Recent developments and history of the Dutch HCM

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Abstract

Around 1995 the need for a Dutch Highway Capacity Manual (HCM) was felt within Rijkswaterstaat (Rijkswaterstaat is the executive body of the Dutch Ministry of Infrastructure and the Environment). Previously the American HCM was used, but specific circumstances in the Netherlands made it necessary to develop a Dutch HCM. This led to the introduction of the Dutch HCM, Handboek Capaciteitswaarden Infrastructuur Autosnelwegen in 1999, followed by the 2nd edition in 2002. Then, after a long period a completely new 3rd edition was published in 2011 and a fourth edition was completed in 2015.

More than 15 years of research on highway capacities and the experience in using the manual has resulted in a practical handbook with an obligation to use it in planning studies for new and renewed highways in the Netherlands. The manual is one of the guidelines implemented in a working process system for planning studies.

Although different indicators have been used over the years in transportation policy, the volume-to-capacity ratio is still the main indicator for the traffic flow quality in the Dutch HCM. Before the introduction of the Dutch HCM (< 1999) this indicator had been used most frequently.

The most recent fourth version of Dutch HCM includes the research of capacities of tapers, cloverleaves, rush hour lanes and 4 lanes freeways. Weaving sections received special attention, as they are still simulated with the microsimulation model FOSIM. The new information was mostly added after requests of users. Because of a bigger role of consultants and less involvements of experts of Rijkswaterstaat in the highway designing process, guidelines become much more obligatory and nowadays contain specific minimum values and other specifications of the highway elements.

Analysis has also been performed of capacity measurements at more than 200 locations. The influence of, among others, lane width, speed limit, absence of emergency lanes, tunnels and bridges have been analyzed. Also different road work configurations have been analyzed. The results from these analyses have been used in the fourth version of the Dutch HCM to state the influence of different infrastructure elements on the capacity and to validate and update previously stated values.

Keywords: Dutch HCM, road design, managed lanes, traffic management, FOSIM, highway capacity

1 History of the Dutch HCM

At least since 1968 Rijkswaterstaat has researched the level of service (LOS) on the main roads in the Netherlands. The LOS according to the HCM was calculated every 2 years. This research was
done yearly after 1973 and continued until at least 1989. In 1986 Rijkswaterstaat conducted a first research on the capacity on Dutch freeways (Toorenburg, 1986), made possible by the installation on several freeways of the Motorway Traffic Management system (MTM). Among other functionalities, MTM counts traffic flows and measures speed on a large scale on the designated freeways (see paragraph 3.1 for further details on MTM). This has led to more knowledge about capacity values specifically for the Dutch situation.

In the 1990s Rijkswaterstaat had started the CIA-1 project for researching capacity. This culminated in the first Dutch HCM in 1999 (Rijkswaterstaat Adviesdienst Verkeer en Vervoer, 1999) with specific capacities for freeways (only freeways are covered in the Dutch HCM), volume-capacity-ratio and the congestion probability. Hereby the values for the capacity and the Dutch methods for determining the Level of Service achieved an official status. Other reasons for introducing a Dutch HCM and not using the American HCM anymore included: the specific situation on Dutch freeways with higher speeds and smaller inter-vehicular gaps, new traffic management systems (like ramp metering and MTM), peak hour lanes with narrow widths, and the need to update the manual more frequently. The software FOSIM (Freeway Operation SIMulation; see www.fosim.nl) was used for estimating capacity for weaving sections because of the lack of means for measuring the capacity.

Soon after, a new, second, version of the document was introduced in 2002 (Schuurman, 2002). Then, after a long period a new third version was published in 2011 (Witteveen + Bos and TU Delft, 2011). The main reason for this long hiatus of 9 years was the necessity for research. Other causes included changes in the organization and a lack of priority. The third version was updated with new insights of the capacity of 2 and 3 lane freeways (per direction) and a more user-friendly approach for calculating the estimated capacity for weaving sections. Also the passenger car equivalent (PCE) of trucks was set on 2.0 instead of the previously used 1.5.

Since 2011 measurements of capacity and simulations with FOSIM were executed annually to prevent a longer waiting time for a new version. In 2015 the fourth version was introduced (Grontmij, 2015), which includes more capacity values based on real-life capacity measurements. Also the text has been adapted to facilitate a change in users for the Dutch HCM: from freeway design primarily done by employees of Rijkswaterstaat, to a situation where contractors and consultants do most of the design and Rijkswaterstaat acts as supervisor. This asks for more obligatory guidelines which nowadays contain specific minimum values for several design elements and other specifications of the highway elements.

The fourth version of the Dutch HCM also covers the capacities of tapers, cloverleaves, rush hour lanes and 4 lane freeways. In particular, weaving sections are given special attention as they are still simulated with FOSIM. Additional information has been added after requests from some users.

2 Indicators for freeway capacity

2.1 Early years: level of service

Rijkswaterstaat has a long history of observing the quality of the traffic flows on national roads (both freeways and highways) by measuring flow and speed. The first measurements were done manually, to identify possible traffic jams. The first traffic jam in the Netherlands occurred on the 29th of May 1955 (during Whit Sunday).

As far as is known, Rijkswaterstaat has monitored and published the level of service yearly since 1968. During these years the level of service is presented with the letters A to F, following the definition from the U.S. Highway Capacity Manual. As an example the Nota nr. 73-11 (Rijkswaterstaat Dienst Verkeerskunde, 1973) states the level of service in 1972, indicating that “170 km of freeways and nearly 650 km of other national roads have a low level of service”. Here levels D, E and F were considered low levels of service. It was also stated that “the biggest concentration of problems with capacity were located in the Randstad” (the Midwest of the Netherlands).
The level of service was stated for the normative rush hour, which was defined as the rush hour with a traffic flow that is exceeded 10–50 times a year and with a relatively high number of rush hours with around the same amount of traffic flow. The levels of service A – F are an indication of the ratio between the traffic flow and the capacity of the freeway section. The nota stated in 1973 that the growth of the freeway network and freeway capacity did not keep up with the growth of traffic. The same nota also stated the need for a MTM-system. These kinds of nota’s were published yearly until at least 1985.

2.2 SVV-2, NVVP and NoMo

In 1988 the Tweede Structuurschema Verkeer en Vervoer (SVV-2) (Ministerie van V&W en VROM, 1988) was published by the Ministry of Transportation, which set forth the policy for the coming years. The LOS of the HCM became less in use in the Netherlands, because the meaning of LOS A – F was difficult to explain to the public. Influence of the public in government projects was increasing and was thus an important reason to adopt another type of indicator for the LOS on the main roads. The SVV-2 introduced a new indicator for the level of service: the congestion probability. The idea was that the chance for a driver to encounter a traffic jam should be capped by a maximum probability. Freeway congestion is defined in The Netherlands as a speed lower than 50 km/h.

The SVV-2 sets the goal that all roads connecting the Rotterdam harbor and Schiphol Airport to the hinterland should have a congestion probability of less than 2% and all other freeways less than 5%. The congestion probability is determined by a simulation based on the free capacity and the amount and distribution of traffic flow over the day. It represents the theoretical chance that a driver will encounter congestion on a random moment of the day. According to SVV-2, all proposed projects for new roads or widening of existing roads should meet this goal.

In 2001 the congestion probability is replaced due to new transportation policy, the NVVP (Ministerie van V&W en VROM, 2001). Performance and necessity for freeway projects are now judged based on average speeds over longer freeway stretches. The average speed on freeway stretches of more than 30 kilometers should not be lower than 60 km/h.

In 2005, a new policy indicator for the quality of the traffic flow is introduced: the NoMo-norm. The NoMo-norm bases the quality of the traffic flow on the ratio between average travel time during rush hour versus the travel time outside rush hour. The travel time is measured over longer stretches of freeway. Recently a new policy indicator has been presented, which calculates the economic costs of the delays per motive for every bottlenecks. This new indicator is implemented in the traffic models of Rijkswaterstaat and will be used in planning studies in the future.

2.3 Dutch HCM: volume-to-capacity ratio as indicator for design

Even though the official policy uses the congestion probability as the main indicator at the time, the first version of the Dutch HCM states that “as a rule of thumb, a volume-to-capacity ratio of less than 0.8 allows for sufficient reserve capacity. A ratio of 0.9 is in a transition area. [...] At a ratio above 1.0, the congestion is structural.” The target audience for the Dutch HCM are freeway designers, so the volume-to-capacity ratio is used to determine the quality of the traffic flow for individual freeway segments. This despite the fact that the official policy indicator for the quality of the traffic flow was still the congestion probability. For the size of the traffic flow an average working day hourly volume is used, usually a 1-hour-volume average over 1 year. This differs from the 30th – 50th busiest hourly volume when the HCM (TRB) was used.

With the second version of the Dutch HCM in 2002, the congestion probability is removed from the manual due to the new policy from the NVVP. But the volume-to-capacity ratio still stays the key indicator for the Dutch HCM and is used to present the quality of the traffic flow for freeway segments.

When the third version of the Dutch HCM is published in 2011, it explicitly states that the NoMo-norm is a policy indicator. It now states that the volume-to-capacity ratio should be below 0.8 to be free of congestion. Between 0.8 and 0.9 there will be congestion, but not on a daily basis.
Between 0.9 and 1.0, congestion will occur on a daily basis. At a (demand) volume-to-capacity ratio of more than 1.0, daily heavy congestion will occur.

The fourth version of the Dutch HCM has explained the use of the volume-to-capacity ratio in more detail. It also presents the probability that congestion will occur given 30 minutes of traffic at a given volume-to-capacity ratio (see Table 1). These congestion probabilities are obtained using a large number of traffic simulations (using the simulation program FOSIM) and observing the percentage of simulations at which congestion had occurred within the first 30 minutes.

<table>
<thead>
<tr>
<th>V/C ratio</th>
<th>Probability of congestion within 30 minutes</th>
<th>HCM (TRB) LOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.3</td>
<td>0%</td>
<td>A</td>
</tr>
<tr>
<td>0.3 – 0.8</td>
<td>&lt; 1%</td>
<td>B - D</td>
</tr>
<tr>
<td>0.8 – 0.9</td>
<td>≤ 20%</td>
<td>E and F (congestion)</td>
</tr>
<tr>
<td>0.9 – 1.0</td>
<td>20 – 100%</td>
<td>E and F (congestion)</td>
</tr>
<tr>
<td>&gt; 1.0</td>
<td>100%</td>
<td>F (congestion)</td>
</tr>
</tbody>
</table>

Table 1: Probability of congestion at different volume-to-capacity ratios

3 Measuring Dutch highway capacity

3.1 Data sources

More than 40% of the Dutch freeway network has been equipped with MTM (Motorway Management Traffic system), which consists of induction loops measuring traffic volume and speed combined with overhead variable message signs on gantries per lane. This combination of induction loops and gantries with variable message signs is typically located every 300 to 600 meters. Part of MTM is an Automatic Incident Detection system (AID), which detects traffic jams and sends a signal to the overhead variable message signs showing a lower maximum speed (50 at the location of the traffic jam, upstream 50 with flashers and further upstream 70 with flashers). The AID uses a threshold of 35 km/h to detect a traffic jam.

MTM also stores the average speed and volume per lane every minute. This data is stored for use in all kinds of traffic analyses and applications. The introduction of MTM created the opportunity to measure the flow and speed around the moment of traffic breakdown and using those indicators to determine the capacity of that road segment. Before that, research into freeway capacity was much more difficult, due to a sparse number of permanent monitoring locations and often the need for visual measurements.

In 1986 Rijkswaterstaat conducted the first highway capacity calculations with traffic data from induction loops from the MTM-system (Toorenburg, 1986). In 1986 the number of freeway segments where this data could be collected was still limited in the Netherlands. In the decennia after 1986, both the network of freeways with MTM and the possibilities to store and use large amounts of data have increased exponentially. This led around 2006 to Rijkswaterstaat’s wish to measure the highway capacity of a larger amount of bottlenecks and also under varying circumstances (e.g. dry versus rainy, light versus dark).

3.2 Methods for estimating highway capacity

There are several methods to determine the capacity of a highway segment based on measurements of flow and speed. In 2007, Arane (2007) has conducted a research to find the best possible method(s) to determine the freeway capacity, that not only gave reliable capacity values but were also practical for use with a large number of locations with a large data set (e.g. 2 years of data).

This research evaluated seven different methods for determining both free flow capacity and queue discharge capacity:

1. Fitting on the fundamental diagram
2. Empirical distribution function
3. FOSIM-method (maximum flow before breakdown)
4. Product Limit method (variant Van Toorenburg/Botma, parametric)
5. Product Limit method (variant Van Toorenburg/Botma, non-parametric)
6. Product Limit method (variant Brilon, parametric)
7. Product Limit method (variant Brilon, non-parametric)

(See Arane (2007), Minderhoud, Botma, & Bovy (1997) and Brilon, Geistefeldt, & Regler (2005) for a description of the methods above).

Arane (2007) concluded that the best methods for estimating the free flow capacity were an adapted version of the Product Limit method of Brilon (non-parametric), followed by the FOSIM-method. The adaptation of Brilon method was to also take into account a short period before the breakdown. Tests showed that in a lot of cases the flow was actually higher a short period before the breakdown than during the breakdown period. Without adaptation, the Brilon-method would underestimate the capacity.

Arane (2007) also concluded that the empirical distribution function was the only method suitable to estimate the queue discharge capacity. The other methods either did not produce reliable results or were too sensitive to the initial estimation of parameters (Fitting on the fundamental diagram).

3.3 Producing capacity estimates

With the three selected methods a study in 2008 was conducted to produce capacity estimations for 75 bottleneck locations in the Dutch freeway network (Van Rij & Henkens, 2009). The results of this study were used in the third Dutch HCM version in 2011. Thereafter, a second large scale study was started to estimate the capacity for more bottleneck-locations (Arcadis, 2013). This study included a more detailed look at weaving sections (which included measuring also the percentages of both weaving and through going traffic) and measurements at road work locations.

The Brilon method and the empirical distribution function were not useable for all freeway segments that were analyzed in the latest study, due to a lack of frequent congestion (Arcadis, 2015). Because of the wish/need to gain more insight into the capacity of some specific freeway segment (peak hour lanes (see section 5.2), four and five lane roads), some capacity estimations have been performed at these types of locations without (frequent) congestion but where the traffic flow was close to the saturation point. Here the capacity was estimated with a combination of the 99.9th percentile, the value of the 100th highest flow measurement and expert judgement based on measurements plotted on the fundamental diagram (flow versus speed).

The combined capacity measurements from the period 2008 – 2015, capacity estimations for more than 200 locations, have been analyzed as input for the recent fourth version of the Dutch HCM (Henkens & Abma, 2015). Some highlights from this analysis will be discussed further on in this paper.

4 Determining the capacity of weaving sections

4.1 The use of FOSIM for determining freeway capacity

FOSIM is a microscopic traffic simulation program that can take a variety of road geometry and traffic factors into account. FOSIM is owned by Rijkswaterstaat and developed specifically for Dutch freeways. FOSIM is developed to simulate stretches of freeways, to determine driver behavior, congestion and freeway capacity. It was developed in the early nineties and has been improved and updated with added functionality over the years and is currently at its sixth major version.

FOSIM has been validated for simulating symmetrical (number and distribution of lanes of the entry and exit legs are identical) weaving sections (Vermij, 1997) and asymmetrical weaving
sections (Minderhoud & Kirwan, 2001) meeting the Dutch guidelines and based on Dutch traffic regulations and driver behavior.

Since weaving sections can vary on several important factors (e.g. number of lanes on the entry and exit legs, length of the weaving section and percentage of traffic that is weaving), it is impossible to measure all kinds of variations in real life. FOSIM can therefore be used to simulate a proposed design for a weaving section and determine the (expected) capacity. A large part of the capacity values in the Dutch HCM have been determined with the traffic simulation program FOSIM. The Dutch HCM lists a lot of tables with capacity values of weaving sections with different layouts (e.g. 2+1 → 2+1, 2+2 → 3+1, etc.), lengths of the weaving section, percentage of trucks (5%, 15% and 25%) and different percentages of weaving traffic. When new weaving sections need to be designed, the designer needs to find the combination of factors in the Dutch HCM that corresponds to the new weaving section and use the corresponding capacity value. If (some of) the factors differ too much from the available values in the Dutch HCM, than a dedicated FOSIM simulation needs to be conducted to determine the capacity value.

4.2 Measuring the capacity of weaving sections

For the third version of the Dutch HCM, some capacity measurements have been performed based on traffic data (Van Rij & Henkens, 2009). These calculations were only based on data from existing induction loops, so the amount of weaving traffic could not be determined. Since the amount of weaving traffic has a large influence on the capacity (see also Figure 1), these measurements could not be used directly to validate or substitute capacity values obtained with FOSIM simulations.

In the period 2011-2013 additional capacity measurements have been conducted at weaving sections (Arcadis, 2013). Data from the combination of video cameras and loop detectors was used to measure flow, speed and origin and destination around the weaving section (from which entry leg to which exit leg, based on registrations of license plate numbers at the entry and exit legs). This data was then used to calculate the capacity of the weaving section and to calculate the percentage of weaving traffic from both entry legs.

![The influence of weaving traffic on the capacity (2+2 symmetrical weaving section)](image)

**Figure 1:** The influence of weaving traffic on the capacity (Witteveen + Bos and TU Delft, 2011)

For the fourth version of the Dutch HCM, it was attempted to validate the capacity values for weaving sections that were based on FOSIM simulations, with the performed capacity measurements. It turned out that the performed measurements were not easily comparable with the ‘standard’ values from the FOSIM simulations, because the percentages of weaving traffic in the measurements often differed strongly from the ones available in the Dutch HCM. Therefore a more general comparison/validation was made, whereby the measured capacity values for weaving
sections of a certain layout were compared with the bandwidth of capacity values that was given for that layout with different amounts of weaving traffic. Most of the real-life capacity measurements fell within the bandwidth of capacity values given by the FOSIM simulations (Grontmij, 2015). Further validation of FOSIM could be performed by simulating the specific weaving sections where the measurements were performed and using the measured percentages of weaving traffic as input to see if the capacity values obtained with FOSIM are more closely comparable with the outcome of the real-life measurements. That was however not within the scope of the Dutch HCM update.

5 Analysis of highway capacity measurements

5.1 Standard highway capacity

The most important and most used values from the Dutch HCM are the capacity values for ‘standard’ freeway segments with a different number of lanes (1 up to 7 lanes). ‘Standard’ meaning a freeway segment with:

- A maximum speed limit of 100 or 120 km/h;
- 15% freight traffic (vehicles with a length of more than 5.6m);
- A design according to the Dutch design guidelines for freeways;
- No large objects near the road side (e.g. noise barriers);
- No distractions caused by objects or events near the road;
- No steep gradients (<2.5%) or less steep gradients over a longer distance;
- Day light and with dry weather (less than 2 mm/hour precipitation);
- Good quality road surface (very porous asphalt);
- MTM equipped;
- No other active traffic management measures.

The capacity values for freeway segments with two or three lanes (the most common in the Netherlands) have been based on capacity measurements at bottleneck locations with on-ramps or segments with a lane drop (left side lane ends). The measured capacity varies between specific locations. The standard values given in the Dutch HCM are the average of a set of representative locations. For the recent fourth version of the Dutch HCM, the capacity was also measured/estimated (a combination of measurements at locations without congestion and expert judgement) for 4 and 5 lanes. The capacity values for 6 and 7 lanes were estimated based on the other capacity values.

Table 2 shows the capacity values given in the versions 1 through 4 of the Dutch HCM. For three lanes and up, the capacity values have been lowered over the years, since capacity measurements showed lower values. In the first two versions of the Dutch HCM, it was assumed that the freeway capacity had an autonomous increase of about 0.5% per year due to an increase in road and vehicle quality (Rijkswaterstaat Adviesdienst Verkeer en Vervoer, 1999). Based on capacity measurements conducted for the third version of the Dutch HCM, this assumption turned out to be invalid.
5.2 Peak hour lanes

One of the shortcomings of the first three versions of the Dutch HCM was that there was little available data for reliable capacity estimations for freeway segments with peak hour lanes.

Peak hour lanes exist in two main forms in the Netherlands: Peak hour lanes on the right side of the road (spitsstrook rechts, on the emergency lane) or on the left side of the road (spitsstrook links or plusstrook). See also Figure 2 for an example of both situations. The peak hour lanes are normally narrower than the standard freeway lane width in the Netherlands (3.5 meters (Rijkswaterstaat GPO and Witteveen + Bos, 2015)). On the right side, the peak hour lane is normally a bit wider (2.90 – 3.30 meters for a two lane freeway plus peak hour lane) than on the left side (2.50 – 3.05 meters) (Kraaijевeld & Hennink, 2013), primarily due to restrictions on vehicle width for the peak hour lane on the left side (often restricted for vehicles with a width of more than 2.0 meters).

![Figure 2: Example of peak hour lane on right side (picture left) and peak hour lane on the left side (picture right) (source: Google Streetview)](image)

The freeway segment with peak hour lane is hardly ever the primary bottleneck. Usually a segment downstream with a lower capacity, a weaving section, merging lane, et cetera is the primary bottleneck and therefore not representative of the capacity of the peak hour lane. There was therefore a lack of reliable data to estimate the capacity of a freeway segment with peak hour lane versus a ‘normal’ freeway segment with the same number of lanes. In 2015, as part of data collection for the fourth version of the Dutch HCM, a study was conducted to estimate the capacity of peak hour lanes based on available data (Arcadis, 2015). The freeway segments with peak hour lanes were not congested, but the flow during peak hour was close to the expected capacity. As described earlier, a combination of measurements of the 99.9th percentile, the 100th highest flow measurement and expert judgement were used to determine the estimated capacity for peak hour lanes.

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<tr>
<th></th>
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<th></th>
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</tr>
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<tbody>
<tr>
<td>1 lane (longer than 1,500 meter)</td>
<td>1,900</td>
<td>1,900</td>
<td>1,900</td>
<td>1,900</td>
</tr>
<tr>
<td>1 lane (shorter than 1,500 meter)</td>
<td>2,100</td>
<td>2,100</td>
<td>2,100</td>
<td>2,100</td>
</tr>
<tr>
<td>2 lanes</td>
<td>4,300</td>
<td>4,300</td>
<td>4,200</td>
<td>4,300</td>
</tr>
<tr>
<td>3 lanes</td>
<td>6,700</td>
<td>6,700</td>
<td>6,300</td>
<td>6,200</td>
</tr>
<tr>
<td>4 lanes</td>
<td>9,000</td>
<td>9,000</td>
<td>8,200</td>
<td>8,200</td>
</tr>
<tr>
<td>5 lanes</td>
<td>11,300</td>
<td>11,300</td>
<td>10,000</td>
<td>10,250</td>
</tr>
<tr>
<td>6 lanes</td>
<td>13,400</td>
<td>13,400</td>
<td>11,500</td>
<td>12,000</td>
</tr>
<tr>
<td>7 lanes</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>13,500</td>
</tr>
</tbody>
</table>

Table 2: Standard capacity values over the years

<table>
<thead>
<tr>
<th>Freeway segment</th>
<th>Capacity (veh/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 lanes plus peak hour lane (right side)</td>
<td>5,300</td>
</tr>
<tr>
<td>2 lanes plus peak hour lane (left side, lane width 3.10m)</td>
<td>6,100</td>
</tr>
<tr>
<td>2 lanes plus peak hour lane (left side, lane width 2.50-2.75m)</td>
<td>5,800</td>
</tr>
</tbody>
</table>

Table 3: Measured/estimated capacity for peak hour lanes (15% freight traffic) (Grontmij, 2015)
This method has led to the standard capacity values given in Table 3. When compared with the capacity for standard 3 lane highways, both segments with peak hour lanes on the left and on the right side have a lower capacity. The added capacity of a standard third lane can be set at 1,900 veh/h (6,200 – 4,300). The benefit of a peak hour lane on the left side with a width of 3.10m is then about 5% lower than a normal third lane. The difference here is very low, because the lane is still fairly wide and the narrower left lane will only be used by cars and not by wider truck traffic. A peak hour lane on the left side with a significantly smaller width than the standard (in this case a width of 2.5-2.75m) has a lower benefit (21% lower than a standard third lane). The lower width here has more influence on the capacity. The peak hour lanes on the right side has a much lower benefit compared to a normal third lane. The added capacity of the peak hour lane is almost half (47%) that of a normal third lane. This is probably due to a combination of factors: the right lane is used more by truck traffic (so the narrower lane has more influence on the wider truck traffic), the absence of an emergency lane and studies have shown that the peak hour lane on the right side is used less than a normal lane.

5.3 Influence of road design

For the fourth version of the Dutch HCM, the relationship between several road design factors and the measured capacity values was analyzed (Henkens & Abma, 2015). Some factors that have been analyzed are: presence of noise barriers, presence of an emergency lane, influence of lane width, influence of the size of the obstacle-free zone, the influence of the maximum speed limit and the influence of tunnels and bridges.

To analyze the influence of these factors on the capacity, these factors have been recorded for all available freeway segments where capacity measurements were conducted (216 locations). Then the capacity values have been judged on the plausibility of the measured capacity values (e.g. problems caused by incomplete traffic measurements or inconsistent results during the measurement period). All non-plausible values have been filtered from the analysis (70 locations). From the remaining group of locations, a selection of representative locations with two or three lanes were selected (excluding weaving sections and other special types of discontinuities). The analysis was then performed on this group of locations (69 locations).

One important observation of the analysis was that the measurements, performed on data ranging from 2005 till 2014, showed no significant change in average capacity over the years. Early assumptions about capacity values had stated that freeway capacity had an autonomous growth, caused by improvements in motor vehicles. The third version had already rejected this assumption based on measurements in 2009 and the new analysis supports this rejection based on the additional measurements over a longer period.

Analysis on the influence of lane width showed a difference in capacity for the left lane of about 20% between a width of 2.5 versus 3.5 meters. This difference was not statistically significant, in part due to a low number of locations with narrow lanes. The difference of 20% is comparable to the decrease seen for narrow peak hour lanes on the left side.

The absence of an emergency lane did not seem to influence the capacity value significantly when other relevant road design factors did meet the standards. The absence of an emergency lane, when combined with narrower lane widths than the standard, did seem to cause lower capacity values. However, the number of locations without emergency lanes was low, so the reliability of these observations is also low. The presence of a noise barrier or a very small obstacle-free zone seems to have a small negative influence on the freeway capacity, but these differences were also not significant.

The influence of the maximum speed limit has been analyzed using freeway segments with a maximum speed limit ranging from 80 to 130 km/h. No real difference in average capacity value has been found, confirming previous Dutch research that maximum speed limit has little or no influence on the capacity (at least in the range 80 to 130 km/h). At segments with a speed limit of 80 km/h, the average capacity was some percentages lower. However the difference is minimal and the variation is high. Since a freeway speed limit of 80 km/h is rare in the Netherlands, no significant effect of the speed limit is mentioned in the Dutch HCM.
Bridges with a normal lane width and emergency lane do not seem to lead to a lower capacity. One Dutch bridge with a much narrower lane width had a capacity of about 17% lower than standard for a two lane freeway. Only one Dutch freeway tunnel was suitable to perform capacity measurements: the (old) Coentunnel (a 590m long 2 x 2 lane tunnel in Amsterdam). In this tunnel, a capacity of about 4.5% lower than standard was measured. This is probably caused by a combination of the lack of emergency lane and obstacle-free zone and a relatively steep gradient. However, the design of the Coentunnel is not representative of all Dutch freeway tunnels.

5.4 Road work capacity

For the fourth version of the Dutch HCM about 40 segments with road works were also monitored to analyze the effect of different road work configurations on the capacity. These road works varied in duration from short term (a few days/week) to long term (up to around 6 months). The Dutch HCM states the capacity of road work segments in queue discharge capacity instead of free flow capacity, because road works are a temporary situation during which some congestion is accepted.

An important conclusion of the measured capacity values, is that the mean queue discharge capacity per lane is about 23% lower for road work segments than for a reference group of ‘normal’ freeway segments. This is likely to be caused by a combination of:

- narrower lanes. Narrower lanes have several effects on traffic behavior, all of which (can) lead to a lower capacity (e.g. more complicated driving task, lower speeds, less overtaking and larger headways (Grontmij, 2015));
- distraction caused by the road works. Research conducted in North America showed that the difference in capacity reduction between active and non-active road work on site could be between 1.8 and 12.5% (Al-Kaisy & Hall, 2002). The amount of distraction is influenced, among others, by the number and size of road work vehicles, the road work tasks performed, the distance between the road work and the traffic and the kind of barrier used. Shielding road works from view can therefore have a positive impact on the capacity (Arcadis, 2004);
- lower maximum speed limit. Based on the fundamental diagram, optimum capacity is reached at a speed around 90 km/h. A maximum speed limit of 70 km/h will therefore lead to a lower capacity;
- unfamiliarity with the new (temporary) situation. A new situation may cause drivers to drive more carefully (slower and with larger headways). If the road works last longer, the capacity may increase;
- the design of the start and end of the road work segment. Typically, the road works start and end with an S-curve between the original road and the road works and vice versa. A bad design of these S-curves (e.g. too narrow curve radius) can cause the S-curve to be the bottleneck of the road works (Voorrips, 2013). The guidelines for designing the S-curves (given in (CROW, 2013)) have to be followed to avoid a lower capacity.
- and in some cases the length of the road works in combination with a lack of opportunity to overtake slower vehicles (when there is only 1 lane available, or when the lane width is so narrow that drivers avoid overtaking wider trucks).

One also has to take into account that the variance between measured capacity values for different road work segments is larger than for a comparable group of ‘normal’ freeway segments. This will be due to differences in the amount of the above mentioned factors present at a specific road work location (e.g. there can be no or little distraction during the period that measurement were conducted or there could be a lot of distraction due to busy visible road work, or the width of the remaining lanes could be standard, or can be considerably reduced).

Overall the average capacity values measured during road works were comparable with the values stated in the previous third version of the Dutch HCM. There was therefore no need to change the values for road work capacities in the fourth version (the capacity values for road works are described in more detail in an earlier paper about the third version of the Dutch HCM (Daamen,
Because the capacity values for road work are given as queue discharge capacity and some congestion during road works is accepted, the maximum acceptable flow/capacity ratio is 1.0. Given the large differences that were observed from the standard or average capacity value for a certain road work configuration, care has to be given to the actual construction and use of the road work site. Deviations from the design guidelines (e.g. narrower lanes, tight S-curve at begin or end) or larger distractions can cause a lower capacity than stated in the Dutch HCM.

6 Conclusions

The Dutch HCM and the usage of freeway capacity values have evolved over the years. With new transportation policies being adopted, the official indicators for the quality of freeway traffic flow have changed over the years, but for freeway designers, the volume-to-capacity ratio has continued to be an important indicator for the design of freeway segments.

Since 1986, research has been conducted in the Netherlands on specific capacity values for Dutch freeways. The first versions of the Dutch HCM were based on a limited number of measured capacity values and in a large part on traffic simulation with FOSIM. For the third and fourth version, extensive measurements were conducted on freeway capacity, leading to measurements on more than 200 congested locations, including weaving sections and road works. This made it possible to update and validate more standard capacity values stated in the Dutch HCM, thereby meeting the wish of users of the manual.

The text of the fourth HCM has also been adapted to a wider audience. A necessity caused by an increased role of contractors and consultants in the design of freeways. The Dutch HCM remains an important and mandatory guideline in designing Dutch freeways. It is also still a source of background information on freeway capacity and an easy to use document to look up capacity values for specific types of freeway segments.

References


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