A Model for Capacity Reduction at Roadwork Zone

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Abstract

This paper presents an investigation of capacity reduction in connection with roadwork zones. The paper presents a state-of-the-art description on roadwork effects on capacity. Based on the literature on this topic the most important parameters that should be incorporated in a Swedish capacity manual for the operation and maintenance roadwork are: the proportion of heavy traffic; lane width; number of closed lanes; closed road shoulder; proportion of commuter traffic; and length of roadwork zone. The paper presents a comparison of a composite model of correction factors from Germany, USA and Denmark and the Dutch model for computation of capacity reduction. The comparison show that the two models essentially gives the same results. Based on these results a model was developed. The model developed was validated using empirical data from a full scale test at the motorway network in Gothenburg. The throughput was measured in two cases during the morning and afternoon peak hour. The capacity for the normal site conditions was estimated based on traffic flow and speed data from the same site. The result shows that the empirically estimated capacity reduction is consistent with the reduction calculated with the new model for the different road work designs evaluated. The conclusion is that the model developed seems to be valid for capacity reduction estimations of roadworks on Swedish motorways but that more empirics are needed to ensure general validity.

Keywords: roadwork, workzone, motorway, capacity

1 Introduction

People are in constant motion and in the metropolitan areas it is difficult to perform the necessary operation and maintenance work of the road network. At some parts of the urban motorway network maintenance operations are only allowed during the night time off peak. Maintenance of the existing network normally implies roadworks including closing or narrowing of lanes and/or slow moving maintenance vehicles. Thus, roadwork zones have a significant impact on traffic flow as these often constitute bottlenecks, resulting in queues with delays as a result. Knowledge of the road's capacity at
roadwork areas is crucial for traffic planners in planning the operation and maintenance activities. Although the problems are not tied to a specific road type the effect is usually greatest in the semi-urban motorways, which in general carries the highest traffic volumes.

In general, national guidelines and manuals give good estimates of road capacity. Several capacity manuals also give good enough estimates on the average capacity reduction at roadwork zones. However, there is a lack of knowledge about which factors that affect the work zone capacity and how variation in those factors influence the capacity. Various studies (mostly micro-simulations) show that there can be a large variance of the impact on the capacity for variation in different factors such as number of lanes closed, lane widths, roadwork length, time of day, type of roadwork, etc. This means that the effect of such factors on capacity is not clear. In general, there are (too) few empirical studies focusing on the differences in capacity caused by these situation-specific variables. This might be due to that traffic measurements in connection with roadworks have had lower priority compared to traffic measurements for normal conditions or that measurements in connection with roadworks are more difficult to conduct due to that the measurement devices obstruct the maintenance work. Anyway, the lack of empirical data and analysis constitutes an important gap.

The aim of this paper is to present a model for estimation of capacity reduction at roadworks that consider relevant influencing factors and which is applicable for Swedish traffic conditions. This was achieved by first investigating and analyzing the roadwork zone capacity models available in the literature and studying their applicability in a Swedish context. Based on the state-of-the-art comparison a model for estimation of capacity reduction on Swedish motorways was developed. The model developed was then validated using results from a field study in Gothenburg where throughput was measured in two road work cases during a morning and afternoon peak hour.

The paper is organized as follows: a review of the state-of-the-art is given in Chapter 2, a new model for capacity at roadwork zone at motorways is presented in Chapter 3; Chapter 4 gives a description of a full scale real world validation of the model developed; Chapter 5 ends the paper with concluding remarks and suggestions for further research.

2 Literature review

There are two countries that are in the lead in terms of simple models for the calculation of capacity at roadwork zones, it is the Netherlands (Rijkwaterstaat, 2011) and Germany (BASt, 2011). Both countries have in slightly different manners estimated correlations between roadwork capacity and a number of restrictive parameters. In the Dutch capacity manual for roadworks (Rijkwaterstaat, 2011) capacity values is described for different roadwork configurations. Also background to capacity in relation to roadworks and the factors that influence the ongoing roadworks is described. HCM 2010 (Transportation Research Board, 2010) includes models for capacity reduction for roadworks on motorways, which gives an estimate of capacity and average values, not specific values for specific situations (TRB 2010). A study that analyzes driving behavior in connection with road work shows that with more cooperative driving the capacity can be increased by 37.5%, the reverse is when a minimally cooperative driving occurs then capacity can be reduced by 36% (Heaslip et al 2008).

In US (Lindly et al 2004) and UK (Department for Transportation UK 2006) software’s have been developed in which a small road network is represented, which making it a bit more complex to do a quick estimate of the capacity, queue length and delay since a lot more data is necessary. Denmark has a simple model that considers roadworks on both motorways and two lane rural highways (Vejdirektoratet, 2010). Temporary short-term roadworks with a relatively short duration, generally give a lower capacity than long term roadworks. If a temporary roadwork lasts for a long time, drivers will get acquainted with the situation and thus have a safer/more effective behavior. This has a generally positive effect on capacity.
At roadworks with narrow lanes, there is a narrowing of the cross section which directly or indirectly has a negative effect in terms of deterioration of the driving task (Hogema, 2005, Godley, Triggs and Fieldes, 2004), free flow speed (Chitturi and Benekohal, 2005), reduced number of overtaking/passages (Hogema and Brouwer, 1999), higher percentage of aborted overtaking’s/passages (Kuile, 2006), reduced use of the left lane (Kuile, 2006) and larger time gaps (Gunay, 2007).

According to the literature that has been investigated the length of a closed lane seems to, especially in narrow lanes, affect capacity. Hogema and Brouwer (1999) found that a narrower roadway gives fewer overtaking’s. Which means that the spacing between platoons of vehicle (as a result of differences in velocity) fills less quickly, which in turn causes the vehicle density to decrease, thus reducing the capacity. The same principle applies for longer one lane sections where speed differences, gaps in traffic flow and platoons result in a lower capacity.

Since the roadworks are often associated with narrow lanes, a large proportion of heavy trucks in these situations lead to a further increase of the driving task (Hogema, 2005). This in turn has an influence on the driving speed, and thus the capacity. A study of the capacity of highways in Canada at roadwork zones (Al-Kaisy and Hall, 2003) shows a significantly lower capacity at narrower lanes. Instead of the normal capacity value of 2160 vehicles/h/lane, the capacity was measured to 1800 vehicles/h/lane. In addition, the studies showed a decrease of 7 - 16 % of capacity in a situation with fewer commuting drivers, i.e. on weekends and during off-peak hours. The study also showed that different speed limits and types of separation/barrier cause a difference in the reduction of capacity in the range of 1 - 5.12 %.

During the duration of a roadwork there may be occasions when the roadwork is not active. Al-Kaisy and Hall (2003) found a difference between situations where no staff where working at the roadwork zone and when staff are working. In situations where no work or non-visible work was carried out, the relative capacity was higher, in the order of 5 to 10 %. To shield the roadwork zone from road users can thus be a positive measure which affects capacity, this is because road users are distracted less and they can pay more attention to driving.

The tutorial BAS1 (2011) presents a method for different roadwork zones on motorways based on RBAP’96 (BMV, 1996). The purpose of the method is to get an idea of the expected congestion based on the difference between the requested flow during peak hours and capacity through the roadwork zone. In addition to the lane width the model includes the variables, cross over, reduction of number of lanes and percentage of commuting traffic, see Table 1.

<table>
<thead>
<tr>
<th>Correction factor</th>
<th>Reduction</th>
<th>Capacity $C_{PCU}$ (pcu/h/lane)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lane width $hv \geq 3.25$ m or Lane width $pc \geq 2.75$ m</td>
</tr>
<tr>
<td>Base capacity</td>
<td>1.0</td>
<td>1830</td>
</tr>
<tr>
<td>Cross over (Co) or Reduction of number of lanes (Rnl)</td>
<td>0.95</td>
<td>1740</td>
</tr>
<tr>
<td>Cross over (Co) and Reduction of number of lanes (Rnl)</td>
<td>0.95-0.95</td>
<td>1650</td>
</tr>
<tr>
<td>Commuter traffic &lt; 50 % (C50)</td>
<td>0.9</td>
<td>1640</td>
</tr>
<tr>
<td>C50 and Co or C50 and Rnl</td>
<td>0.9-0.95</td>
<td>1560</td>
</tr>
<tr>
<td>C50 and Co and Rnl</td>
<td>0.9-0.95-0.95</td>
<td>1480</td>
</tr>
</tbody>
</table>

*Table 1: Lane capacity reductions at roadwork zone under various boundary conditions (BASt 2011).
The correction parameters in Table 1 are only valid if the chicanes at the cross-over do not deviate too much from the German or Dutch standards for traffic control plans (CROW 2012). Otherwise, it may provide a different capacity than specified in the table above.

There are more studies for German conditions (Weinspach, 1988) indicating that narrow lanes has an effect on capacity. The studies claim that lane width less than 3.50 m gives a capacity reduction of up to 15%. However, in BASi (2011) the threshold was updated to 3.25 m.

In general, the guidelines and manuals used in different countries, gives a good estimate of capacity and a good enough average value of the capacity reduction at roadwork zone on the highway. But there is a lack of knowledge on how the different variables that affect the capacity vary between different situations. Various studies (mostly micro-simulations) show that there is a large variance of the impact on the capacity of a variable. This means that the effect of variables on capacity is not clear. In general, there have been (too) few empirical studies focusing on the differences in capacity caused by these roadwork situation-specific variables.

The effect of the length of the roadwork zone is not evident. The studies presented in the literature show different results, some indicate a positive effect for increasing roadwork zone length (Ullman et.al. 2009 and Karim et.al. 2003) and some no effect at all (Benekohal et.al. 2010). However, in some countries' capacity manuals the length of roadwork zone is a parameter with a significant effect, such as Denmark (Vejdirektoratet, 2010). Even lane width (Vejdirektoratet, 2010), duration (Maze & Bortle 2005), time of day (Benekohal et al 2003) and location of the roadwork (Karim et al 2003) is found to be significant.

Thus, there is no clear conclusion about the effect of the duration of a roadwork zone on capacity. Capacity differs not only between different roadwork designs but also between the roadwork with similar design. Thus, one can conclude that there is a high variation due to surrounding elements, such as the type of work and external effects such as rain (which affects the capacity even under normal conditions).

The differences that exist in capacity estimation for roadwork zones on motorway sections can be said to consist of four situation-specific variables. These four variables are: the percentage of heavy vehicles, type of road and the width of the remaining (open) lanes and diversion of traffic to the opposite carriageway (crossover). An increasing proportion of heavy vehicles have a negative impact on roadwork zone capacity. An increasing complexity of work, from light barrier works to very heavy bridge repair, has a negative impact on traffic performance. An increased lane width has a positive effect on capacity. The diversion of traffic to the opposite carriageway is often the cause of the bottleneck and is therefore of great significance.

The results from the literature study are sometimes ambiguous, the effects of different variables differs widely between different studies and within studies. This shows the complexity and the wide number of parameters that influence the capacity at work zones. The results of the literature review shows that especially the proportion of heavy vehicles has a large impact on capacity, however, the influence of road gradient and the sight distance is quite small. It seems like markings before the roadwork zone and a barrier with paling between the road and roadwork zone, to prevent insight, gives positive effects on the capacity.

The conclusion from the literature review is that the most important variables that should be incorporated in a Swedish capacity manual for the operation and maintenance roadwork are: the proportion of heavy traffic; lane width; type of roadwork; number of closed lanes; closed road shoulder; proportion of commuter traffic; and length of roadwork zone.

3 A Model for Capacity Reduction at Roadwork Zones

The model developed calculates the remaining capacity at work zones based on the capacity on the motorway without the roadwork and a set of correction factors. We therefore start with a short
description on how the capacity on motorway segments is calculated according to the Swedish Capacity Manual (Trafikverket, 2014) and Guidelines for effect calculations (Trafikverket, 2015).

3.1 Capacity at motorway sections in the case of no roadwork zones

The model starts from a base capacity, $C$, which is corrected for the proportion of heavy traffic, divided in trucks without trailers and trucks with trailers. The total flow to passenger car units (pcu) conversion factor is calculated as

$$f_{HV} = \frac{a}{1 + P_T (E_T - 1) + P_{TT} (E_{TT} - 1)},$$

(1)

where:

- $P_T$ = proportion of trucks without trailers and buses
- $P_{TT}$ = proportion of trucks with trailers
- $E_T$ = pcu for trucks without trailers and buses according to Table 2
- $E_{TT}$ = pcu for trucks with trailers in accordance with Table 2
- $a = 0.975$ for sight class 1 and 0.94 for sight class 2

<table>
<thead>
<tr>
<th>Gradient (%)</th>
<th>$E_T$</th>
<th>$E_{TT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 3</td>
<td>1.3</td>
<td>1.7</td>
</tr>
<tr>
<td>3-4</td>
<td>2.0</td>
<td>2.6</td>
</tr>
<tr>
<td>&gt; 4</td>
<td>2.6</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Table 2: Values of pcu for trucks ($E_T$) and trucks with trailers ($E_{TT}$) dependent of gradient.

The capacity in terms of pcu/h, $q_{cap}$, is then calculated as

$$q_{cap} = C \cdot f_{HV},$$

(2)

where:

- $C$ = capacity according to speed-flow relationship (vehicles/h) (Trafikverket, 2015)
- $f_{HV}$ = pcu conversion factor calculated according to equation (1)

3.2 Basic capacity model at roadwork zones

The model for capacity reduction at maintenance work on motorways is based on data and correction factors for different roadwork situation-specific variables from Germany, the US and Denmark. In the model the reduced capacity of a lane that is continuously kept open is calculated as

$$q_{Red} = f_{rs} \cdot f_{co} \cdot f_{nlt} \cdot f_{c50} \cdot f_i \cdot f_{lw} \cdot q_{cap},$$

(3)

where:

- $q_{cap}$ = capacity (pcu/h) calculated according to equation (2)
- $f_{rs}$ = correction parameter for closed road shoulder according to Table 3
- $f_{co}$ = correction parameter for cross over according to Table 3
- $f_{nlt}$ = correction parameter for reduction of the number of lanes according to Table 3
- $f_{c50}$ = correction parameter for commuter traffic according to Table 3

† Sight class is a type of road alignment class used in the Swedish capacity manual, see Trafikverket (2014, 2015)
\( f_I = \) correction parameter for the length of the work zone according to Table 3
\( f_{bw} = \) correction parameter for lane width according to Table 4

The remaining capacity \( q_{red}^i \) is calculated for each remaining open lane, closed lanes are not counted. The correction factor for reduced capacity due to a closed road shoulder, \( f_{rs} \), should only be used for the right lane and not for the other lanes (see comment in the ‘Usage’ column in Table 3). The remaining capacity of the open lanes are aggregated to a total remaining capacity as

\[
q_{red} = \sum_{i=1}^{n} q_{red}^i
\]  

(4)

### 3.3 Correction parameters

The basic correction parameters (used in equation 3) are determined according to Table 3-5. Reduction of commuting traffic should not be used for roadworks with duration shorter than 1-2 weeks. Commuter traffic refers to mornings and afternoons, non-commuting traffic refers to other times including weekends.

Table 3 presents the utilized correction parameter values for closed road shoulder; cross-over; reduction of number of lanes; commuter traffic; and length of road work zone. The values in Table 3 are from the German tutorial (BASt, 2011) except for \( f_I \) that is taken from the Danish Guidelines (Vejdirektoratet, 2010). Table 3 presents the correction factor related to the lane width. These parameter values are from the Danish capacity manual (Vejdirektoratet, 2010), which is based on measurements at various roadwork areas.

<table>
<thead>
<tr>
<th>Correction parameter</th>
<th>Correction factor</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed road shoulder ( f_{rs} )</td>
<td>0.8 (0.9 in combination with other measures)</td>
<td>Reduce the closest lane</td>
</tr>
<tr>
<td>Cross over ( f_{co} )</td>
<td>0.95</td>
<td>Reduce the capacity for the whole roadway</td>
</tr>
<tr>
<td>Reduction of number of lanes ( f_{rnl} )</td>
<td>0.95</td>
<td>Reduce the capacity for the whole roadway</td>
</tr>
<tr>
<td>Commuter traffic &lt; 50 % ( f_{c50} )</td>
<td>0.90</td>
<td>Reduce the capacity for the whole roadway</td>
</tr>
<tr>
<td>Length of roadwork zone &gt; 2000 m ( f_I )</td>
<td>0.95</td>
<td>Reduce the capacity for the whole roadway</td>
</tr>
</tbody>
</table>

**Table 3:** Correction parameters for motorway at various design of roadwork zone. Values based on BASl (2011) and Vejdirektoratet (2010).

<table>
<thead>
<tr>
<th>Average lane width (m)</th>
<th>( f_{bw} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \geq 3.50 )</td>
<td>1.00</td>
</tr>
<tr>
<td>3.25</td>
<td>0.95</td>
</tr>
<tr>
<td>3.00</td>
<td>0.90</td>
</tr>
<tr>
<td>2.75</td>
<td>0.85</td>
</tr>
<tr>
<td>2.50</td>
<td>0.80</td>
</tr>
</tbody>
</table>

**Table 4:** Correction factor for the average lane width of the motorway with roadwork from the Danish capacity manual (Vejdirektoratet 2010).
Since the correction parameters come from different sources it is of great importance to calibrate and validate each of them, but also the combinations. Some of the parameters come from Denmark, which is the neighbor country of Sweden, have broadly the same road design philosophy and driver behavior as in Sweden. This could imply that the correction factors are approximately the same in the two countries.

4 Model verification and validation

The model developed was verified by comparing results from the model and the partly empirical based road work capacities published in the Dutch road work capacity manual (Rijkswaterstaat, 2011). The model was then validated for Swedish road work traffic conditions by conducting a field trial on the motorway E6 in Gothenburg.

4.1 Verification of the model

Table 5 shows four configurations (out of a total of 16 in the comparison) for which capacity reductions have been calculated using the model developed (Equation 3-4). The figure also includes capacity reductions based on the road work capacities presented in the Dutch manual (Rijkswaterstaat, 2011). There are some minor differences but on the whole the two models seem to be consistent. A correlation test of the Dutch model and the modelled correction factors for the 16 different lane configurations results in a correlation coefficient of 0.996, thus it is possible to conclude that the model is applicable for Dutch roadwork zones.

<table>
<thead>
<tr>
<th>Lane configuration</th>
<th>Definition</th>
<th>Correction factor (New model)</th>
<th>Correction factor (Netherlands)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 lanes with right shoulder at normal traffic. - otherwise normal lane width. 90 kph-20 kph</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2 lanes and right shoulder closed. - otherwise normal lane width. 90 kph-20 kph</td>
<td>0.88</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>2 lanes and right and left shoulder closed. - limited lane width in lane 1 (Right lane) 3,00 m and lane 2 (Left lane) 2,75 m. 90 kph-20 kph</td>
<td>0.74</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>2 lanes and lane 2 closed and traffic in right shoulder. - otherwise normal lane width. 90 kph-20 kph</td>
<td>0.78</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Table 5: Examples of comparison of 4 configurations of a total of 16 between correction factor for roadwork zones at motorway for the Netherlands (Rijkswaterstaat, 2011) and the new model for Sweden with parameters based on the US, Denmark and Germany handbooks.
4.2 Validation of the model

To validate the model developed three different road work configurations was tested at a field trial on the E6 in Gothenburg, 29 September 2014. An initial validation was conducted in order to investigate the need for potential calibration of the model parameters. Data from radar detectors in the Motorway Control System (MCS) was used to estimate the capacity in the case of no roadwork for the two field-trials locations. Both visual observations and measurements of speed and flow upstream and downstream of the roadworks were collected. The three configurations selected were (see also illustrations in Table 6):

1. Right lane closed on a 2 lane motorway with hard shoulder
2. Shoulder closed on a 2 lane motorway with hard shoulder
3. Right lane closed on a 3 lane motorway without hard shoulder

<table>
<thead>
<tr>
<th>Configuration Nr.</th>
<th>Lane configuration</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>![Diagram](1lane open and 1 lane closed and no use of shoulder. - otherwise normal lane width. 80 kph-30 kph (50 kph)</td>
<td>1 lane open and 1 lane closed and no use of shoulder. - otherwise normal lane width. 80 kph-30 kph (50 kph)</td>
</tr>
<tr>
<td>2</td>
<td>![Diagram](2 lanes open and right shoulder closed. - otherwise normal lane width. 80 kph-30 kph)</td>
<td>2 lanes open and right shoulder closed. - otherwise normal lane width. 80 kph-30 kph</td>
</tr>
<tr>
<td>3</td>
<td>![Diagram](2 lanes open and 1 lane closed. - otherwise normal lane width. 80 kph-30 kph)</td>
<td>2 lanes open and 1 lane closed. - otherwise normal lane width. 80 kph-30 kph</td>
</tr>
</tbody>
</table>

Table 6: Lane Configurations for the three different test occasions.

This was achieved by testing configuration number 1 and 2 after each other, first the right lane was closed using a maintenance vehicle (configuration number 1) and when measurements were completed for configuration 1 the maintenance vehicle was moved to the road shoulder and then only the shoulder were closed and measurements were collected for configuration number 2. In configuration number 3 there is no hard shoulder and only the rightmost lane was closed. The measurement for configuration 1 and 2 was performed in two steps, both of 20 minutes duration each during peak hour. For configuration 3 measurement were collected during 30 minutes. The measurements in the northbound direction (configuration 1 and 2) were carried out during the morning hours, 06:23-07:11 and the measurements in the southbound direction (configuration 3) during the afternoon hours, 15:30-17:00, according to the schedule in Table 7.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Time</th>
<th>Measure</th>
<th>Place</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>06:23-06:43</td>
<td>Right lane closed</td>
<td>GPS-Coordinit 57.682728, 12.005976</td>
<td>E20 North</td>
</tr>
<tr>
<td>2</td>
<td>06:43-07:11</td>
<td>Shoulder closed</td>
<td>GPS-Coordinit 57.682728, 12.005976</td>
<td>E20 North</td>
</tr>
<tr>
<td>3</td>
<td>15:30-16:00</td>
<td>Right lane closed</td>
<td>GPS-Coordinit 57.674834, 12.010664</td>
<td>E20 South</td>
</tr>
</tbody>
</table>

Table 7: Measure scheme for the three different configurations.

The study required a stretch of 1-2 MCS-portals (~1 km) uninterrupted traffic upstream the measure point and one portal downstream (~0.5 km). The closure was performed by using an arrow at
the VMS-sign on the maintenance vehicle. The speed limit at the upstream portal was decreased to 50 kph and at the portal downstream of the closure the speed limit was set to 70 kph. The speed limit at the site is 80 kph.

The measurement was collected during peak hours and to the point when the capacity had been reached and the average speed had dropped to about 60% of the free flow speed. The assessment was conducted by comparing the flow upstream and downstream to ensure that demand is greater than capacity (flow through the “roadwork zone”). The capacity was then determined as the flow through the roadwork zone. The field trial was also filmed as a back-up to data from the MCS-database, if there where data-loss during the field trial.

Radar detected vehicle data were extracted from the MCS-database. The data was divided by lane and vehicle class of vehicles. Except data from the experiment day, data were also extracted for other days in order to estimate the base capacity of the two sites. For the estimation of the capacity a speed reduction criteria of 40% of free flow speed were used. A total of 8 capacity breakdowns were used to estimate the capacity of the 2 and 3 lane sections, respectively. The capacity for the 2 lane section was estimated as 3650 pcu/h with a standard deviation of 91 pcu/h and the estimate for the 3 lane section was estimated as 5150 pcu/h with a standard deviation of 130 pcu/h.

The reduction in capacity on the basis of the model developed was calculated for all three cases. The model calculated capacity reduction values were compared to the average empirical based capacity reduction, see Table 8. As can be seen in the table, the model predictions are in the same range as the empirical observations. The range in values for the empirical reduction estimates are due to the variation in the estimation of the base capacity (i.e. due to that capacity vary from day to day).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Lane configuration</th>
<th>Model</th>
<th>Empirical confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>North bound am</td>
<td>2 lane with shoulder closed</td>
<td>0.88</td>
<td>0.82 – 0.85</td>
</tr>
<tr>
<td>North bound am</td>
<td>2 lanes with right lane closed</td>
<td>0.45</td>
<td>0.44 – 0.46</td>
</tr>
<tr>
<td>South bound pm</td>
<td>3 lanes with right lane closed</td>
<td>0.63</td>
<td>0.64 – 0.66</td>
</tr>
</tbody>
</table>

1) 95% confidence interval
2) Question mark whether the flow is recovered or not after the first measurement and the capacity was not reached.

Table 8: Empirical reduction and model-based estimated reduction of capacity.

Based on the initial validation there are no indications for need of further calibration of the two correction parameters, closed road shoulder and reduction of the number of lanes. However there where limited empirics, and more empirics are needed to ensure a more trustworthy general conclusion.

5 Discussion

Besides the two validated correction parameters there are five other parameters with different level of validity, see Table 9. The validity was assessed from the difference in road design and driver behavior between the origin of the parameters and Sweden. The estimated validity is also based on the correlation between different studies, and the verification made in this paper.
Table 9: Correction parameters for motorways at various design of the roadwork zone.

<table>
<thead>
<tr>
<th>Correction parameter</th>
<th>Estimated validity</th>
<th>Comment/Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed road shoulder ($f_{rs}$)</td>
<td>Good</td>
<td>Based on the performed validation.</td>
</tr>
<tr>
<td>Cross over ($f_{co}$)</td>
<td>Low</td>
<td>Mainly taken from the German guideline, which are likely assume a standardized motorway design, if there are a deviation from this, the difference is likely to be large.</td>
</tr>
<tr>
<td>Reduction of number of lanes ($f_{nl}$)</td>
<td>Good</td>
<td>Based on the performed validation.</td>
</tr>
<tr>
<td>Commuter traffic &lt; 50% ($f_{c50}$)</td>
<td>Average</td>
<td>Several studies that have produced results in the same range.</td>
</tr>
<tr>
<td>Length of roadwork zone &gt; 2000 m ($f_{l}$)</td>
<td>Average</td>
<td>Only Danish reference</td>
</tr>
<tr>
<td>Lane width ($f_{lw}$)</td>
<td>Average</td>
<td>Only Danish reference</td>
</tr>
</tbody>
</table>

The two most valid parameters, ‘closed road shoulder’ and ‘reduction of number of lanes’, has been validated in a full-scale trial in Sweden and can be considered to have good validity. For ‘commuter traffic’ impact several studies shows approximately the same effect, thus it can be considered to have good validity. The parameters ‘length of roadwork zone’ and ‘lane width’ comes from Denmark, which is a neighboring country to Sweden with approximately the same road design and driver behavior. With this background, the validity of the parameters ‘length of roadwork zone’ and ‘lane width’ is considered average. The least valid parameter is ‘crossover’. The effect of crossover, highly depends on how the rules of temporary traffic control plans are designed and the validity of the crossover correction factor is therefore marked as low.

6 Conclusions and further research

The results from the literature study are sometimes ambiguous, the effects of different variables differs widely between different studies. However, it is possible to distinguish four situation-specific variables that are of most importance. These four variables are; the percentage of heavy vehicles, type of roadwork and the width of the remaining lanes and cross over. The percentage of heavy vehicles have a negative impact on roadwork zone capacity, even type of roadwork, from light rail works to very heavy bridge repair has a negative impact on capacity. An increased width of the lane has a positive effect on capacity. Cross-over is often the part of the roadwork zone that is the bottleneck and therefore is of great importance for the capacity. Also marking and signing before roadwork zone and the shielding between the roadway and the roadwork zone to prevent the insight has a positive effect.

Effects of the duration of a roadwork on capacity are not conclusive. Roadworks with a duration of more than a month shows no significant difference in capacity, and after more than two months there are an increase in capacity in about half the cases, and the other half of the cases shows no significant difference. Consequently there is no clear conclusion on the effect of the duration of a roadwork zone on capacity.

In general the guidelines and handbooks that are used in different countries gives a good estimate of capacity and a good enough average value of the capacity reduction at roadwork zones on motorways. But there is a lack of knowledge of how the different variables that affect the capacity vary between different situations. Various studies (mostly micro-simulations) show that there is a large variance of the impact on the capacity of a variable. This means that the impact of variables on capacity is not clear. In general, there have been (too) few empirical studies focusing on the differences in capacity caused by these situation-specific variables. In the literature, there are two
countries that have progressed further than others in terms of simple models for calculation of capacity at roadwork zones. Both Netherlands and Germany have in slightly different manners developed simple relationships with correction factors for a number of limiting variables. US and UK uses models in which a smaller road networks are represented, making it a bit more complex to quickly estimate the capacity, but that on the other hand gives results also for queue length and delay. Also Denmark has a simple model which includes both motorways as well as two lane rural roads.

The conclusion is that the important parameters that should be treated in a model for Swedish road and traffic conditions should include the following variables, closed road shoulder, reduction of number of lanes, commuter traffic, length of roadwork lane width, and cross over. Also type of roadwork and the time of day that has a focus on the proportion of commuter traffic (habit-road users) are of interest. In a comparison between the Dutch model for the calculation of capacity reduction and the model developed based on a composite of correction factors from Germany, the US and Denmark got essentially the same results, only small differences were observed.

At the field trial in Gothenburg throughput was measured in two cases: morning and afternoon peak hour. The result shows that the empirically estimated capacity reduction is in line with the reduction calculated with the new model developed for the specific roadwork designs. This indicates that the model developed is valid for capacity reduction estimations of roadworks on Swedish motorways.

The various roadwork configurations or correction parameters that are not yet verified should be continuously studied to improve and further validate and if needed calibrate the model. This can be done either using data from the MCS portals available on that particular part of the motorway road network or with video recording which is then used to calculate flows. The crossover is expected to be one of the most important variables that should be calibrated and validated. At cross over, at the start of a roadwork zone, the percentage of trucks, the longitudinal design and width (i.e., the lateral deviation of the crossover) is likely to affect the capacity. The hypothesis is that these parameters play a major role. Also the correction parameter type of roadwork, if it is implemented, is of great importance. A first step would be to study a roadwork zone and verify the model proposed in this paper. A completion would then be using traffic data to calibrate a micro-simulation model and study the flow at different proportions of trucks and geometric design.

A parameter which according to the literature study has major effects is foreclosure of roadwork zone to prevent insight, which in some studies has as much as 10 % increased capacity (Al-Kaisy et.al. 2003). To quantify this correction parameter for Swedish conditions, before and after studies in a number of roadwork zones are needed.

Another issue that needs to be studied in more detail is how the use of various roadwork configurations should look like and what requirements should be set depending on the flow level. This could be developed based on calculations with a macroscopic flow simulation models, e.g. the Calmar-model (Strömgren, 2015), supplemented with delay cost and cost for different designs of roadwork zones. A further important aspect is to study roadwork zones on other types of roads as oncoming separated 2+1-roads, which are significantly affected by roadwork zones.

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