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DOI
10.1016/B978-0-12-817696-2.00005-6

Publication date
2019

Document Version
Final published version

Published in
Autonomous Vehicles and Future Mobility

Will self-driving cars impact the long-term investment strategy for the Dutch national trunk road system?

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1 Introduction

The Netherlands has a long history of strategic planning for its national infrastructure. The current National Infrastructure Fund (Note 1) has budgets for a total of €81 billion allocated for large national investments (both maintenance and new projects) up to 2030. The policy document "structuurvisie infrastructuur en Ruimte" sets out the policy framework that defines the spatial economic, water, mobility, and sustainability/viability projects for the Netherlands towards 2040 and sets the focus on government investment.

In March 2017 elections were held in the Netherlands, and now a coalition is being formed. In order to prepare the necessary information for the coalition's negotiations on the challenges the Netherlands faces regarding long-term investments in infrastructure, a comprehensive strategic study was executed called "the national market and capacity analysis" (NMCA) (Note 2). This study investigated what challenges remain after implementing the projects that are defined in the current National Infrastructure Fund until 2030.

To do so, forecasts were made for 2030 and 2040 in both a high- and low-economic scenario in order to get insights into the bottlenecks that will remain or come up after 2030. The new long-term scenarios that are used for this study are set up by the PBL National Environmental Assessment Agency (PBL) and the CPB Netherlands Bureau for Economic Policy Analysis (CPB). These scenarios were published in November 2015. They were set up in a different way than the previous ones that covered a wide bandwidth between the high and low scenarios (see paper by H. Hilbers "An uncertain future caught in a workable bandwidth," ETC 2015). The bandwidth between the high and low scenarios that were published in fall 2015 is smaller than in previous long-term scenarios.

The scenarios are to be combined with additional "uncertainty explorations." One of the uncertainty explorations that was defined for NMCA was whether in 2040 the

Autonomous Vehicles and Future Mobility. https://doi.org/10.1016/B978-0-12-817696-2.00005-6

presence of self-driving cars (SDCs) and trucks could have an impact on bottlenecks and hence the need to invest in the trunk road system.

In 2015 a preliminary study was undertaken to assess how the effect of SDCs and trucks on road capacity and congestion, and the modeled choice behavior, could tentatively be explored with the National Model System (NMS). In 2016 the proposed implementation was realized in the NMS that was released for use in the NMCA in November 2016.

This chapter describes how the potential effects of SDCs and trucks were implemented in the NMS, how the scenarios were defined to execute the uncertainty exploration, which results were found from this analysis, and the conclusions that were drawn from this regarding the investment challenges in the trunk road system for the Netherlands.

1.1 Structure of the chapter

The chapter first describes how the functionality to study effects of SDCs was implemented in the Dutch NMS. Then the SDC scenarios are described. The results of the scenarios are given and interpreted, and finally conclusions are drawn.

2 Implementing self-driving cars in the national model

The Dutch NMS is a multimodal strategic model for long-term policy analysis. It has been developed and used for (national) policy analysis since 1985. A new version for the NMCA, with improved modeling of rail and base year 2014, was released in November 2016.

During the project to re-estimate the NMS, the functionality to model SDCs was implemented both for personal travel as well as for the modeling of trucks. Fig. 1 gives the general concept of what was implemented. The asterisk (*) means that the models have been adjusted to model SDCs. Also, a "split and merge" module has been implemented to model SDCs, by modeling them as a separate user group.

The preliminary study on how to implement SDCs in the NMS concluded that the two key variables to model the behavioral response on SDCs are the value of time

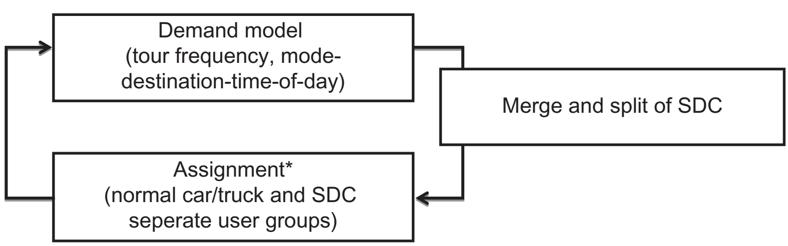

Fig. 1 General concept of SDC implementation (Snelder et al., 2016b).

(VOT), or better put, the penalty for driving time, and the impact of SDCs on road capacity. Therefore the NMS was adapted (resulting in an experimental version of the NMS for modeling SDCs) so that the following key variables can be defined:

- Percentage of SDCs in the fleet.
- Percentage of self-driving trucks that can drive in platoons.
- Impact of SDCs on the VOT/penalty for driving time when driving in automatic mode both for car drivers and for trucks separately.
- Impact of a self-driving vehicle (car or truck) on road capacity by defining different Passenger Car Equivalence (PAE) factors.

Fig. 2 gives the detailed implementation in the NMS.

The SES (modeling mode, time of day, and destination choice of primary tours for all modeled purposes) was changed so that regular ("regulier") and SDC (Zelfrijdende Auto's ZRA) car drivers are modeled. The higher-order destination models, SECDEST (modeling of secondary destinations within the primary tour) and NHBTRIPS (modeling higher-order, non-home-based destinations within the primary tour), were adapted to model regular and ZRA car drivers. From this, the synthetic matrices for regular and ZRA drivers are obtained. From these, the SDC/ZRA fractions are obtained. The matrices are merged for the pivoting process via the programs ASSGNMAT (creating the synthetic growth matrix) and PIVOT (pivoting the calibrated car driver base matrix

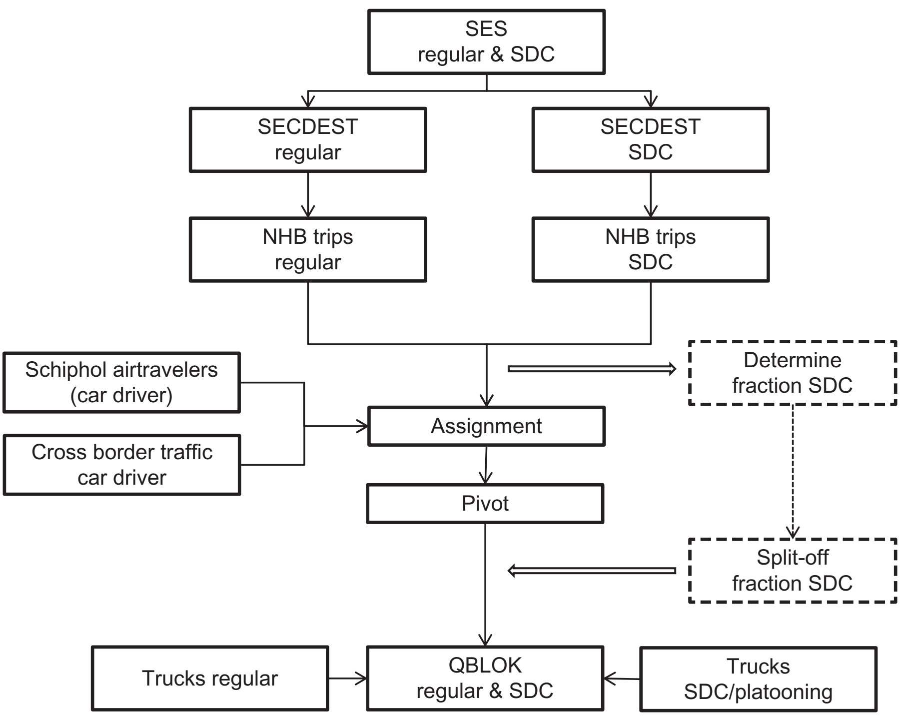

Fig. 2 Implementation of SDCs in the National Model System (Snelder et al., 2016b).

to create the matrix that will be assigned with the assignment software Qblok). The resulting future matrix for car driver is split up into a "regular" car driver matrix and an SDC matrix using the fractions from the synthetic matrices. Together with the freight matrices that are also split into a regular matrix and a self-driving/platooning matrix, the assignment procedure Qblok determines the network flows and Level Of Service. Qblok has separate settings for the pae factors and VOT of SDCs and trucks.

Note that for a forecast year the model iterates over the car driver LOS from Qblok and the mode, destination, and time-of-day models to determine the equilibrium between congestion/LOS and demand.

The implementation in the model was such that the benefits of self-driving vehicles are only present on the infrastructure where activating the self-driving capabilities of the vehicle are allowed. This makes it possible to evaluate the impact of level-4 automation where automated driving is allowed only on specific roads.

The impact on VOT can be defined in the model as one single factor to scale the travel time coefficient in the mode/time of day destination choice (MDTOD) models and on the VOT in the assignment software. For example, a 20% lower VOT will result in a lower impact of travel time in the MDTOD models resulting in a higher chance of choosing car driver as a mode, and higher chance of choosing destinations with a higher travel time.

For the assignment, automated driving and platooning are implemented as separate user groups, with their own VOT and PAE on the specific parts of the infrastructure. This affects the route choice based on generalized cost and the link-time calculation based on the total PAE.

3 Definition of the self-driving car scenarios

Scenarios for SDCs as well as self-driving trucks/truck platooning were developed. The scenarios were developed for 2040 and evaluated in the high-growth scenario as developed by the national planning agencies.

To define the scenarios the five SAE levels were grouped into the following two categories:

1. Levels 1, 2, and 3 were grouped as one type of vehicle with no impact on VOT and road capacity.
2. Level 4 is a separate category with impact on VOT and road capacity when the automated modus is activated.

   Level 5 can be considered a special case of level 4 in the model where activation of the self-driving capacity of the vehicle is allowed on the entire infrastructure. However, the case where people without drivers' licenses can ride cars is not considered. Empty rides are also not considered.

For 2040 the assumption is made that level-5 automation is not yet present in the fleet. Hence only scenarios for levels 1–4 were developed.

For freight there is no explicit modeling of behavioral responses to SDCs. Self-driving (platooning) trucks are only considered in the assignment where the truck matrix for the forecast year is split up into a part containing "normal" trucks and a part containing SDC/platooning trucks with the associated effects on VOT and pae.

Given the deep uncertainty in how self-driving vehicles will develop, four scenarios were proposed:

Table 1 definition of the SDC scenarios (Snelder et al., 2016b)

	Reference run	**SDC run 1**	**SDC run 2**	**SDC run 3**	**SDC run 4**
Share self-driving car	0%	0%	*30%*	30%	30%
Share platooning truck	0%	*40%*	40%	40%	40%
Pae[a] self-driving car	1	1	*1.15*	*0.7*	0.7
Pae[a] truck, platooning	1.75	*1.3125*	1.3125	1.3125	1.3125
VOT self-driving car, index	100	100	*95*	95	*80*
VOT truck platooning, index	100	*80*	80	80	80

Italic value is to indicate the differences with the previous run.
[a] Pae: "Personenauto Equivalent": the relative impact on capacity compared to the general impact of a normal car. Pae truck is a reduction of 25% for the normal Pae factor of 1.75: $1.75-(0.25\times1.75)=1.3125$.

1. Run 1 with no self-driving cars, only self-driving trucks that can drive in platoons. This impacts only on the capacity and VOT of trucks.
2. Run 2 with self-driving cars that are autonomous (not interacting with other vehicles/the infrastructure) and truck platooning. In this scenario the self-driving car will have a negative impact on road capacity. This is based on the assumption that autonomous technology will not be able to realize the same headway as car drivers that can see and interpret traffic conditions. There is a limited impact on VOT for the car driver.
3. Run 3 with cooperative self-driving cars and truck platooning. In this scenario there is a positive impact on road capacity for both cars and trucks but a limited impact on VOT for car drivers; the same as in Run 2.
4. Run 4 with cooperative self-driving cars and truck platooning. In this scenario the same positive impact on road capacity for both cars and trucks is assumed, and a higher impact on VOT for car drivers.

For all scenarios the assumption is made that enabling the self-driving mode on the vehicle is only allowed on the trunk road system.

Table 1 summarizes the scenarios.

3.1 Growth in the base scenario

For the NMCA 2040 forecasts are made relative to the base year 2014.

The growth of the high and low scenario in trips and kilometers traveled are given in Fig. 3.

The congestion, especially in the high scenario increases considerably. In 2040 the congestion in the high scenario is almost twice the congestion in the base year 2014. This is given in Fig. 4.

4 Results

The NMS allows for evaluating the effects of SDCs in two ways. It can show the "first-order" effects where the original car and freight traffic of the reference run is assumed to be split into self-driving and "normal" vehicles. This result shows the

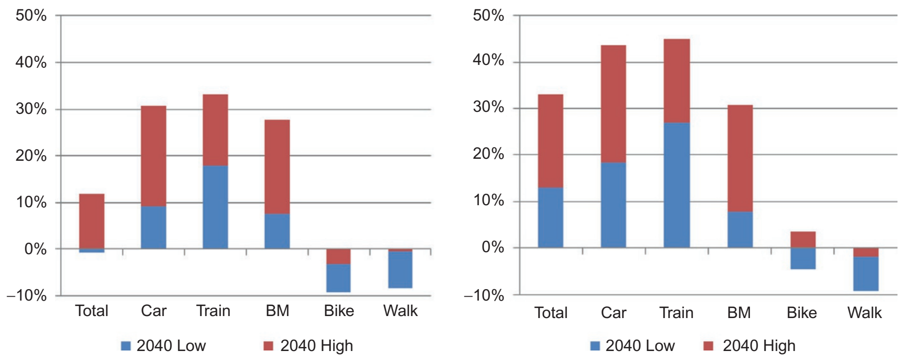

Fig. 3 Growth of trips *(left)* and kilometers traveled *(right)* for the low *(blue)* and high *(red)* scenarios. From left to right: total, Car, Train, Bus Tram Metro, Bike and Walk.
Figure from NMCA report, page 19.

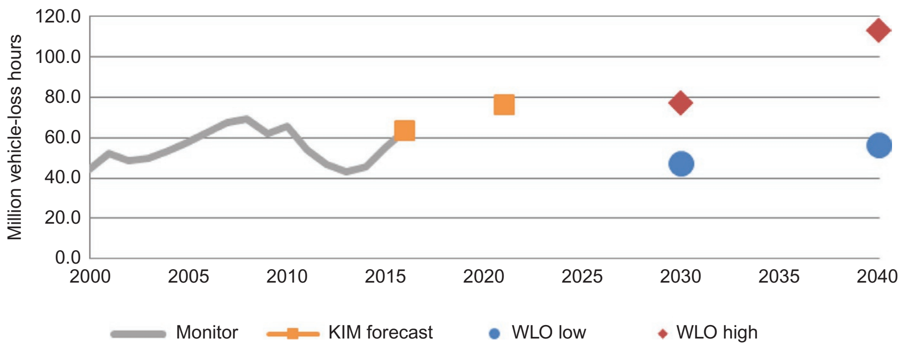

Fig. 4 Congestion; historical trend, short term prediction (*yellow*) and 2030–2040 predictions for the low (*blue*) and high (*red*) scenario relative to the base year.
Figure from NMCA report, page 26.

potential result of the same traffic, but with the (capacity) effects of self-driving cars. The final run of the NMS also models the effect on mode, time of day, and destination choice. In scenarios where VOT for SDC is reduced, and SDCs have an impact on road capacity, the following behavioral responses can be expected:

1. Route choice of SDCs towards use of trunk roads where SDCs are allowed.
2. Reduction of peak period congestion can result in more people choosing the peak period for their trips (both for SDC drivers and “normal” car drivers).
3. Reduction of congestion can result in more people choosing cars as their travel mode (both for SDC drivers and “normal” car drivers).
4. Reduction of congestion (i.e., decreased travel times) can result in choosing destinations further away (both for SDC drivers and “normal” car drivers).
5. Reduction of VOT for SDC drivers can result in a higher chance of this user segment choosing car driver as travel mode and choosing further away destinations.

First-order results

The first-order results will only be given from the Qblok assignment procedure. These results reflect the potential effect of SDCs when no behavioral effects on mode, time of day, and destination choice are modeled.

The reference are the results of the 2040 high-growth scenario with no SCD modeled. The results of the reference have an index of 100.

For the trunk road system the results are given in Table 2.

Table 2 Indices for Qblok kilometers traveled and congestion, first-order effects (2040 high scenario)

	Morning peak	**Evening peak**	**Off-peak**	**Total**
kms trunk roads				
Run 1	100.5	100.4	100.5	100.4
Run 2	99.8	100.3	99.7	100.1
Run 3	102.5	101.1	102.5	101.5
Run 4	103.3	101.9	103.3	102.3
Congestion trunk roads				
Run 1	93.8	89.4	95.0	92.9
Run 2	108.3	110.8	110.8	110.0
Run 3	70.4	66.9	72.2	70.0
Run 4	72.7	68.7	73.9	71.9
kms other roads				
Run 1	99.5	99.5	99.6	99.5
Run 2	100.3	99.8	100.4	100.0
Run 3	97.3	98.7	97.5	98.2
Run 4	96.6	97.9	96.8	97.5
Congestion other roads				
Run 1	98.6	98.7	98.3	98.6
Run 2	100.8	99.7	100.7	100.4
Run 3	94.6	98.1	94.0	95.7
Run 4	93.9	97.2	93.0	94.8
kms all roads				
Run 1	100.1	100.1	100.1	100.1
Run 2	100.0	100.1	100.0	100.1
Run 3	100.5	100.3	100.5	100.3
Run 4	100.7	100.5	100.7	100.5
Congestion all roads				
Run 1	96.3	95.0	96.7	96.0
Run 2	104.4	104.2	105.6	104.7
Run 3	83.0	85.6	83.5	84.1
Run 4	83.7	85.7	83.8	84.4

4.1.1 Discussion of the first-order results

The first-order results model the following effects:

1. the effect of the SDC on road capacity, and
2. the effect of lower VOT of SDC in route choice; cars and trucks with level-4 automation will feel less costs on roads where they are allowed to activate the self-driving mode of the car. Therefore they will have a higher chance of choosing a route using this infrastructure.

In run 1, 40% of the trucks have level-4 automation and can platoon on the trunk road system, with a positive effect on road capacity. As a result modest changes in kilometers traveled and congestion are achieved. Due to lower congestion on the trunk roads and small changes in route choice of trucks towards the trunk roads, a small increase of kilometers traveled on the trunk roads is realized. This results in a small decrease of kilometers traveled on other roads, and therefore a small reduction in congestion as well.

In run 2, in addition to 40% of the trucks, 30% of the cars have level-4 automation, but the automation is autonomous and therefore there is a negative impact on capacity for car drivers with SDCs, and a modest impact on VOT for these car drivers. As a result, congestion on the trunk roads increases, more kilometers are "pushed" to the other roads, and the congestion on all roads increases. Note that this is a combined effect of the reduction of congestion by platooning trucks of run 1, and increased congestion due to the SDC introduced here. Compared to run 1 the negative impact of introducing autonomous SDCs on the congestion on the trunk roads is 17%.

In run 3, 40% of the trucks can platoon on trunk roads, and 30% of the cars have connected level-4 automation. This results in a positive impact on road capacity. In run 3 a modest effect on VOT is assumed. The big impact on road capacity results in more usage of the trunk roads and less on the other roads. A 30% reduction of congestion on trunk roads is realized, and for all roads there is 17% less congestion than in the 2040 high-growth scenario.

Run 4 is similar to run 3, but a higher impact on VOT for car drivers is assumed. The result is that car drivers make more use of the trunk roads. This results in more kilometers traveled on trunk roads, and less on other roads. The overall result is that there is still a considerable effect on congestion. But the increase of congestion on the trunk roads compared to run 3 is not compensated by less congestion on the other roads. Overall the effect on congestion of run 4 is a bit smaller than run 3 but still considerable: 27% less congestion on trunk roads and 16% less congestion on all roads.

4.2 Second-order results

The results of the SDC scenarios relative to the 2040 high scenario after calculating the mode, time of day, and destination effects are given in Tables 3 and 4.

4.2.1 Discussion of the second-order effects

After modeling all the behavioral responses, we obtained the following results:

In run 1 the extra road capacity due to the fact that trucks can platoon on the trunk roads result in a very small growth of kilometers traveled by car drivers. The effect on mode

Table 3 Index of SES tours and kilometers relative to the 2040 high-growth scenario

	Train	Car driver	Car Passenger	BTM	Bike	Walk	Total
Tours							
Run 1	99.9	100.0	100.0	100.0	100.0	100.0	100.0
Run 2	100.1	100	100.0	100.0	100.0	100.0	100.0
Run 3	99.6	100.2	100.1	99.8	99.8	99.9	100.0
Run 4	99.6	100.3	100.1	99.8	99.8	99.8	100.0
Kilometers							
Run 1	99.9	100.5	100.3	100	100	100	100.3
Run 2	100.1	99.7	99.5	100	100	100	99.8
Run 3	99.6	102.8	101.4	99.8	99.8	99.9	101.9
Run 4	99.6	103.9	101.1	99.8	99.8	99.8	102.6

choice is negligible. The small increase in kilometers traveled reduces the first-order effect on congestion. Instead of 7% reduction of congestion on the trunk roads, 2% reduction of congestion remains.

In addition to run 1, in run 2 car drivers can use autonomous SDCs. These SDCs have a negative impact on road capacity, and only a small reduction of the VOT. The first-order effect on congestion is a 10% increase on the trunk roads. As a result, destinations closer by are chosen. The effect on mode choice is again very small. As a result of the shorter distances traveled, the 10% first-order effect on congestion on the trunk roads is reduced to an increase of 5%. This is the combined effect of platooning trucks from run 1 (reducing congestion) and the introduction of autonomous SDCs. The negative impact compared to run 1 of 17% more congestion on the trunk roads from the first-order effects in the previous section is now reduced to 7%

In run 3 SDCs are connected. This results in a 30% reduction of the PAE factor for car driver. In this run the impact on VOT is still modest. As a result, the effect of choosing destinations further away for SDC drivers is relatively small. However, the fact that congestion is reduced considerably as a first-order effect results in a small effect on mode choice, and a larger effect on destination choice. As a result, 12% remains of the initial gain of a 30% reduction in congestion on the trunk roads.

In run 4 the modeled impact of 20% reduction in VOT results in a stronger effect on mode (+0.3%) and especially destination choice (kilometers traveled + 6%). The 6% increase of kilometers traveled by car driver results in a final reduction of the initial first-order effect on congestion of 28% to a reduction of 9% for the trunk road system. This is relative to the 2040 congestion in the high scenario. As can be seen from Fig. 4 the congestion in the 2040 high scenario is twice as much as the congestion in 2014.

5 Conclusions

This study was one of the uncertainty explorations that was executed for the Dutch NMCA.

Table 4 Index of Qblok results after mode, destination, and time of day effects, relative to the 2040 high-growth scenario

	Morning peak	Evening peak	Off-peak	Total
kms trunk roads				
Run 1	100.9	100.8	100.9	100.8
Run 2	99.1	100.2	99	99.8
Run 3	105.3	103.2	105.4	103.9
Run 4	106.4	105	106.7	105.5
Congestion trunk roads				
Run 1	97.6	95.9	99.6	97.8
Run 2	103.6	107.9	104.7	105.3
Run 3	91	80	91.9	87.9
Run 4	94	83.9	95.1	91.3
kms other roads				
Run 1	99.8	99.7	99.9	99.8
Run 2	99.8	99.7	99.9	99.8
Run 3	99.2	99.2	99.3	99.2
Run 4	98.5	98.6	98.8	98.6
Congestion other roads				
Run 1	99.5	99.3	99.6	99.5
Run 2	99.1	99.1	99	99.1
Run 3	99.7	99.3	99.6	99.5
Run 4	98.9	99.2	98.6	98.9
kms all roads				
Run 1	100.5	100.4	100.5	100.4
Run 2	99.4	100	99.4	99.8
Run 3	102.9	101.8	102.9	102.1
Run 4	103.3	102.8	103.5	103
Congestion all roads				
Run 1	98.6	97.9	99.6	98.7
Run 2	101.2	102.6	101.8	101.9
Run 3	95.5	91.5	95.9	94.3
Run 4	96.5	93.1	96.9	95.5

The study proved that it is possible to implement (experimental) functionality in the Dutch NMS to model the impact of SDCs and platooning trucks. The results seem plausible and lead to the following conclusions that can be drawn from the SDC scenarios:

1. The modeled effects of the SDC scenarios are considered to be plausible
2. There is a small impact on mode choice
3. The impact on destination choice is the main effect
4. The initial first-order effects on congestion are for a large part reduced by the second-order effects of mode, time of day, and destination choice, where destination choice is the main driver for this change.

Overall the NMCA study concluded that the potential impact of SDCs on the mobility challenges that are identified in this policy study is not very large. The evolution (or revolution?) of SDCs will have no large impact on long-term mobility challenges.

6 Notes

Note 1: https://www.mirtoverzicht.nl/.

Note 2: https://www.rijksoverheid.nl/documenten/rapporten/2017/05/01/nationale-markt-en-capaciteitsanalyse-2017-nmca.

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