) attractiveness of cycling remained unaffected

Cycling has no direct modeled impact, meaning that cycling speeds and other input cycling parameters remain unchanged. However, in reality cycling bottlenecks can occur, which may increase travel time for cyclists and make cycling less attractive due to crowding on cycle paths. As the modal share of cycling increases, congestion on cycling paths can result in reduced speeds and lower comfort levels. Intersections, in particular, may become problematic bottlenecks. Additionally, while the increase in cycling along cycling priority routes could hinder yielding traffic flows (such as cars and public transport), travel times for yielding traffic could increase indirectly as well.

On the other hand, fewer cars and more separated bicycle paths could improve the comfort, speed, and overall utility of cycling. Less nuisance from car (pollution and noise) could make cycling more attractive. The attractiveness of cycling could also increase if USLR policy benefits the (perceived) safety of cyclists.

We think the effects of increased cyclist volumes on travel times of all modes would only be local effects and have no significant net effect on modal travel times and attractiveness.

The conventional bike and e-bike are modelled as one mode with an average speed of 20km/h. Though we think it could be more realistic to use nests instead, we think the simplification of cycling is justified. The average speed is in line with literature. On dedicated cycle paths the average speed for e-bike is 23,8km/h and for conventional bike 21,2 km/h, according to revealed data (25.000 observations) in Toronto, Canada (Hassanpour & Bigazzi, 2024). On shared space with pedestrians the observed average speed was lower (17.4 and 21.7km/h for conventional bike and e-bike respectively). When compared to the dutch urban setting this research can give an overestimation. The urban setting in the Netherlands shows lower cycling speeds for conventional bikes according to a smaller study (46 participants in total, of which 14 on conventional bikes). In the dutch urban area, the conventional bike has an average speed of 17.8km/h, whereas the e-bike has an average speed of around 25km/h (Twisk et al., 2021) [2].

3.6. Policy impact analysis: output of the simulation model

The outcomes of the used model simulation are analysed to determine where relevant differences in mobility occurs after policy is implemented. Travel behaviour and modal split can be analysed by comparing the OD matrices. The change in passenger volumes between each zone and for each street or PT line are a direct output of the model.
Other KPI's are:

1. Travel time of PT vehicles per time period. This is further split up into:
   (a) total travel time (including dwell time but excluding end of line layover time)
   (b) travel time per PT line
   (c) travel time per street
2. PT passenger volumes per time period. This is further split up into:
   (a) total passenger volume per mode
   (b) passengers per PT line
   (c) passengers per street

For each public transport line the effect of USLR policy on round trip travel time and the effect per part of the line is determined using the impact of speed reduction per street. Here, end-of-line time margins are excluded as those were not available. Additionally, the daily required timetable hours are calculated for both policy scenarios. With fixed predefined frequencies per line and new travel times, the change of timetable hours can be estimated by multiplying the travel time with the amount of trips).

PT lines are cut into several sub-lines. Because of the data input format, in the model a PT line is modelled one-directional, meaning that a line round trip consists of two sub-lines (back and forth). In addition, some lines are split up into more sub parts. Those additional (shortened) transit-line are needed to for example represent short-turning of some vehicles on those lines, or when lines are relatively long.

[2] Twisk et al. (2021) differentiated the e-bike between pedelecs speed pedelecs. Pedelecs support human pedalling with less than 250 W and only up to a speed of 25 km/h, while speed pedelecs support human pedalling with less than 4000 W and support human pedalling up to a speed of 45 km/h. For pedelecs and speed pedelecs the average speeds were 20.6km/h and 28.2km/h respectively (Twisk et al., 2021)

The impact of USLR policy on timetable hours is analysed both per PT sub-line and summed for the entire PT line. For timetable hours, the sub-lines gave no additional insights and are therefore not discussed in the final results.

However, the impact on PT passenger volumes can differ per direction, or differ for a smaller part of the line. This made merging changes passenger volumes of the sub-lines into one line unrealistic, as negative and positive changes on two paired sub-lines would cancel each other out. Therefore, the results on passenger volumes are analysed per PT sub-line instead of per line.

The modal share is calculated using Equation 3.4. Modal share is expressed as the amount of daily trips per mode divided over the total daily trips (all modes combined). The calculation is based on the main mode, for an average working day. For example, public transport with access and egress by bicycle is only counted as a trip by public transport. Also, P+R with last mile by bike or public transport is considered as a single trip by car. This prevents double counting of trips during determination of the modal share. Simulation output consists of amount of cars instead of amount of car trips. Therefore, car trips are calculated by multiplying the average occupancy per car (1.3) with the amount of cars. So while during simulation the car occupancy rate is per motive, during the modal share calculation it is not per motive.

The modal share for bike, public transport and car is calculated based on all trips towards, from and within the case study city, given per origin-destination. The modal share is calculated for each origin and destination (OD) combination. The OD zones are 8 city districts, and 1 zone representing all external locations combined. Because the total amount of trips can change to/from a zone, the modal share is calculated separately for the reference scenario and USLR policy scenario.

$$\text{Modal share of mode } \boldsymbol{m} = \frac{T_{ijm}^{mode}}{T_{ij}^{total}} \tag{3.4}$$

T_{ijm}^{mode} = number of trips from zone ***i*** to zone ***j*** using mode ***m***,
T_{ij}^{total} = number of trips from zone ***i*** to zone ***j*** for all modes combined.

Data processing:
Software tool Excel is used during data sorting and filtering. Passenger volumes are estimated per public transport (sub-)line and per time period. The model is good at simulating behavior of groups, but not individuals. This means that the results are more reliable for bigger volumes and less reliable for small passenger volumes. Therefore, for each time period, an arbitrary threshold of 100 passengers per line is used to filter out data points below 100 passengers (in reference scenario) when analysing passenger volumes at line level, because of data reliability. Sub-lines with fewer than 100 passengers per time period are filtered out beforehand. This causes buslines 44, 383, 384, 386 and 827 to be filtered out during passenger analysis at line level.

4

Case study

This chapter is confidential and therefore removed from the thesis.

5 Conclusion and discussion

The primary goal of this thesis is to assess the impact of Urban Speed Limit Reduction (USLR) policy on public transport (PT) operators, using The Hague as a case study. **The results show that USLR policy does not significantly affect modal share and thus PT income, but does increase travel times, and thereby overall costs for PT operators.** This section discusses the implications of the findings, and considers how these results can inform future policy and research. Afterwards, we will examine the strengths and limitations of the methodology.

5.1. The first order effects of USLR policy

USLR policy has multiple effects on both transportation systems and society. **The first-order impacts, such as small increases in travel time for public transport, do not result in a notable modal shift away from public transport.** In the case study, we observed a negative effect of USLR policy on $\simeq$40% of the targeted streets used by public transport in terms of reduced PT driving speeds. While the operational efficiency of PT reduces slightly -in our case study the PT in-vehicle travel time increases with 1-1.2% on average- the mode remains as popular as before. However, the increased travel times lead to additional operational costs. The case study shows that income from ticket sales will not improve for local PT operators, while operational costs rise, creating a financial strain on PT operators. This is contrary to a major goal of USLR policy, which is to stimulate a modal shift towards sustainable modes, as lower PT speeds increase travel time and operating costs.

Results from our study match those in literature. Grey literature analysing the effect of USLR policy in Rotterdam estimated a yearly increase in TTH of 16.000, or 5.000 and 11.000 for the tram and bus respectively (Gemeente Rotterdam et al., 2023). Our study shows a similar trend of increased TTH for bus and tram. Rotterdam is a larger municipality than The Hague, explaining the larger absolute change of TTH Rotterdam. Unfortunately, the relative change of TTH is not mentioned in the study.

Though not quantified, the case study of Rotterdam shows decreasing PT ridership on lines with increased travel times, while ridership increases on metro, train, and 'fast tramlines' (Gemeente Rotterdam et al., 2023, p. 25). Those ridership increases are the result of a modal shift from car to PT and bicycle. Still, the city-wide modal share of PT is unaffected (Gemeente Rotterdam et al., 2023, p. 25).

The lack of a modal shift in our USLR policy is also reflected by real life results from an observational study in Edinburgh (Nightingale et al., 2021). Interestingly, the USLR policy in Edinburgh was much larger -targetting 30% of streets-, but there were no enforcement measures and key arterial routes remained out of scope.

The **rippling effects** of USLR policy on public transport are considerable, affecting both the service performance and passenger experience.

Timetable readjustment is unavoidable, but can have severe consequences. Increased vehicle travel times cause increased operating times. This means both vehicles and drivers take longer shifts, or more shifts are needed. Both longer shifts or more shifts will cause the amount of required timetable-hours to increase in order to fulfill the same service level. This means operational costs will increase. When staff or fleet is already planned in at their maximum capacity, the public transport operator is forced to make large and time-consuming investments, or cut services. In The Hague already 5% of services is cut due to a driver shortage (omroepwest, 2024). This serious shortage of bus drivers is extensive and not only limited to the case study of The Hague. The Netherlands, where 20% of vacancies for bus drivers (6.000 vacancies) remain unfilled, experiences the most severe driver shortage in Europe (Verheggen, 2024). Meanwhile, in Europe the driver shortages will increase from 105.000 to 275.000 between 2023 and 2028 (IRU, 2023). Therefore, any additional required timetable-hours caused by USLR-policy inflicts additional pressure on a already tense staff capacity, and this issue has further application beyond just the case study. On top of that, if current levels of service are to be maintained, PT operators will need additional vehicles to accommodate for the higher timetable hours, leading to high one-time investments on top of increased operating costs.

Without financial compensation this inevitability leads to service cuts. From a financial point of view, it makes most sense to have those service cuts take place on services with already low ridership and further passenger volume decline. After all, to balance costs and income it makes most sense to cut a few services with a large (financial) net loss, instead of having to cut many services each with a small net loss. A potential risk is that equity-oriented PT services are hit in particular, causing mobility equity decline as undesired side-effect of USLR policy.

Reliability also plays a crucial role in the rippling effects. Adding the additional driving time caused by USLR policy onto the timetable can enhance reliability by smoothing irregularities in driving times, but subtracting it from current dwell times would lead to a decreased reliability.

Under normal conditions, drivers may speed to catch up when running late, but the reduced speed limits under USLR policy limit this option. For instance, speeding 5 km/h over the limit results in a more significant relative increase on roads with lower speed limits—about 18% faster on 30 km/h roads compared to only 10% on 50 km/h roads. This reduced variability in travel speeds can actually improve overall reliability[1], as a reduced variability in travel speeds results in a reduced variability in driving time. While the potential gains are nuanced and depend on factors like dwell time and slack time, the reduced variability in travel times could lead to fewer unexpected delays. From the operator's perspective, this increased reliability also means that less slack time needs to be built into timetables, which could help reduce costs.

However, when the increased travel time is subtracted from current dwell times, the PT reliability will likely decrease. From a passenger perspective, PT service reliability affects both travel time and crowding. Delays lead to longer waiting times and uncertainty, while reduced reliability increases the likelihood of passengers arriving late or early. In addition to impacting travel time variability, crowding and the likelihood of finding a seat also play a role in overall passenger satisfaction. If public transport becomes too unreliable or uncomfortable, passengers may shift to other modes, causing a negative feedback loop for PT operators.

Besides an effect on timetable reliability, operational reliability might improve due to enhanced safety. With fewer or less severe accidents, disruptions to public transport services would decrease, allowing operations to resume normal schedules more quickly.

5.2. The second order effects of USLR policy

Beyond these immediate effects, there are second-order impacts based on existing literature. **USLR policy is linked to lower CO2 emissions, although no consensus is yet reached on the policy effect on pollutants like NOx and PM**. Our case study showed a 0.2% modal shift from cars to bicycle. This observed minimal modal shift strengthen the conclusions of existing papers that assumed no modal shift (Gressai et al., 2021; Rossi et al., 2020; Tang et al., 2019). Nonetheless, even a small decline of cars results overall in less polluters and less congestion, further reducing pollution. However, USLR policy with enforcement measures can negatively affect pollution locally, due to re-routing and more frequent braking and accelerating resulting from the kangaroo effect[2].

[1] The potential gains can be nuanced, as trip time variability does not only depend on the distribution of travel time, but also on the distributions of dwell times, slack times and stopping times (van Oort, 2022, p. 24). Therefore, the effect on total trip time variability scales less than the effect on driving time variability.

[2] The kangaroo effect describes driver behaviour where vehicles are braking before road humps, speed cushions or cameras and accelerate afterwards. Instead of speed compliance the enforcement measures could sometimes lead to kangaroo jumps. This could result in emissions increasing and unpredictable speed profiles (De Ceunynck, 2017; Tang et al., 2019).

Safety improves with lower speed limits, especially for vulnerable road users like cyclists and pedestrians, making this policy an important tool for urban safety. However, we argue the safety effects of USLR policy depend on how the policy is implemented. If car traffic remains constant and cyclists are moved into shared lanes with cars, USLR would actually increase exposure to hazards, potentially undermining the desired safety benefits. When cyclists retain dedicated lanes and car traffic is reduced, the hazards are diminished, and the policy achieves its intended safety goals.

USLR's impact on safety is also highly dependent on driver behaviour. Drivers who unintentionally exceed the speed limit pose a hazard. In a fragmented USLR implementation, where speed limits change frequently, drivers might struggle to keep track of the applicable limit. This increases the likelihood of unintended speeding, particularly for car drivers. **This makes a city-wide USLR policy preferable, as it provides clarity and reduces confusion for drivers.** With a consistent 30 km/h limit throughout most streets as default, the need for constant monitoring of speed signs is reduced, decreasing cognitive workload in urban environments where distractions and interactions between road users are already high. Fewer street signs mean fewer stimuli to process, allowing drivers to focus more on other road users.

Even in a city-wide implementation, some streets will likely retain higher speed limits (50 km/h) due to their role in the transport network. However, having 30 km/h as the default and 50 km/h as the exception is generally safer. Namely, driving too slowly on a 50 km/h street is safer than driving too fast on a 30 km/h street, particularly for vulnerable road users. This approach minimizes unintended speeding, especially on streets where mixed traffic increases the risk for vulnerable users.

Additionally, **USLR policy may increase response times for emergency services**. Lower speed limits slow down overall traffic, and when emergency vehicles cannot overtake other road users, their response times are extended. Street redesigns, such as speed bumps, road narrowing, and reduced lines of sight, further delay emergency vehicles. Emergency services must adjust their speed when they encounter speed bumps, road narrowing and a reduced line of sight. Speed bumps are in particular problematic for fire trucks carrying water (due to the momentum of the heavy water body) and ambulances carrying patients (due to the patient stability). On-street PT stops —default in the new GOW30 street design— instead of off-street PT stops also hinder emergency vehicles, adding to the challenges in responding to emergencies efficiently (Kennisplatform CROW, 2023).

5.3. Recommendations for USLR policy implementation and PT adaptation

Policymakers should weigh the increased costs for public transport operators against the broader societal benefits of USLR policy, such as reduced accidents and emissions. While USLR policy does contribute to broader urban liveability and safety goals, the findings from this study suggest that its direct impact on public transport operators is less straightforward. Public transport speeds are only marginally affected, but the increase in operational costs without an accompanying increase in ridership poses a challenge.

Our case study showed a 0.2% modal shift from cars to bicycle, and an unaffected PT modal share. Comparing the findings of Nightingale et al. (2021) and Gemeente Rotterdam et al. (2023) with our own suggest that **different USLR policy types do not result in a notable modal shift.** PT ridership did not increase after USLR policy with strict enforcement measures (assumed in our study), speed segregation as mitigation (assumed by Gemeente Rotterdam et al. (2023)), or a large quantity of streets (assumed by Nightingale et al. (2021)). Therefore, if a modal shift is still desired, synergistic policies are needed such as traffic calming and constructing semi-metro corridors. Though those come with high investment costs, they would contribute to the goals of USLR policy, and could simultaneously increase accessibility and benefit the financial position of PT, saving timetable hours while increasing ridership.

Governments should consider how to respond on the increased PT timetable hours needed. If not mitigated, USLR policy causes as undesired side effect either increased fares or forced service cuts resulting in reduced PT service levels. To reduce the cost impact on PT operators, alternative solutions should be explored, such as financial compensation or infrastructure investments to minimize the increase in PT travel times. **Public transport provides broader benefits to cities, so it is important to consider not only how to mitigate the effects of USLR policy on PT, but also how PT can actively contribute to achieving the goals behind USLR.** This involves looking beyond just safety and environmental concerns to include factors like equity, effective mobility, and creating an efficient city (see e.g. Van Oort et al. (2017) for the wider benefits of PT). Already, in our case study the effects of USLR policy were not equally dispersed over the city. Therefore, an integral approach is needed.

Policy makers should consider where to mitigate and which mitigation option is most efficient. Though speed segregation for public transport offers a promising mitigation potential, it is not recommended as the primary strategy. In our case study PT reached only at 10% of the USLR affected streets the reference 50km/h speed limit. Therefore we think the PT operational and ridership gains from PT speed segregation are limited compared to other solutions, especially on shorter street segments. The same holds for speeding up elsewhere. For example, applying travel time compensation at the end of the line could help mitigate an increase in required timetable hours, but this would have little effect on PT attractiveness or passenger volumes.

More strategic solutions, such as mitigating measures on streets with high passenger volumes or with significant increases in required timetable hours, could improve public transport attractiveness while reducing operational costs. Therefore, we believe that strategically applied mitigating measures have the potential to turn USLR policy in favour of public transport, only if both operator costs and ridership are considered.

Potential solutions to prevent further delays include modal filters, dedicated lanes, intersection priority, and restricting turning movements at intersections. These options align well with the goals of USLR policy —improving liveability and safety— by reducing conflict points and promoting a modal shift. Dedicated lanes, in particular, allow PT vehicles and emergency services to travel smoothly without being hindered by congestion, thus improving reliability and overall service quality. Such mitigation options could prevent increase of PT operational costs and simultaneously improve PT usage. Further research on the effectiveness of mitigating options is recommended.

5.4. The limitations of this study

The traffic simulation model used in this study provides valuable insights but is ultimately a simplified representation of reality. Several assumptions were made in constructing the model, particularly around how travelers adjust to new speed limits. In the formulated USLR policy we assumed that enforcement measures make both cars and PT adhere to the new speed limit, but cause no additional comfort penalty for PT users. In both the reference and USLR policy scenario we assumed that travelers know the costs of all alternative routes and modes. In theory, people would fully adapt based on the new conditions, but in reality, some may hold onto habits or are unaware of the new choice set, resisting such changes. Additionally, behaviour in the model is aggregated per group instead of individually. This aggregation - based on categories like motive, urbanity level, or car availability - overlooks regional preferences, such as varying modal preference between suburban areas and small towns. To overcome this, calibration brings the simulation outcome closer to observed reality, but it does not capture the underlying choice mechanisms. As a result, the model's precision is reduced in areas with more nuanced behavioural patterns.

Calculations and calibrations, like those for increased travel times, **are central to the analysis, but they come with uncertainties.** Public transport driving speeds are derived from timetable speeds. Public transport speeds and conditions vary in reality, and while the model estimates effects on a local level, speeds are optimised for a macro-level. Therefore, actual travel times could differ due to local differences and daily disruptions.

Since we draw general conclusions on the effects of USLR policy on travel behaviour, modal share and timetable hours amongst others, the limitations are acceptable. However, the discussions on a local level made in the case study should not be used for direct policy making, but instead be used as indication for where further research is needed.

Finally, the effects in this study were determined **without considering mitigating adaptations in the street network for public transport.** However, the type, location, and quantity of PT mitigating measures applied could significantly change the results and should therefore be carefully considered.

5.5. Generalisability of case study and further research

The findings from The Hague on the modal share are largely generalizable to other Dutch cities with similar public transport networks. However, caution is needed when applying these results to cities with a different modal split or transport infrastructure. For example, cities that rely more on metros or trains will need to consider different factors. Also, different infrastructure characteristics result in different TTH effects, such as PT priority, dedicated lanes and segment length of uninterrupted driving. The results are most applicable to mid-sized European cities with bus and tram networks similar to The Hague's.

In the analysed USLR policy, the majority of targeted streets in The Hague were flow streets. Still, alternative flow streets are available which can explain the absence of a modal shift. However, for city wide or district wide USLR policy our conclusions can not be used. We think a more extensive USLR policy could stimulate a modal shift as district wide speed reductions leave fewer re-routing options for cars to mitigate the car travel time effects. Further research is therefore recommended where this study is repeated with different USLR policies.

Further research should focus on refining the model and exploring indirect effects of USLR policy. If this study were to be repeated, improvements in modelling traveller behaviour and regional differences would be beneficial. Introducing more detail around the behavioural responses to speed limit changes, especially around habitual vs. elastic responses, could improve model accuracy.

5.6. Conclusions

In conclusion, this study demonstrates that while USLR policy increases operational costs for public transport operators, it does not significantly alter modal share or ridership. The model, while a simplification, allows to quantify the financial impact of USLR policy on PT operations. **Policymakers must balance the increased costs of PT operators against the broader benefits of USLR policy, such as improved safety, reduced pollution, and enhanced urban liveability.** Furthermore, policymakers should focus their USLR policy mitigation efforts on streets with a high PT frequency and passenger volumes and where vehicles consistently achieve speeds above the target USLR policy speed. These findings provide a foundation for urban policymakers and public transport operators to plan for the financial and operational impacts of USLR policy.

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A

Scientific paper

The impact of urban speed limit reduction policy on public transport

Using a simulation model to study the impact of urban speed limit reduction policy on public transport in a case study of The Hague

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Abstract

Urban Speed Limit Reduction (USLR) policies, aimed at enhancing road safety and reducing emissions, pose substantial implications for public transport (PT) operations. This study evaluates the impact of implementing a USLR policy in The Hague, Netherlands, reducing speed limits from 50 km/h to 30 km/h on select streets. A multimodal simulation model was employed to quantify changes in PT travel times, operational costs, and modal share. Results indicate a modest average increase of 1.2% in PT travel times, with corresponding timetable hours (TTH) rising by 0.9% and no increase in PT modal share. This would lead to elevated operational costs without increased ridership or revenue. On a city level, the modal share of bikes increases with 0,2% while the modal share of cars decreases with 0,2%. Locally, the results show changing trip destination choice, mode choice, and route choice to circumvent the USLR policy. The findings underscore the need for targeted mitigation measures, such as traffic flow optimizations and speed segregation, to offset increased costs and maintain PT efficiency. This research highlights the nuanced trade-offs of USLR policies, providing actionable insights for urban policymakers and transport operators.
Keywords: *speed limit, public transport, travel time, modal share, transport model, Urban Speed Limit Reduction (USLR) policy*

1. Introduction

1.1. Problem context

All over the world, cities struggle with the impact of mobility on the liveability of cities. Infrastructure causes space scarcity, congestion causes delays, and vehicles cause pollution and accidents (Gressai et al., 2021).

To tackle these socio-economic costs, policies around the world are formulated focusing on the liveability of cities. The Dutch House of Representatives (*tweede kamer*) adopted a motion to make 30km/h the default speed limit in urban areas (*bebouwde kom*) (NOS, 2021). Deviation from the new norm is still possible for individual roads, but needs to be well reasoned and safe.

Urban Speed Limit Reduction (USLR) policy is a set of road interventions dictated by the city council, aiming to reduce vehicle speeds. Commonly, the maximum speed is reduced from 50km/h to 30km/h. This speed limit reduction can be applied on a selection of roads, a city zone, or at a citywide level. Furthermore, reduction of the speed limit can happen with or without physical measures to enforce the new speed limit.

The effects of urban speed limit reduction (USLR) policy are an emerging topic in scientific literature. Studies on the effects of USLR policies focus mostly on the motivations for the policy, namely the liveability and safety of cities. There is common acceptance that the policy will improve safety (Archer et al., 2008; Cairns et al., 2015; Gressai et al., 2021; Rossi et al., 2020), reduce noise pollution (Borowska-Stefańska et al., 2023; Cleland et al., 2021; Gressai et al., 2021; Rossi et al., 2020), and reduce CO2 emissions (Cairns et al., 2015; Gressai et al., 2021; Rossi et al., 2020; Tang et al., 2019).

While the positive consequences on the liveability and safety of cities has been established, research on how USLR policy affects traffic and accessibility in general is less conclusive. A literature review byRossi et al. (2020) expects an improved traffic flow from USLR policy, due to less stop and go traffic.

This is in line with Nitzsche and Tscharaktschiew (2013) and Cleland et al. (2020), who found that a more uniform speed or a reduced speed leads to a smoother traffic flow. Grey literature of case studies implementing USLR policy with no calming measures reviewed by Nightingale et al. (2021) showed small reductions in observed average speeds: in Manchester (0,7mph reduction), Bristol (2,7mph reduction), Edinburgh (pilot scheme) (1,9mph reduction), and Portsmouth (1,3mph reduction). Meanwhile, 3 other case studies where traffic calming measures have been included show a 9mph speed reduction, according to the literature review by Cairns et al. (2015). This suggests changing the road design and incorporating enforcement measures results in higher levels of speed change.

While USLR policy is expected to affect travel speeds, the effect hereof on modal split is less clear. Borowska-Stefańska et al. (2023) used a simulation model to simulate the effect on modal split and found a 0,38% increase of modal share for public transport, 0,57% increase of modal share for active modes, and 0,27% decrease of private car modal share. A simulation study by Nitzsche and Tscharaktschiew (2013) concluded that the modal share of public transport doubles from 9% to 18%. However, the simplifications used in this study are severe. For example, public transport travel speed is modelled as a city wide flat speed of 18km/h and not impacted by USLR policy, while assuming a congestion free public transport network. In both paper the impact on modal share was a side deliverable and not a research objective. Gressai et al. (2021) conclude further research is needed on the effect on modal shift, for who and where the impact on travel time differs, and the reconfiguration of traffic management (e.g. intersections, road marking and public transport timetable).

Based on the current literature and ongoing debate, a knowledge gap has been identified in the effects USLR policy on modal share, travel times and traffic assignment on the road network. Changes in these values can have dramatic changes in how people travel through the urban environment. Particularly, public transport (PT) operators are worried the impact of urban speed limit reduction policy will be negative for PT operators (NOS, 2021; van Vliet, 2022). However, the perspective of public transport operators has not yet gained attention in scientific literature.

1.1.1. Problem statement

The impact of urban speed limit reduction policy on public transport (PT) is feared to be negative by PT operators (NOS, 2021; van Vliet, 2022). Lower operating speeds can result in higher operational costs with reduced passenger volumes. For the PT operator in Rotterdam (RET) lower operating speeds due to proposed urban speed limit reduction policy is expected to result in an annual additional 16.000 timetable hours, increasing the operational costs by €2.3 million annually (Gemeente Rotterdam et al., 2023). In Amsterdam the policy can cause up to 66.000 additional timetable hours annually (Royal HaskoningDHV Nederland B.V., 2022).

These alarming prognoses suggest the PT operators worries are justified. Unfortunately, academic studies on the effects of urban speed limit reduction policy do not quantify the effect on modal share and travel time, or how to mitigate such effects. Therefore, this research aims to quantify the impact urban speed limit reduction policy has on public transport in terms of travel time, timetable hours and passenger volumes.

1.2. Research objective

The main goal of this research is to quantify the impact on public transport operators when policy on lowered urban speed limits is implemented. Since literature on the effect of USLR policy on PT operators is limited, and interviews are subjective, we decided a simulation model was the best approach. This allowed for an objective, ex-ante, and ceteris paribus study on the impact of USLR policy on public transport. To determine the impact on public transport operators, both the operational costs and income are considered. The effect on operational costs is estimated by quantifying the increase of travel time and resulting additional required timetable hours. To determine the effect on income, the modal share and passenger volumes are quantified.

1.3. Scope

Cars, buses and trams are the only modes that are assumed to be directly affected by USLR policy. Pedestrians, bikes, metros, boats and trains have no change of speed and therefore unaffected *absolute* attractiveness. After all, these modes of transport do not use the public road network, or are already travelling below 30 km/h.

USLR policy reduces the maximum speed on affected streets. The maximum speed affects the travel time between two points, which is a major factor for trip distribution, mode choice and trip assignment. It is assumed that people will reconsider their travel behaviour when travel times change.

USLR policy can affect the needed timetable-hours for PT operators and PT service levels via the frequencies. In this study, the public transport service level remains the same, meaning that public transport frequencies, locations of stops, line network, etc. are not affected. Instead the timetable-hours will increase when travel time increases. It is thus assumed that PT fleet size and personnel are no constraint. This allows us to calculate the resulting change in timetable-hours, and thus costs for PT operators.

To confine the scope, the USLR policy will only include changes in the road network itself in terms of speed limits and road category. No additional policies will be modelled, but they will be discussed as future research suggestions.

2. Research methods

The study uses the following methodological steps: selection of the study area and reference scenario for the study area, formulation of a USLR policy scenario, estimating USLR effect on speed for PT and car, and implementation of the scenarios into a simulation model.

2.1. Selection of the case study area: The Hague

The case study city for this research is The Hague, in the Netherlands. The Hague is on the verge of implementing a new USLR policy and is currently shaping its vision for this initiative. This presents an opportunity for greater collaboration with policymakers and facilitates access to relevant documents. Furthermore, the Hague's policy is particularly relevant as it targets streets heavily utilized by public transport.

The proposed USLR policy in The Hague aims to reduce the maximum speed limit from 50 km/h to 30 km/h on an extensive network of streets. This includes the implementation of physical measures to enforce the new speed limits.

While the USLR policy is only implemented in The Hague, the wider region Metropoolregio Rotterdam-Den Haag (MRDH) is included in the simulation model to be able to capture all traffic passing the streets of The Hague. This region consists of a polycentric network of cities where activities are concentrated in multiple dense locations, preserving open spaces in between (Broitman & Koomen, n.d.).

The Hague is located next to the North Sea and consists of 8 city districts. The central zone of The Hague is a corridor perpendicular to the North Sea, from Scheveningen towards the city centre (Gemeente Den Haag Dienst Stedelijke Ontwikkeling, 2015, p. 13). The Hague has an extensive PT network served by bus, tram, light-rail and heavy rail. Tram lines operate in mixed traffic, on dedicated lanes at street level and via a 3km semi-metro corridor underneath the city centre. The Hague is connected with other major cities via light-rail (to Rotterdam) and heavy rail.

2.2. Simulation model set up

To account for the urban developments that will occur during the implementation of the USLR scenario, the year 2030 is used as assessment year. The used traffic simulation model will have to simulate both an approximation of the reference traffic network and the expected effects of USLR policy. For this reason, the choice is made to use a detailed transport network representation on street level, since USLR policy is per street. Furthermore, the simulation model needs to be multimodal and distinguish between rush hour and non-rush hour. Therefore we use a variant of the classical four-step transport model (De Dios Ortúzar & Willumsen, 2011, p. 21).

The used model consists of four basic steps. During the first step - the trip generation - the model computes the expected travel demand to and from each location in The Hague metropolitan area. Parallel to the first step, the second step - skim generation - calculates the costs to travel for each possible trip. This gives generalized costs between each location and for each possible mode and motive, based on travel time, travel distance and other costs. In the third step - trip distribution & modal split - the number of trips between each location, and mode of transportation is calculated. For this, the demand and costs to travel calculated in the first steps is used. The lower the costs, the more likely a trip will be made. Finally, in the fourth step - trip assignment - trips are divided over possible routs based on route attractiveness. This results in the model output in the form of traffic flows per transport mode.

The ”Verkeersmodel Metropoolregio Rotterdam Den Haag 3.0” (V-MRDH model 3.0) is used, a pre-existing simulation model running on the software package OmniTRANS version 8.1.0 Schoorlemmer et al. (2023).

This model distinguishes per travel motive, time period of the day and transport mode. The model consists of 3 time periods for an average working day: morning rush hour (7-9am), afternoon rush hour (4-6pm) and the rest of the day.

We used an existing predicted scenario for 2030, where no speed limit policy is included as a reference scenario. This is a copy of the ”Stedelijke referentie 2030” scenario in the V-MRDH3.0 model Schoorlemmer et al. (2023). The reference scenario includes the current development plans on a neighbourhood, zonal or regional level. Planned and ongoing infrastructural projects are also included when expected to be finished before 2030. Furthermore, the reference scenario embraces policies, cultural, societal and economical changes for the year 2030.

2.3. Methodology for establishing a USLR policy

Since the actual USLR policy of the city of interest in 2030 is still in the making, we need to formulate a close approximation of the expected USLR policy. The method developed in this study is based on a method used in a previous case study by Nightingale et al. (2021). The developed method consists of five steps:

1. *Start with available list of potential locations for USLR policy from the city council.* Used in this study was the report of van Oosterom and Swart (2021), commissioned by municipality of The Hague (department of mobility).
2. *Adjust the list based on (written reports of) discussions by main stakeholders.* Those stakeholders are municipality representatives, emergency services and transit authorities. Relevant discussions for The Hague had previously been performed by 18 representatives from PT operator HTM, emergency services, transit authority and municipality of The Hague. Though the results are not public, permission to documents and maps was allowed for this research.
   Meanwhile, Bigalke et al. (2023) made a selection of all streets that have maintenance planned before or during 2030, based on city documents. The result is a list with 90 streets/locations, of which 45 streets are used by PT.
3. *Personal judgement by the researcher.*
   Google streetview is used to determine the current speed limit, the current street type, and the alternative street design options based on current layout and the assessment framework described by (van Oosterom & Swart, 2021) (Veilig50 principle, GOW30, ETW50 or ETW30). The width of the street limits the possibilities. To determine whether cycling lines are possible to implement, the removal of parking spaces, trees, lanes, or the narrowing of side-walks and similar features was weighed against the interests of relevant stakeholders. To include the opinion of the local community, we searched for online (news) articles about the street and its neighbourhood via Google search engine. In some cases, the necessity for a 50 km/h speed limit is determined by emergency services, while in other areas, parking pressure, crowded side-walks and expected commotion are decisive factors in determining the alternative street design options.
   Safety is a major factor, and around schools, it is the leading concern, guided by the city’s ambitions and policies. Cycle suggestion lanes and shared space are not considered safe on 50km/h streets (Kennisplatform CROW, 2023). This means the maximum speed is reduced to 30km/h unless the street width allows separated cycle lanes. Outcome of this step is a list of selected streets explaining the change of the speed limit and the change of the road category. When relevant the resulting list includes the expected effect on vehicle speeds, and possible options to mitigate the effects on travel time for public transport.
4. *Review the list via consultation.* Discussions were held with one or more representatives from the city council, PT operator and relevant mobility consultants.

Using the above steps, a USLR policy was formulated consisting of a list of streets and corresponding speed change and street category changes. Since 30 km/h is already in effect on most local access streets -*erftoegangswegen (ETW)*-, the formulated USLR policy primarily affects flow streets -*gebiedsontsluitingswegen (GOW)*-. In the following section these changes are incorporated into the simulation model to create the USLR policy scenario in the model.

2.4. Methodology for implementing USLR policy into a traffic simulation model

USLR policy is implemented only on the streets that will be redesigned and given a new maximum speed. We therefore focus on USLR policy incorporating physical traffic calming measures. Those streets are represented as (multiple) links in the model.

2.4.1. Modelled impact on cars

Three characteristics of the links are changed:

1. The modelled maximum speed is reduced depending on the new speed limit and change in street type. The speed limit goes from 50km/h to 30km/h, which is a 40% decrease. In the used model the link speed can have deviations from the legal speed due to calibration effects. Therefore, we used a 40% speed reduction instead of legal speed limits to prevent interference with calibration. When the street category changed from arterial street to local street, instead a 60% speed reduction is used to reflect the additional usage of enforcement measures and resulting reduced street attractiveness.
2. The BPR-parameter values are set to the values of the new street category, if relevant.
3. The link is given a tag to allow easy selection of all links affected by the USLR policy, helping adjustments during the sensitivity analysis. This makes it possible to optimise the simulation model based on newly gained insights benefiting future research.

A new street category -GOW30- will be implemented that does not officially exist yet in the Netherlands. This is a flow street with a speed limit of 30km/h. However, guidelines for the new street design are being made, and a provisional guideline is available to support road authorities (CROW, 2021; Kennisplatform CROW, 2023). For the BPR parameter, the choice is made to use the same α and β GOW50 values for the new street category GOW30. The new category GOW30 has a focus on traffic flowing. This is in contrast to road categories ETW50 or ETW30 which function is to focus on access, parking, halting and stopping, meaning that many vehicles stand still or interact.

Furthermore, it is assumed that USLR policy will have no effect on intersection capacity and corresponding travel time delays to cross the intersection. This assumption is based on the macroscopic fundamental theorem of road traffic: $Q = \rho * V$. Where traffic volume Q (veh/h) is the product of the vehicle density ρ (veh/km) and the spatial average speed V (km/h).

2.4.2. Public transport speed adjustment using an offset

No revealed PT driving speeds are available in the simulation model. Instead, per PT line the travel time is included for each stop from the previous stop per time period. However, this travel time consists of dwell time, time to accelerate/decelerate, driving time, and time lost to disturbances.

In order to come up with reasonable driving speeds for PT, the following steps were performed:

1. Timetable times (per time period and per direction) on PT lines were projected onto street links. This means when multiple lines use the same street link, the link receives multiple times.
2. Based on the timetable times and link length, for each link the minimum, maximum and average timetable speeds are calculated. This is done for each time period, in both directions. As a result, each street link has 3 (speeds) * 2 (directions) * 3 (time periods) = 18 new values added.
3. The projected PT speeds are judged by the author to determine if and how the travel speeds can be translated to a reasonable assumed driving speed. This is done by personal judgement, where internal HTM rapports containing reported speeds (when available) are compared to the modelled network.
4. The assumption is made that the calculated speed derived from the timetable lies 5km/h lower than the real driving speed. This is assumed since the speed calculated based on the timetable time includes dwell time, time to accelerate/decelerate, driving time, and time lost to disturbances. Therefore, the USLR policy speed limit of 30 km/h is instead applied to PT speeds as 25 km/h.
5. PT link speeds are changed using the following logics (per time period and per line):

(a) Links speed below 25 km/h are not changed, since the estimated driving speed does not exceed 30 km/h and therefore USLR policy has no effect.
(b) Links already in the range of 25-42km/h are set to a flat 25km/h, meaning a speed reduction less than or up to 40%.
(c) All links with speeds between 42 and 51km/h had their speed reduced by 40%.

Furthermore, all links with speeds above 42 km/h have been assessed individually to check if a 40% reduction is realistic. The preceding and succeeding links have been examined, as well as the street location. An estimate was made of the current speed and expected impact and a 40% speed reduction was deemed realistic for all links.

6. Finally, PT link speeds were converted back to timetable times, to update timetable travel times and allow regular working of the model.

Evaluating the assumed 5 km/h PT speed correction

As mentioned above, the assumption is made that the calculated PT speed derived from the PT timetable lies 5km/h lower than the real driving speed. This is assumed since the speed calculated based on the timetable time includes dwell time, time to accelerate/decelerate, driving time, and time lost to disturbances. A 5 km/h correction was chosen based on the following reasons. Firstly, calculated time table speeds were compared with our own estimations based on Google Street View and feedback from PT operator employees. Furthermore, on a few locations real PT speeds were available (confidential data; provided by PT operator HTM), which were compared to calculated timetable speeds. This suggested 5 km/h gave a good overall fit. Secondly, using a higher offset would have caused a higher number of links to become affected.

To test the assumed 5 km/h PT speed correction, we calculated the theoretical speed profile of tram line 16 on a segment with available driving speeds. Figure 2.1 shows the theoretical speed profile from PT stop Elandstraat towards PT stop Gravenstraat (assuming comfortable linear acceleration and deceleration values of $0,8m/s^2$). The maximum speed of 50 km/h (red line) is reachable on only two segments, but on the other two segments the distance is too short to reach the speed limit of 50km/h. This results in an average speed on this section of 29,5 km/h. When the speed limit is reduced to 30km/h, the average speed goes down to 25,2 km/h leading to a 21 second longer travel time, or 17%. This is because the maximum speed is now reached more often, limiting the driving speed more. However, the true driving speeds for this section are know from measurements by the local PT operator (HTM), which show the average driving speed is 24 km/h, and not the theoretical 29,5 km/h. This is likely due to traffic in the real life situation limiting driving speeds and preventing the vehicle from reaching the maximum speed. This shows why we cannot use theoretical driving speeds in our study, and should rely on timetable speeds. The existing speed in the model for this section is in fact 19 km/h, and not the actual driving speed of 24 km/h. This is because the speeds in the model include dwell time and time lost to disturbances. This test sample therefore validates our assumption that the true driving speeds lie 5 km/h higher than those in our model.

3. Results

3.1. The USLR policy scenario for The Hague

A USLR policy scenario of the Hague was created reflecting the expected changes in 2030, following implementation of the USLR policy scenario. Around 7% of the total street network length in The Hague is included in the USLR policy scenario.

The map of The Hague in Figure 3.1 shows all USLR affected streets in the model. As shown in the figure, the USLR policy sets nearly the entire city centre (orange area) to 30km/h. Furthermore, the formulated USLR policy follows the ambition to replace ETW50 streets with ETW30 or GOW30 (Gemeente Den Haag Dienst Stedelijke Ontwikkeling, 2015). The included streets are spread throughout the city. Exception is the district of Leidschenveen without any targeted street included in our USLR policy.

99 km of streets in the model that are used by PT have been affected by USLR policy. On the majority of these streets (57km out of 99km) PT speeds remain unaffected, as none of the PT lines

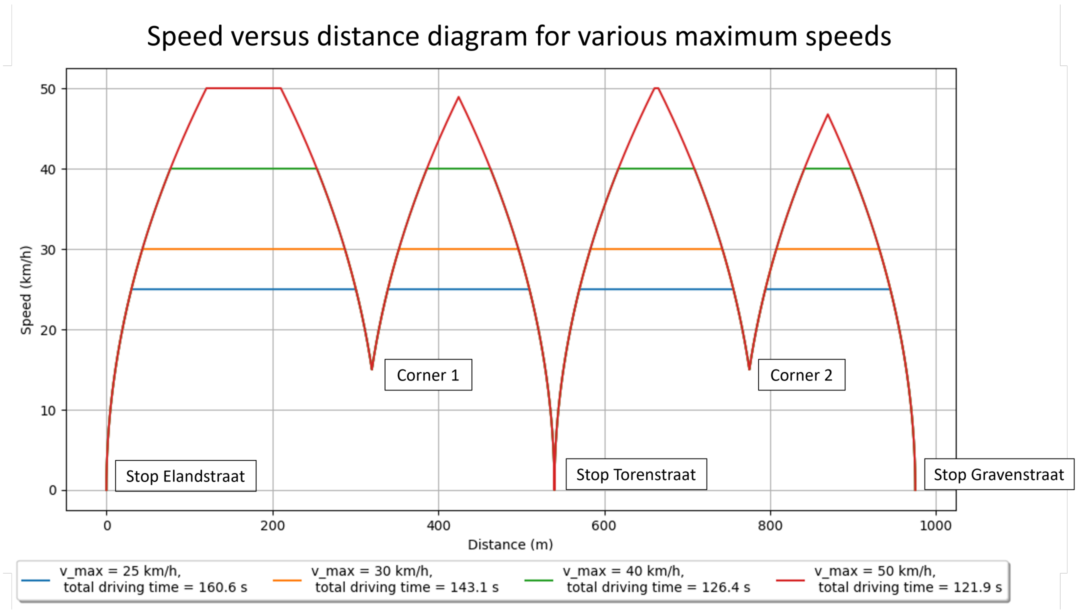

Figure 2.1: Speed versus distance diagram for various maximum speeds.
Speed profile from PT stop Elandstraat (at 0 meter) towards Gravenstraat (at 975 meter). Includes two corners with local speed reductions to 15km/h and one stop in the middle (Torenstraat).

using those links had their current average speed exceeding the new speed limit. At ≃10% of affected PT-used street length at least one PT line reached the reference maximum speed limit outside rush hour.

3.2. Changes in travel time and timetable hours of public transport

Overall, the impact on PT travel time is limited, as can be seen in Table 3.1. Our model shows that half of PT sub-lines driving over a USLR-affected street are hardly affected in their travel times. Speeds vary per line, location, and time of the day. While some lines had no effect, other lines experience an reduction of the average speed up to 7,7%.

Interestingly, bus lines experience a notable larger effect than tram lines. Though it partly is because not every line uses as much USLR policy affected streets, but might also be the result of different driving behaviour resulting from different vehicle manoeuvrability.

On average, travel times of PT lines travelling over USLR-affected streets increase with 1,2% or 28 seconds outside rush hour. PT speed changes are the same for morning rush hour, and slightly less during evening rush hour. The limited overall impact on PT travel time is likely the result of only small parts of PT route being affected. Also, PT travel times is expected to have less impact than cars because PT operates wider vehicles and has to brake and accelerate for each stop, leaving for less time travelling at the speed limit.

Table 3.1: Average effect of USLR policy on PT vehicle travel time per sub-line

	Morning rush period			Non-rush period			Evening rush period		
	tram and bus	*tram*	*bus*	tram and bus	*tram*	*bus*	tram and bus	*tram*	*bus*
Relative travel time change (average of all USLR-affected sub-lines)	**1,2%**	0,5%	1,7%	**1,2%**	0,5%	1,7%	**1,1%**	0,6%	1,4%
Absolute travel time change in seconds per sub-trip (average of all USLR-affected sub-lines)	**28**	*10*	*40*	**28**	*11*	*40*	**23**	*11*	*31*
Number of sub-lines with at least 1 minute travel time increase	**13**	*2*	*11*	**12**	*1*	*11*	**11**	*2*	*9*

When considering all public transport lines using USLR-affected streets, the total daily TTHs are estimated to increase by 0.9% (Table 3.2). Figure 3.2 shows the relative and absolute changes in TTHs for buses and trams. The relative increase of TTH (indicated by the yellow line and right Y-axis) ranges from 0% (no effect) and 6%. The largest relative TTHs increases occur on bus lines. In contrast, the largest absolute TTH increases occur at tram lines. Particularly, tram line 9 shows a 3.7 hour daily

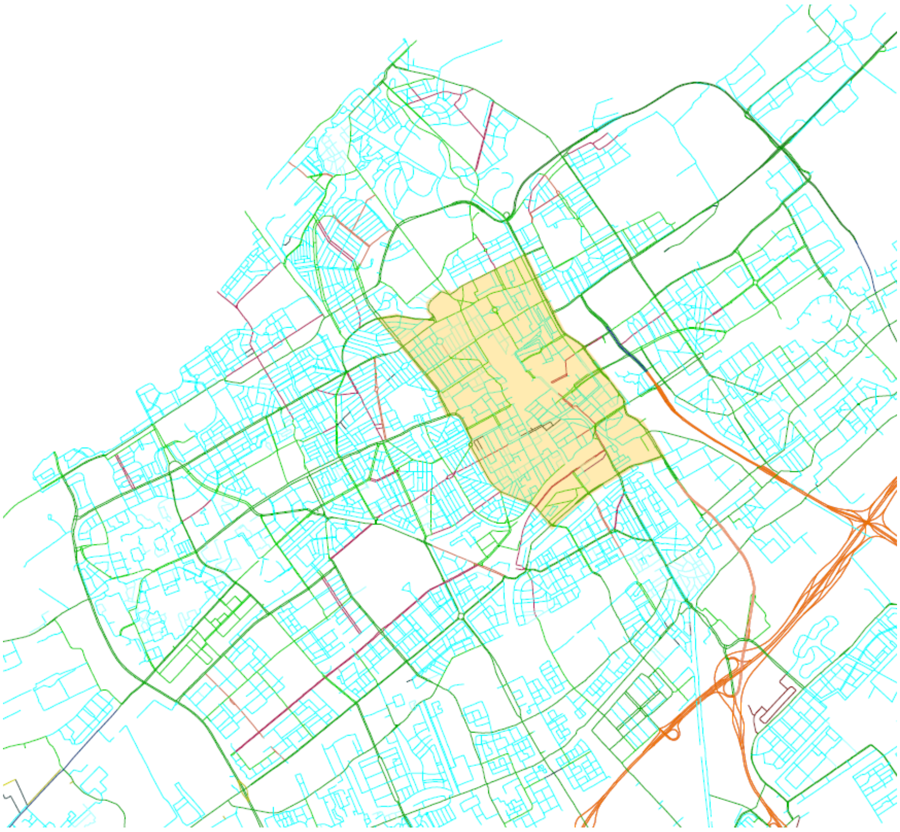

Figure 3.1: Overview of the simulated USLR policy scenario. The policy sets the entire centre (orange area) to 30km/h. Furthermore, the purple streets are targeted streets and go from 50km/h to 30km/h as well. Brown streets change from street category GOW50 to ETW30.

increase in TTHs. As a result of the majority of trips taking place outside rush hour, this also shows the largest increase in TTH (shown in orange).

In the city centre frequencies per street are often higher, due to (overlapping) lines merging when closer to the city centre to accommodate high demand levels in the centre. Despite the speed reduction in the city centre being limited, the high PT frequency still causes a large overall increase of TTH. Outside the centre large increases of TTHs (per street) are caused by larger speed changes, rather than high frequency.

Table 3.2: Change of TTH per year due to USLR policy. Hours are rounded to the nearest hundred. Yearly change of TTH is split up between three time periods of the day, and split between tram and bus.

	TTH morning rush period			TTH non-rush period			TTH evening rush period			total TTH		
	tram and bus	*tram*	*bus*	tram and bus	*tram*	*bus*	tram and bus	*tram*	*bus*	tram and bus	*tram*	*bus*
Reference scenario	131.300	*72.300*	*59.000*	419.200	*269.200*	*150.000*	134.800	*70.500*	*64.300*	685.300	*412.000*	*273.300*
USLR policy scenario	132.800	*72.800*	*59.900*	422.900	*270.900*	*152.000*	135.900	*71.000*	*65.000*	691.600	*414.700*	*276.900*
TTH change (absolute)	1.400	*500*	*900*	3.700	*1.700*	*2.000*	1.100	*500*	*600*	6.300	*2.700*	*3.600*
TTH change (relative)	1,1%	*0,7%*	*1,5%*	0,9%	*0,6%*	*1,3%*	0,8%	*0,7%*	*1,1%*	0,9%	*0,7%*	*1,3%*

3.3. Travel behaviour and PT ridership change in the case study

The dispersion of PT passenger volumes changes slightly. Generally, the PT lines with declining passenger volumes have an increase of their travel time. However, an increase of PT travel time does not always result in a decrease of passenger volumes. This is a result of a combination of changing trip destination choice, re-routing PT passengers switching PT lines, and competitiveness of PT with car and bicycle resulting in a changed mode choice.

The increase in travel time due to USLR policy inflicts a travel resistance upon The Hague, resulting in a more local trip choice, as seen in Table 3.4. Consequently, the average PT passenger trip length

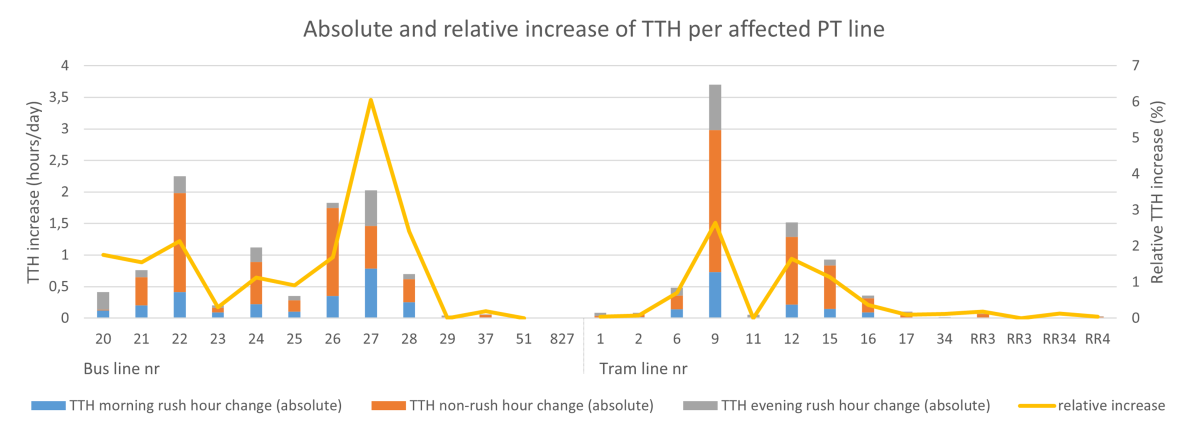

Figure 3.2: Total increase of timetable hours (TTH) per affected bus line (left) and tram line (right). The absolute increase of timetable hours (hours/day) is shown per PT line as a column. In this column, the three time periods are stacked to give the daily increase per line (left axis). Meanwhile, the relative increase of timetable hours per PT line is given by reading the yellow value on the right axis.

decreases with -0.73% for bus and tram lines. Also, for districts at the inland edge of The Hague some trips through the city are replaced with external trips to avoid longer travel times, as USLR policy is not applied outside The Hague.

The USLR policy scenario does not result in a modal shift. The modal share of public transport citywide remains 18.6% after USLR policy implementation. Only a small shift of 0.2% from car to bike is notable, as can be seen in Table 3.3. Furthermore, a small modal shift on longer distances from cars to PT is seen, benefitting regional (heavy) rail services. At the same time, on shorter distances a small modal shift occurs from PT to cycling.

Table 3.3: Modal share in the reference scenario, and the change of modal share in percentage point. Given for the entire city and for four city districts. Modal share of the car consists of both trips made by the car driver and car passenger.

	Car		Public transport		Bike	
	modal share	change	modal share	change	modal share	change
City wide	*35,8%*	*-0,2%*	*18,6%*	*0,0%*	*45,6%*	*0,2%*
Centre	25,9%	-0,2%	29,8%	0,0%	44,3%	0,2%
Laak	29,9%	-0,2%	19,9%	0,0%	50,3%	0,1%
Escamp	38,2%	-0,3%	15,7%	0,0%	46,1%	0,3%
Loosduinen	39,5%	-0,2%	8,9%	0,0%	51,6%	0,2%

Table 3.4: Change of total departing external trips (of all modes combined). The three seaside districts are marked bold.

District	Relative change of external trips
The Hague (complete)	*0,06%*
Centrum	0,09%
Laak	0,18%
Escamp	0,01%
Loosduinen	-0,15%
Segbroek	-0,45%
Scheveningen	-0,13%
Haagse Hout	0,29%
Leidschenveen	0,07%
External	0,00%

While the impact of USLR policy on passenger volumes is uncertain, revenue from public transport ticket sales is expected to stay stable. On one hand, the USLR policy could advantage inter-regional public transport operators, but on the other, it might reduce the earnings of local operators due to shorter and potentially fewer trips.

However, increase in timetable hours will lead to increased operating costs for the public transport operators in The Hague. Therefore overall the transport operators are expected to incur a net loss on the evaluated urban speed limit reduction. On top of that, if current levels of service are to be maintained, PT operators will need additional vehicles to accommodate for the higher timetable hours, leading to high one-time investments on top of increased operating costs.

4. Discussion and conclusion

The primary goal of this thesis is to assess the impact of Urban Speed Limit Reduction (USLR) policy on public transport (PT) operators, using The Hague as a case study. **The results show that USLR policy does not significantly affect modal share and thus PT income, but does increase travel times, and thereby overall costs for PT operators.** This section discusses the implications of the findings, and considers how these results can inform future policy and research. Afterwards, we will examine the strengths and limitations of the methodology.

4.1. The impact of USLR policy

USLR policy has multiple effects on both transportation systems and society. **The first-order impacts, such as small increases in travel time for public transport, do not result in a notable modal shift away from public transport.** In the case study, we observed a negative effect of USLR policy on one-third of the targeted streets used by public transport in terms of reduced PT driving speeds. While the operational efficiency of PT reduces slightly -in our case study the PT in-vehicle travel time increases with 1-1.2% on average- the mode remains as attractive as before. However, the increased travel times lead to additional operational costs. The case study shows that income from ticket sales remains unchanged, but operational costs rise, creating a financial strain on PT operators. This is contrary to a major goal of USLR policy, which is to stimulate a modal shift away from private cars, as lower PT speeds increase travel time and exploitation costs.

Results from our study match those in literature. Grey literature analysing the effect of USLR policy in Rotterdam showed a yearly increase in TTH of 16.000, or 5.000 and 11.000 for the tram and bus respectively Gemeente Rotterdam et al. (2023). Our study shows a similar trend of increased TTH for bus and tram Rotterdam is a larger municipality than The Hague, explaining the larger absolute change of TTH Rotterdam. Unfortunately, the relative change of TTH is not mentioned in the study. For Rotterdam, speed segregation on dedicated lanes is assumed, meaning that PT is unaffected on dedicated PT lanes. This results in a small effect on travel times for tram lines -often on dedicated lanes- increasing with 0-1 minute, while the effect of travel time on bus lines being much larger, with 1-3 minutes increase Gemeente Rotterdam et al. (2023). As our USLR policy excludes speed segregation, tram lines in The Hague running on dedicated tracks experience larger increased travel times. Though not quantified, the case study of Rotterdam shows decreasing PT ridership on lines with increased travel times, while ridership increases on metro, train, and 'fast tramlines' (Gemeente Rotterdam et al., 2023, p. 25). Those ridership increases are the result of a modal shift from car to PT and bicycle. Still, the modal share of PT is unaffected (Gemeente Rotterdam et al., 2023, p. 25). The lack of a modal shift in our USLR policy is also reflected by real life results from an observational study in Edinburgh Nightingale et al. (2021). Interestingly, the USLR policy in Edinburgh was much larger -targetting 30% of streets-, but there were no enforcement measures and key arterial routes remained out of scope.

The **rippling effects** of USLR policy on public transport are considerable, affecting both the service performance and passenger experience.

Timetable readjustment is unavoidable, but can have severe consequences. Increased vehicle travel times cause increased operating times. This means both vehicles and drivers take longer shifts, or more shifts are needed. Both longer shifts or more shifts will cause the amount of required timetable-hours to increase in order to fulfill the same service level. This means operational costs will increase. When staff or fleet is already planned in at their maximum capacity, the public transport operator is forced to make large and time-consuming investments, or cut services. In The Hague already

5% of services is cut due to a driver shortage (omroepwest, 2024). This serious shortage of bus drivers is extensive and not only limited to the case study of The Hague. The Netherlands, where 20% of vacancies for bus drivers (6.000 vacancies) remain unfilled, experiences the most severe driver shortage in Europe (Verheggen, 2024). Meanwhile, in Europe the driver shortages will increase from 105.000 to 275.000 between 2023 and 2028 (IRU, 2023). Therefore, any additional required timetable-hours caused by USLR-policy inflicts additional pressure on a already tense staff capacity, and this issue has further application beyond just the case study. On top of that, if current levels of service are to be maintained, PT operators will need additional vehicles to accommodate for the higher timetable hours, leading to high one-time investments on top of increased operating costs.

Without financial compensation this inevitability leads to service cuts. From a financial point of view, it makes most sense to have those service cuts take place on services with already low ridership and further passenger volume decline. After all, to balance costs and income it makes most sense to cut a few services with a large (financial) net loss, instead of having to cut many services each with a small net loss. A potential risk is that equity-oriented PT services are hit in particular, **causing mobility equity decline as undesired side-effect of USLR policy**.

The PT reliability might increase, if the increased travel time is added to the timetable. During delays drivers are commonly speeding to catch up on schedule. 5km/h speeding above the speed limit means 18% faster on 30 roads, but only 10% faster on 50 roads. Reduced variability leads to increased reliability[1]. Furthermore, irregular dwell times are less impact-full on total travel time since the in-vehicle time increases.

However, when the increased travel time is subtracted from to the dwell time, the PT reliability will likely decrease. From a passenger perspective, PT service reliability affects both travel time and crowding. Delays lead to longer waiting times and uncertainty, while reduced reliability increases the likelihood of passengers arriving late or early. In addition to impacting travel time variability, crowding and the likelihood of finding a seat also play a role in overall passenger satisfaction. If public transport becomes too unreliable or uncomfortable, passengers may shift to other modes, causing a negative feedback loop for PT operators.

The case study confirmed USLR policy increases travel time for both cars and PT. This increase in travel time makes fewer jobs and facilities reachable within the same amount of time, resulting in a more local trip choice. This was observed most strongly for the seaside districts of The Hague, due to these districts having to travel through The Hague for any destination, and therefore always having increased travel time. The question is if a more local orientation is a problem, for any point along a route, vehicles cause pollution to their surroundings, bring a safety hazard to street users and cost time for the person who makes the trip. Therefore, shorter trips by default improve pollution and safety and thus contribute to the goals of USLR policy. However, municipalities should ensure basic needs can be reached within acceptable times, and if needed more amenities should be created nearby (in particular relevant for the seaside districts).

As the impact of USLR policy greatly varies per district of The Hague, there is a risk for decreased equity. This was also noted by Nitzsche and Tscharaktschiew (2013), who suggest that a city wide USLR policy may have a negative effect on overall welfare, while only positively impacting the city centre. For instance seaside districts suffer most disadvantages by becoming less accessible, while the most advantages are experienced by citizens of other districts which experience fewer through traffic. Therefore, we think inclusivity needs to be addressed when mitigating the effects of USLR policy is discussed.

4.2. Recommendations for USLR policy implementation and PT adaptation

Policymakers should weigh the increased costs for public transport operators against the broader societal benefits of USLR policy, such as reduced accidents and emissions. While USLR policy does contribute to broader urban livability and safety goals, the findings from this study suggest that its direct impact on public transport operators is less straightforward. Public transport speeds are only marginally

[1] The potential gains can be nuanced, as trip time variability does not only depend on the distribution of travel time, but also on the distributions of dwell times, slack times and stopping times (van Oort, 2022, p. 24). Therefore, the effect on total trip time variability scales less than the effect on driving time variability.

affected, but the increase in operational costs without an accompanying increase in ridership poses a challenge.

Our case study showed a 0.2% modal shift from cars to bicycle, and an unaffected PT modal share. Comparing the findings of Nightingale et al. (2021) and Gemeente Rotterdam et al. (2023) with our own suggest that **different USLR policy types do not result in a notable modal shift.** PT ridership did not increase after USLR policy with strict enforcement measures (assumed in our study), speed segregation as mitigation (assumed by Gemeente Rotterdam et al. (2023)), or a large quantity of streets (assumed by Nightingale et al. (2021)). Therefore, if a modal shift is still desired, synergistic policies are needed such as traffic calming and constructing semi-metro corridors. Though those come with high investment costs, they would contribute to the goals of USLR policy, and could simultaneously increase accessibility and benefit the financial position of PT, saving timetable hours while increasing ridership.

Governments should consider how to respond on the increased PT timetable hours needed. If not mitigated, USLR policy causes as undesired side effect either increased fares or forced service cuts resulting in reduced PT service levels. To reduce the cost impact on PT operators, alternative solutions should be explored, such as financial compensation or infrastructure investments to minimize the increase in PT travel times. **Public transport provides broader benefits to cities, so it is important to consider not only how to mitigate the effects of USLR policy on PT, but also how PT can actively contribute to achieving the goals of USLR.** This involves looking beyond just safety and environmental concerns to include factors like equity, effective mobility, and creating an efficient city (see e.g. Van Oort et al. (2017) for the wider benefits of PT). Already, in our case study the effects of USLR policy were not equally dispersed over the city. Therefore, an integral approach is needed.

Policy makers should consider where to mitigate and which mitigation option is most efficient. One way to determine where mitigation measures are most needed is by looking at the financial impact on PT operators, which can be measured in increased TTH. The largest increases in TTH for The Hague following USLR policy is seen for tram lines running on USLR affected streets. This is because the locations where tram lines are affected have relative high frequencies, leading to a large total effect on TTH. In contrast, affected bus lines have comparatively low frequencies. Furthermore, operating costs of trams are higher in general, meaning each additional TTH is more expensive (Royal HaskoningDHV Nederland B.V., 2022) Therefore, when mitigating costs for PT operators, policymakers could focus on tram lines and segments with high frequencies. Besides mitigating the costs for PT operators, also the travel time costs for PT passengers should be considered. Since passengers rarely travel from the beginning to the end of a line, not every USLR effected street costs as much time for passengers as a whole. Hence, mitigating measures will have a larger impact for passengers on busier lines, even if quieter lines have bigger single trip time increases. To conclude, policymakers should focus their USLR policy mitigation efforts on streets with a high PT frequency and passenger volumes (generally tram lines) but on streets where vehicles consistently achieve speeds above the target USLR policy speed.

Multiple mitigation measures can be considered to reduce the negative impact of USLR policy on PT operators, passengers and other stakeholders. Talks with HTM personnel and our PT speed estimations revealed that crossing traffic is a major cause of speed reductions. Therefore, reducing traffic crossings is an effective way of increasing smooth traffic flow and speeding up PT. Multiple mitigation measures can be employed to achieve this. One way to reduce traffic crossings is by specifically removing left turning traffic crossings. We think this is a suitable policy at intersections where emergency services and PT do not need the left turn, and when alternative intersections are close by. Another solution is to introduce more one way streets. One way streets could even be the solution to maintain 50km/h if desired, as it would allow dedicated bicycle paths in narrow streets. On intersections with traffic lights, PT priority is already used often in The Hague to prioritize PT. This could be expanded further, or should at least be maintained to optimize PT speeds. Another way of prioritizing PT is by changing the street category of roads important to PT from ETW30 to GOW30. This can reduce intersection delays, as GOW30 allows priority at intersections where ETW30 (and ETW50) must yield.

Besides optimizing traffic crossings, modal filters can be applied to block passenger cars from certain streets. Emergency services and PT could benefit, as fewer traffic means fewer disturbances. This also increases reliability of PT, as the speed profile becomes less varied. Freight and logistics benefits from these points as well, and this measure could be combined with hubs for city logistics (Huisman et al., 2022, p. 34).

Applying speed segregation would set a higher speed limit to PT than to cars, allowing PT to still go 50km/h (or in theory even faster if safety allows). The travel time by PT would therefore no longer increase or even decrease when PT can currently not achieve the speed limit. Speed segregation mitigates increased costs for PT operators and thereby prevent increased subsidy. PT passengers would also benefit, as their travel time increase is mitigated. Furthermore, the relative attractiveness of PT compared to the car improves, stimulating a modal shift from car to PT. Speed segregation is a costly measure, so it should be kept in mind for planned street restructuring work, and not as the first go-to mitigation measure.

4.3. The limitations of this study

The traffic simulation model used in this study provides valuable insights but is ultimately a simplified representation of reality. This study made use of the The V-MRDH model, a multi-modal traffic simulation model based on the classic four-step transport model described by De Dios Ortúzar and Willumsen (2011). The high complexity and detail of the model allowed us to identify behaviour changes that would not have been captured in simpler simulation models. The main two limitations of the used model are over-fitting, particularly on a micro-level, and transparency, as a result of the high number of parameters. However, on a macro-scale the model is highly optimized with a strong underlying complexity. Therefore, we believe this was the right model to use for our research question, which focussed on examining the effects of USLR policy on a city wide scale. For future research, further simulations in sensitivity analyses could strengthen the reliability.

The amount of trips for all modes combined increases after implementation of USLR policy with 0,3%. This is contradictory to expectations. Since no changes are made on trip production and attraction, the trip generation sub-model should give the same output for 2030 with and without USLR policy. Our hypothesis is that the increase of total trips might be caused by model calibration on traffic counts. If the simulation model results are off with counts, a correction takes place during traffic distribution. During this step the modal split remains unaffected, because this is a (soft but heavy weight) constraint. The consequence is a redistribution over alternative routes and -we think- an increase of the amount of trips for all modes combined. Therefore, we think that the results on PT volumes could be overestimated.

Since we draw general conclusions on the effects of USLR policy on travel behaviour, modal share and timetable hours amongst others, the limitations are acceptable. However, the discussions on a local level made in the case study should not be used for direct policy making, but instead be used as indication for where further research is needed.

For this study, we formulated a standardized methodology for USLR policy implementation into a simulation model. This standardized methodology provides transparency, is easy to reproduce and easy to adjust during a sensitivity analysis or when renewed insights are gained on speed. The method used distinguishes the effects on cars depending on street category. This allows the simulation of effects on street usage and congestion sensitivity. Adjusting the street category (and associated parameters) assumes that the street is designed according to the street design standards.

The impact on public transport travel speeds, timetable hours and passenger volumes seen in our study is less severe than earlier (grey) research by Bigalke et al. (2023). This can be explained by the different methodologies used. Bigalke et al. (2023) calculated the theoretical relative effect on travel speeds for the free flow situation and multiplied the relative effect with the timetable travel times. This overestimates the effect on streets with large (timetable) travel times, such as congested roads. While formulating our methodology, the unintentional effects on congested roads was for us reason to choose a different methodology for estimating the theoretical speeds. This has resulted in a less severe effect of USLR policy on speeds and timetable hours. The methodology for determine the effect on passenger volumes differs too. We included the effects of USLR policy on both car and public transport via a multi-modal gravity model, while Bigalke et al. (2023) used an elasticity model with fixed demand between each OD pair and the modal share is variable. The latter is more often used in (both academic and grey) literature (Farahani et al., 2013), but relies on the assumption that there are no effects on car speeds and flows. Because USLR policy does cause such changes on cars, elasticity is not reliable.

4.4. Generalisability of case study and further research

The findings from The Hague are largely generalizable to other European cities with similar public transport networks. However, caution is needed when applying these results to cities with a different modal split or transport infrastructure. For example, cities that rely more on metros or trains will need to consider different factors. Also, different infrastructure characteristics result in different TTH effects, such as PT priority, dedicated lanes and segment length of uninterrupted driving. The results are most applicable to mid-sized European cities with bus and tram networks similar to The Hague's.

In the analysed USLR policy, the majority of targeted streets in The Hague were through roads. Still, alternative through roads are available which can explain the absence of a modal shift. However, for city wide or district wide USLR policy our conclusions can not be used. We think a more extensive USLR policy could stimulate a modal shift as district wide speed reductions leave fewer rerouting options for cars to mitigate the car travel time effects. Further research is therefore recommended where this study is repeated with different USLR policies. Future research is also recommended on the effectiveness of corrective policies -policy to mitigate, prevent or compensate undesirable effects on PT- and synergistic policies -complementary policies that work alongside speed limits to amplify benefits-.

Further research should focus on refining the model and exploring indirect effects of USLR policy. If this study were to be repeated, improvements in modelling traveller behaviour and regional differences would be beneficial. Introducing more detail around the behavioural responses to speed limit changes, especially around habitual vs. elastic responses, could improve model accuracy.

4.5. Conclusion

In conclusion, this study demonstrates that while USLR policy increases operational costs for public transport operators, it does not significantly alter modal share or ridership. The model, while a simplification, offers a robust estimate of the financial impact of USLR policy on PT operations. **Policymakers must balance these increased costs against the broader benefits of USLR policy, such as improved safety, reduced pollution, and enhanced urban liveability.** Furthermore, policymakers should focus their USLR policy mitigation efforts on streets with a high PT frequency and passenger volumes and where vehicles consistently achieve speeds above the target USLR policy speed. These findings provide a foundation for urban policymakers and public transport operators to plan for the financial and operational impacts of USLR policy.

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B
Supplementary results

This appendix is confidential and therefore removed from the thesis.

C
Job scripts used during model calculations

This appendix is confidential and therefore removed from the thesis.