Evaluation Field Trials with Dynamic Speed Limits

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On the Dutch freeway network, speed limits vary. Unless otherwise indicated, a speed limit of 120 km/h applies. On some freeways, there is a fixed speed limit of 100 km/h or 80 km/h, for safety or environmental reasons. In specific situations, speed limits are lowered temporarily. At road works sites, speed limits of 90 or 70 km/h may be imposed, and enforced. Also, on the busiest freeways in the Netherlands, the Motorway Traffic Management System (MTM) operates. The MTM system covers 42% of the freeways and warns road users about congestion and slow traffic upstream, by automatically lowering the speed limit to 70 or 50 km/h. These dynamic speed limits are generally not enforced.

Although dynamic speed limits are already widely applied on Dutch freeways, the Ministry of Transport was interested in other potential applications of dynamic speed limits, in order to achieve policy objectives. Dynamic speed limits, that take account of the current traffic, road and weather conditions, are stated as more credible to drivers than fixed limits. The application of dynamic speed limits was therefore made a part of the Dutch traffic management policy. Another reason to consider the use of dynamic speed limits was the unexpected, extra congestion experienced on two freeway sections where a static 80 km/h speed limit was introduced, and strictly enforced, for environmental reasons. It was thought that increasing the speed limit to 100 km/h during peak hours might help to reverse that situation.

In 2006, the Ministry of Transport commissioned a study into the possible application of dynamic speed limits in the Netherlands. The objective was to gain more insight into the impact of dynamic, tailor-made, speed limits. This resulted in the recommendation to test dynamic speed limits with several objectives: to reduce delays, to increase traffic safety during adverse weather conditions and to improve the air quality. To this end, the Dynamax project was started, and Field Operational Tests (FOTs) were carried out in 2009 and 2010 in on the highways A1, A12 and A58 with various dynamic speed limit applications.

The effects of the tests on traffic flow, air quality, noise levels and driver acceptance were investigated and evaluated extensively, in order to answer several questions:
- How well do road users understand the dynamic speed limits?
- How useful do they judge dynamic speed limits to be?
- How do road users change their behaviour?
- To what extent can dynamic speed limits contribute to policy objectives regarding accessibility, traffic safety and the environment?
- What technical and legal aspects should be taken into account?

The results of the evaluation are used by the Ministry of Transport in the decision making regarding the further deployment of dynamic speed limits in the Netherlands.

This evaluation report presents the five Dynamax field trials that were carried out on four locations. It gives a high level description of the set-up and objectives of each field trial, the different algorithms used, and it discusses the effects found.
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REPORT TEMPLATE

Project Name: Field Trials with Dynamic Speed Limits in the Netherlands

Project Code: CEN32

Area Code: CS212

EasyWay Region: CENTRICO
1. Key Evaluation Results

This section presents a brief summary of the key results related to the EasyWay objectives and any other key results.

The effects of dynamic speed limits were evaluated in five field trials with different main objectives on four locations. The detailed results below are described according to the five main objectives involved.

1.1. Impact on Traffic Flow

The use of dynamic speed limits to shorten the travel time in off peak periods (FOT on the A1) achieves its goal. The speed limit was increased from 100 to 120 km/h during quiet periods of the day.

- Travel time was decreased with 7%; this was beneficial for 39% of road users.
- The resulting increase of NO$_2$ emissions (0.75 µg/m$^3$) and PM$_{10}$ emissions (0.1 µg/m$^3$) is very limited compared to the limits (40 µg/m$^3$).
- The noise level per day increased by 0.3 dB (0.4 dB for the night period) and there was no measurable (negative) impact on traffic safety.

If deployment is considered for this application, the (local) limits relating to air quality, noise levels and traffic safety and communication regarding these issues to residents should be taken into account.

The use of dynamic speed limits to decrease the average travel time by damping or resolving shockwaves (FOT on A12 Bodegraven - Woerden). The speed limit was reduced from 120 to 60 km/h to resolve a shockwave with the following results:

- On average, the algorithm activated a lower speed limit 1.6 times per day, resulting in a reduction of 29 vehicle hours of delay per day.
- The applied algorithm has shown to solve (8%) of the shockwaves and thereby avoiding the emergence of new congestion.
- This resulted in a better throughput, at the test site this lead to a reduction of 1-1.5% of total vehicle hours lost.
- The pre-determined safety indicators during the post-test showed the same or a slightly better value than the base-line measurements. In addition, solving shockwaves in general has a positive effect on traffic safety.
- The reductions in NO$_x$ and PM$_{10}$ concentrations were negligible compared to local background concentrations.
- There was no significant effect on noise levels.
- The traffic congestion algorithm can be extended in such manner that in the future more shockwaves can be resolved.

Use of dynamic speed limits to improve traffic flow while preserving the positive effect of the 80 km/h zone for the local air quality (FOT A12 Den Haag - Voorburg). The speed limit was increased from 80 to 100 km/h at the start and the end of the evening peak period (in between, the speed limit may be reduced to 70 or 50 km/h due to congestion). This resulted in:

- The capacity was increased by 8%.
- Travel times were reduced significantly in the evening peak period (by 1.0-1.8 minutes).
- The average number of vehicle hours lost due to delay decreased by 200-400 per day.
• Change in air quality was very small (smaller than the margin of error of the air quality model used).
• The noise level appeared to increase slightly by 0.2 dB (less than the error margins of the model).
• Traffic safety did not change significantly.

1.2. Impact on Safety

For the use of dynamic speed limits to increase traffic safety in rainy conditions (FOT A12 Bodegraven - Woerden), the deployment of the rain algorithm (during heavy rain, the speed limit was reduced from 120 to 100 or 80 km/h) resulted in:
• A reduction (12 km/h at speed limit 100 km/h and 21 km/h at speed limit 80 km/h) of the average velocity. This reduction was significantly larger than the speed adjustment road users themselves apply in the rain (3 km/h to 8 km/h).
• The highest speeds driven declined in a similar way as the average speeds.
• The pre-determined safety indicators showed a significantly better value during the post-measurements than during the base-line measurements.
• The reductions in NOx and PM10 concentrations were negligible compared to local background concentrations.
• There was no significant effect on noise levels.

1.3. Impact on Environment

The use of dynamic speed limits to improve air quality (FOT A58). The speed limit was reduced from 120 to 80 km/h when PM10 concentrations threaten to reach the daily limit value, resulting in:
• A reduction in the number of days exceeding the concentration norm of PM10 by 1.9 days (from 24.4 to 22.5 days).
• The traffic contribution of particulate matter and NOx emissions appeared to decline by 18%. The effect was smaller than expected because the average speeds remained significantly (10 to 25 km/h) above the speed limit of 80 km/h. In general, the use of dynamic speed limits to reduce the annual number of days the concentration norm is exceeded, can only be successful when the traffic emission as part of the total concentration is relatively high and the current number days in excess of the concentration norm is less than 40. A better chance to succeed has the application of Dynamax for the reduction of the air quality at locations with an excess of the annual average NOx emission norm. This measure has a larger scope of application, because the contribution of NOx traffic emissions to the (measured and calculated) total concentrations is larger.
• Strict enforcement is a prerequisite for effective use of the measure.
• Side effects were an increase in travel time by 10 to 15% and a limited (positive) impact on traffic safety and noise emissions.

1.4. Other Key Results

The driver behaviour research showed that the dynamic speed limit is best observed and understood by displaying the dynamic speed limit on the matrix signs above each lane. It is recommended that at least speeds below 120 km/h (the current speed limit) are displayed on the matrix signs.
Upon further application of dynamic speed limits a uniform use of this measure is recommended. This corresponds to the use of dynamic speed limits in the A12 FOT. The compliance of speed limits on the A1 and A58 may therefore even be larger than measured in these experiments.
An important topic regarding traffic behaviour and human factors is the reduced compliance to speed limits below 100 km/h. This is particularly attributable to situations where the speed limit does not match the current road and traffic situation from a road user’s perspective, a so called 'non credible speed limit'. In such situations compliance can be increased by indicating the reason for the desired speed adjustment on a variable message sign (VMS) accompanied by enforcement. The argumentation for throughput and air quality in such situations must be improved.

Acceptance for the different types of measures in the context of dynamic speed limits is reasonably large or large, depending on the measure. Further deployment of dynamic speed limits will be supported in most cases. Issues to be addressed regarding a nationwide deployment are mainly related to communication, the logic of (the appearance of) the measures and the enforcement of dynamic speed limits.

Based on the evaluation results it was recommended that a plan for further development and application of dynamic speed limits would be developed.
2. Description of the Problem

2.1. Sites

In the Dynamax project, five field trials were carried out on four locations (see figure 2.1 for a map). The four locations were:

- A1 near Naarden (between Amersfoort and Amsterdam)
- A58 near Tilburg
- A12 between Bodegraven and Woerden
- A12 near Voorburg (close to The Hague)

The background of the field trials was not specifically to solve a problem, but the overall objective was to gain more insight into the impact of dynamic, tailor-made, speed limits. The Dynamax project intended to test dynamic speed limits with several objectives: to reduce delays, to increase traffic safety during adverse weather conditions and to improve the air quality.

Figure 2.1: Locations of the dynamic speed trials (left) and information panel at the beginning of the A1 trial section (right)
2.2. Issues Addressed

This paragraph describes, for each of the five trials (at four location), the essentials and issues addressed. In the next chapter, the policy objectives and used systems and technologies are described.

**Field trial A1 near Naarden**
The length of the road segment (one direction) on the A1 near Naarden (close to Amsterdam) is around 6.5 km. It starts with two lanes but for the largest part the road segment has three lanes.
In the Dynamax trial, the speed limit was raised from 100 km/h to 120 km/h if the amount of traffic was low.
The objective of this trial was to shorten travel times for road users and to raise acceptance for dynamic speed limits. This trial on A1 lasted for nine months.

**Field trial A58 near Tilburg**
The trial was held on a 6 km long section of the A58 motorway near Tilburg, in two directions. Most of this section has three lanes (in both directions).
In the field trial, the speed limit was lowered from 120 km/h to 80 km/h on days that traffic has a relatively large contribution to the total PM$_{10}$ concentrations (background concentrations plus the contribution from traffic on the trial section). The speed limit was lowered on the days for which it was expected that the limit value would be exceeded, and on one or two days before that. The speed limit of 80 km/h was chosen because speeds of around 80 km/h are the most beneficial for emissions.
The objective of the field trial on the A58 near Tilburg was to improve local air quality, by decreasing the number of days the legal daily limit value for the concentration of PM$_{10}$ (small particles) is exceeded. In the Netherlands, the daily limit value for PM$_{10}$ concentration (50 µg/m$^3$) should not be exceeded on more than 35 days a year.
The trial on the A58 lasted nine months.

**Field trial A12 Bodegraven - Woerden**
The field trial on the A12 from Bodegraven to Woerden (between Gouda and Utrecht) consisted of two trials which each its own policy objective:
1. Improving throughput by using a shockwave algorithm: lowering the speed limit from 120 km/h to 60 km/h (with intermediate speed limits of 100 km/h and 80 km/h) in stagnating traffic, to ensure a more homogeneous traffic flow and resolve shockwaves at that moment.
2. Improving traffic safety by using a rain algorithm: lowering the speed limit from 120 km/h to 100 km/h or 80 km/h during heavy rain situations.

The trials were held on a 16.5 km long section of the A12 motorway between Bodegraven and Woerden, in one direction. The section has three lanes. At the beginning of the trial section, the N11 highway merges with the A12 freeway. Further ahead, shockwaves occur regularly.
These two trials on the A12 lasted six months.

**Field trial A12 near Voorburg**
The field trial was held on the A12 in the direction from The Hague to Voorburg (a 3 km long section). This road section has three lanes at first, then four lanes. At the end, these four lanes split up into two times two lanes. At the field trial an 80 km/h zone was introduced in 2005. Evaluation showed that on this stretch of the A12 freeway the 80 km/h speed limit (enforced with section control with license plate recognition cameras) has led to poorer throughput. The static and strictly enforced speed limit made it more difficult to change lanes efficiently and therefore reduced the capacity of the weaving section. A higher speed limit during peak
hours might improve the situation, which was the reason for the experiment with dynamic speed limits on this section.

The field trial on the A12 near Voorburg had two objectives:

- Improving throughput by raising the speed limit during the peak period from 80 km/h to 100 km/h.
- Improving acceptance by raising the speed limit during the night from 80 km/h to 100 km/h.

A boundary condition was that the air quality improvement, achieved when the 80 km/h speed limit was introduced, should be maintained. This trial on the A12 lasted six months.
3. Description of the ITS Project

3.1. Service Area

The EasyWay Service areas are:
- Traveller Information Services,
- Traffic Management Services,
- Freight and Logistics Services,
- ICT Infrastructure.

In the Dynamax project, the field trials were intended to gain more insight into the impact of dynamic, tailor-made, speed limits. So, the main focus was on traffic management services.

3.2. Key Words

The following key words (highlighted) describe the nature of the Dynamax project and the applications used.

<table>
<thead>
<tr>
<th>Traveller Information Services</th>
<th>Traffic Management Services</th>
<th>Freight and Logistics Services</th>
<th>ICT Infrastructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-trip Traveller Information</td>
<td>Variable Speed Limits</td>
<td>Freight Management</td>
<td>Data Management and Exchange</td>
</tr>
<tr>
<td>On-trip Traveller Information</td>
<td>Speed Control using ANPR</td>
<td>Vehicle Safety Systems</td>
<td>Traffic Management Plans</td>
</tr>
<tr>
<td>Variable Message Signs</td>
<td>Use of Hard Shoulder Parking Areas</td>
<td></td>
<td>DATEX II</td>
</tr>
<tr>
<td>Highway Advisory Radio</td>
<td>Automatic Incident Detection</td>
<td>Hazardous Goods Monitoring and Tracking</td>
<td>Traffic Monitoring</td>
</tr>
<tr>
<td>Driver Behaviour</td>
<td>Use of CCTV</td>
<td>Transport Security</td>
<td>Control Centres</td>
</tr>
<tr>
<td>Comprehension and Compliance</td>
<td>Ramp Metering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic Management using Rerouting</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Services involved in the Dynamax project
3.3. Objectives

The overall objective of the trials was to gain more insight into the impact of dynamic, tailor-made, speed limits. The Dynamax project tested dynamic speed limits in five trials with the following (different) objectives:

- Improving throughput: travel time reduction by increasing the speed limit during quiet periods of the day.
- Improving local air quality, by reducing the speed limit in case of high concentrations of PM$_{10}$.
- Improving throughput, by reducing the speed limit using a specific shockwave algorithm.
- Improving traffic safety by reducing the speed limit using a specific rain algorithm.
- Improving throughput by increasing the speed limit during the peak period, within a certain air quality restriction.

3.4. Systems and Technologies Applied

The following systems and technologies were applied at the four different trial locations.

Field trial A1 Naarden

Road users were informed about the field trial in several ways:

- There were information panels at the beginning and the end of the road segment, which announced the start and end of the dynamic speed limit: “A dynamic speed limit applies here”. See Figure 2.1.
- A dynamic information panel at the beginning of the trial section with information on the current speed limit (100 km/h or 120 km/h), including a traffic sign with speed limit.
- Electronic rotation signs that showed the current speed limit (at the left and right side of the road).

The algorithm that decided that the amount of traffic is small enough to increase the speed limit, used loop detector measurements of speeds and traffic volumes. When criteria regarding speeds, traffic volumes and other boundary conditions (for example, no road works) were met for ten minutes, the speed limit was changed.

In practice, this meant that during the night, and at quiet moments during the day, the speed limit was 120 km/h instead of 100 km/h.

Field trial A58 near Tilburg

During the trial road users were informed about the field trial in several ways:

- Information panels at the beginning and at the end of the field trial section, including the reason for the dynamic speed limits (“smog”).
- Electronic rotation signs that showed the current speed limit (at the left and right side of the road, including the reason (“smog”). See Figure 3.1.

On some days during the trial, extra enforcement took place. For the entire duration of the trial, warnings that enforcement could take place were given on portable variable message signs.

The algorithm that decides on the speed limit used predictions from the Royal Dutch Meteorological Institute (KNMI) regarding the concentrations of PM$_{10}$ (small particles) five days in advance. The speed limit was lowered when the PM$_{10}$ background concentration was predicted to be over 40 µg/m$^3$ (weekdays) or 45 µg/m$^3$ (weekends) for the next two days. For weekdays there is a higher norm than for weekends because of the higher contribution of traffic to PM$_{10}$ concentrations on weekdays, since there are more trucks on the road on weekdays.
Field trial A12 Bodegraven - Woerden
During the trial road users were informed about the dynamic speed limits in several ways:

- Information panels at the beginning and at the end of the road segment with the announcement (and finishing) of the dynamic speed limit, including the reason for the dynamic speed limits.
- Overhead panels that showed the current speed limit, including the reason ('congestion' or 'slippery road'). See Figure 3.1 (lower speed limit imposed by the rain algorithm).

The shockwave algorithm SPECIALIST was developed by Delft University of Technology. It aims at reducing shockwaves by lowering the speed limit from 120 km/h to 60 km/h, with intermediate speed limits 100 km/h and 80 km/h. The algorithm has a very dynamic character; changes in speed limits can follow each other rapidly.

The rain algorithm lowers the speed limit from 120 km/h to 100 km/h (precipitation intensity over 2.5 mm/h) or further down to 80 km/h (precipitation intensity over 6 mm/h). A precipitation intensity forecast was provided by the precipitation radar of the Royal Dutch Meteorological Institute (KNMI).

Because the shockwave algorithm and the rain algorithm were both implemented on the same road section, an algorithm was added that decided which algorithm got priority, depending on the situation.

Figure 3.1: Rotation signs indicating a lower speed limit due to poor air quality on the A58 (left) and Overhead signs (A12 Bodegraven-Woerden) showing speed limits as imposed by the rain algorithm (right)

Field trial A12 near Voorburg
Road users were informed about the speed limit via electronic overhead signs (such as the ones used on the A12 Bodegraven-Woerden, but in this case only showing the speed limit). The enforcement via section control was adapted in order to deal with the dynamic speed limit.

The algorithm implemented worked as follows:

- Normally, the speed limit is 80 km/h.
- During the day, it switched to 100 km/h when traffic volumes were high (over 3500 veh/h, for a 3/4 lane section) or speeds were low (under 50 km/h). A lower speed limit is still shown when there was congestion (and the Motorway Traffic Management systems took over).
During the night (between 23:00h and 05:00h) the speed limit was set to 100 km/h when traffic volumes were low (under 2000 veh/h) and speeds were higher than 70 km/h.

3.5. Costs

The project costs in rough figures below have been given by the project organisation. This includes the costs for preparation and implementation.

<table>
<thead>
<tr>
<th></th>
<th>A1 Naarden</th>
<th>A58 Tilburg</th>
<th>A12 Bodegraven-Woerden</th>
<th>A12 Voorburg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preparation costs</td>
<td>150,000</td>
<td>150,000</td>
<td>400,000</td>
<td>200,000</td>
</tr>
<tr>
<td>ITS capital investments including installation work</td>
<td>1,200,000</td>
<td>1,200,000</td>
<td>3,200,000</td>
<td>1,600,000</td>
</tr>
<tr>
<td>Annual operating costs</td>
<td>30,000</td>
<td>30,000</td>
<td>80,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Annual maintenance costs</td>
<td>120,000</td>
<td>120,000</td>
<td>320,000</td>
<td>160,000</td>
</tr>
</tbody>
</table>

Table 3.2: Dynamax project costs in € (Euros)

3.6. Status of the Project

At the time of writing (November 2011), the field trials are finished and evaluated. The installed systems and measures are still operational and work properly.
4. Evaluation Planned

4.1. Timing and Type of Evaluation

The evaluation study was carried out ex-post in 2009 and early 2010. The evaluation included traffic related effects and questionnaires among road users. Evaluations used a before and after survey.

4.2. Objectives for the Evaluation

The objective of the evaluation was to determine the effects of the five field trials in terms of traffic flows, air quality, noise levels and traffic safety. Besides, the evaluation was intended to lead to (better) requirements and specification for future design and realisation of the used systems and instruments. Finally, the evaluation among road users had to answers questions related to their behaviour and opinion.

The main question the evaluation of the Dynamax field trials needed to answer was as follows:

What is the effect of applying dynamic speed limits on traffic (throughput, safety and environment), how do drivers change their behaviour, and what is the added value of the dynamic nature of the measure?

4.3. Research Questions

The initial research questions were as follows:

- What are the effects on throughput, air quality, noise levels and traffic safety?
- What are the requirements for design, set up and realisation of the measures:
  - How to communicate the speed limit (static sign, electronic matrix sign, with or without red circle)?
  - Is the measure clear and comprehensible for the road user, both the appearance as well as the reason for the measure?
  - Is enforcement necessary, and if yes, under which conditions and in what way?
- Which instruments are needed:
  - What can be achieved with the existing instruments?
  - Are new instruments necessary?
- Does the road user accept dynamic speed limits?
4.4. Study Area for the Evaluation

The study areas for the evaluation are shown on the map of the Netherlands in figure 2.1 and more detailed in the figures below.

Figure 4.1: The four trial sections: A1 Naarden (upper left), A58 Tilburg (upper right), A12 Woerden-Bodegraven (lower left), and A12 Voorburg (lower right)

4.5. Expected Impacts

For every field trial, research questions were formulated beforehand. An example of a research question is: ‘How does the shockwave algorithm affect safety?’ or ‘What is the acceptance of lowering the speed limit for environmental reasons?’

After formulating the research questions, hypotheses were formulated with respect to five aspects that are of importance for answering the main question (throughput, behaviour, safety, air quality and noise). Examples of hypotheses are: ‘The share of time headways under 1 second stays the same’ or ‘The average travel time is shorter if the speed limit is 120 km/h than if the speed limit is 100 km/h’. These hypotheses describe the expected impacts of dynamic speed limits in detail.

4.6. Used Methods

To test the hypotheses, data were needed from which indicators (for example average speed, time-to-collision) could be calculated. Each indicator gave insight into one or more aspects of the evaluation. Mostly, the same hypotheses and indicators were used for the different trials, to ensure comparability of the evaluation results.
Every trial had three measurement periods in which detailed data were collected. These measurement periods lasted two weeks:
1. Before measurement, to measure the situation on the road before Dynamax was implemented;
2. After measurement 1, to measure the situation on the road just after Dynamax was implemented;
3. After measurement 2, to measure the situation on the road two to three months after Dynamax was implemented. It is assumed that at that time drivers were used to the dynamic speed limits.

Data from various sources were combined to get a detailed and complete view on the changes in the traffic situation. The data used were:
- Aggregated traffic data (speeds and volumes) from loop detectors in the road (“MoniCa data”). These data were collected from all loop detectors on the road sections;
- Traffic data at vehicle level (“RESI” data): loop detector data from which speed, variation in speed, traffic volumes and time headways could be determined on lane level, for three vehicle types. These data were collected at specific locations, usually three to four per trial;
- Video data: on specific locations per trial section, data from cameras were collected to study lane changes, unexpected manoeuvres and possible incidents and accidents;
- Loggings from the algorithm were used to determine when which speed limit applied.

Air quality and noise levels were calculated with legally approved models. Also, air quality and noise measurements took place at specific trial location. For some research questions or hypotheses, additional analyses were carried out, for example the acceptance questionnaires among 500 road users and detailed analyses on the effect of the shockwave algorithm.

Traffic safety indicators, such as the share of critical headways and times-to-collision, were used to determine the effects on traffic safety. Furthermore, accident data were collected from the Dutch national accident database (BRON) for the after period (the complete trial periods of 6-9 months) and a much longer before period (1999-2008). However, as the after period was still short, for statistical analyses of the number of accidents occurring before and after implementation of the measure, no conclusions could be based on these data.
5. The Impact of the Project - Results

5.1. Technical Performance

Algorithms were developed to ‘translate’ the traffic monitoring data into actions to activate the dynamic speed limits according to the specific purpose per trial. Shortly after the first activation of the algorithms, it was evaluated whether the algorithms functioned well, by means of interviews with traffic management centre operators and quick scan analyses of traffic data. Minor changes were made to several of the algorithms.

5.2. Results

The effects of the field trials are summarized in table 5.1 below.

<table>
<thead>
<tr>
<th>Field trial location</th>
<th>Objective dynamic speed limit</th>
<th>Manner in which dynamic speed limit was applied</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 near Naarden</td>
<td>Throughput → travel time reduction</td>
<td>The speed limit was increased from 100 to 120 km/h during quiet periods of the day</td>
<td>Travel times during quiet periods of the day were reduced by 7%. The higher speed limit was beneficial for around 40% of the vehicles that drove on the trial section.</td>
</tr>
<tr>
<td>A58 near Tilburg</td>
<td>Environment → air quality improvement</td>
<td>The speed limit was lowered from 120 to 80 km/h when the concentrations of PM$_{10}$ threaten to reach the daily limit value.</td>
<td>The speed limit was lowered from 120 km/h to 80 km/h for 39 days (14% of the time). The number of days that the limit value for PM$_{10}$ was exceeded was reduced by 2 (annually). Average speed stayed at 10 to 25 km/h above the speed limit of 80 km/h.</td>
</tr>
<tr>
<td>A12 Bodegraven – Woerden</td>
<td>Throughput → resolving shockwaves</td>
<td>The speed limit was reduced from 120 to 60 km/u to resolve a shockwave.</td>
<td>On average, the algorithm activated a lower speed limit 1.6 times per day (mostly to a speed limit of 100 km/h), resulting in a reduction of 29 vehicle hours of delay per day.</td>
</tr>
<tr>
<td>A12 Bodegraven – Woerden</td>
<td>Traffic safety</td>
<td>During heavy rain, the speed limit was reduced from 120 to 100 or 80 km/h.</td>
<td>The average speed was reduced by 9 to 13 km/h (on top of the reduction that drivers would apply without the reduced speed limit). Traffic safety was improved substantially.</td>
</tr>
<tr>
<td>A12 near Voorburg</td>
<td>Throughput → reduction of congestion and travel times, with unchanging air quality</td>
<td>The speed limit was increased from 80 to 100 km/h at the start and the end of the evening peak period (in between, the speed limit may be reduced to 70 or 50 km/h due to congestion).</td>
<td>The capacity was increased by 8%. Travel times were reduced significantly in the evening peak period (by 1.0-1.8 minutes). The number of vehicle hours of delay decreased by 200-400 VVU per day. Change in air quality was very small (smaller than the margin of error of the air quality model used).</td>
</tr>
</tbody>
</table>

Table 5.1: Overview of main results of the five field trials
The evaluation results clearly showed that the application of the dynamic speed limits changed driver behaviour and that they can help achieve policy objectives such as improved throughput, traffic safety and reduced environmental impacts. Undesired side effects were shown to be very limited to non-existent.

The compliance with the dynamic speed limits varied. Table 5.2 shows that overall, acceptance is high. The air quality measure on the A58 is least often found acceptable; a reason for this is that there is no direct impact of poor air quality on drivers. Probably as a consequence of that, the compliance on the A58 was far lower than on the other trial locations. Not surprisingly, acceptance is highest for the dynamic speed as applied on the A1, where the objective was to reduce travel times.

<table>
<thead>
<tr>
<th>Field trial</th>
<th>Acceptance - % of drivers positive about the measure</th>
<th>Usage - % of drivers that encounter an increased speed limit</th>
<th>Usage - % of drivers that encounter a reduced speed limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 Naarden (throughput)</td>
<td>93%</td>
<td>39%</td>
<td></td>
</tr>
<tr>
<td>A58 Tilburg (air quality)</td>
<td>64%</td>
<td></td>
<td>14%-21%</td>
</tr>
<tr>
<td>A12 Bodegraven-Woerden (throughput)</td>
<td>82%</td>
<td></td>
<td>0.06%-0.48%</td>
</tr>
<tr>
<td>A12 Bodegraven-Woerden (traffic safety)</td>
<td>78%</td>
<td></td>
<td>1.4%</td>
</tr>
<tr>
<td>A12 Voorburg (throughput)</td>
<td>80%</td>
<td>33%</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: Acceptance and usage of dynamic speed limits

Effects of “rain algorithm”
The evaluation of the effects of the rain algorithm showed that the measure was successful in lowering the average speed and improving traffic safety. Because the reason for lowering the speed limit is visible for drivers, the average speed changes immediately after the adjustment of the speed limit. The question was whether drivers would adjust their speed more than they would do without a lowered speed limit. Figure 5.1 shows a graph with the average speeds (against intensities) on a cross-section. Average speeds as measured in the before and after period are given as a function of the traffic volume for each speed limit set by the rain algorithm. As the lower speed limits were only shown to drivers in the after period, the lower speed limits in the before period are “virtual” speed limits, i.e. the limit that the rain algorithm would have set if it had already been active. The periods when these virtual limits apply were found by applying the rain algorithm to precipitation intensities given by the precipitation radar in the before period. Figure 5.1 shows that drivers already lowered their speed during heavy rain in the before period. However, they reduced their speed more in the after period, when the drivers saw a lower speed limit and a “slippery road” sign. The extra reduction in the average speed was 9 to 13 km/h, depending on the precipitation intensity and the location. With dynamic speed limits, the reduction in average speed during heavy rain is 12 km/h (speed limit 100 km/h) and 20 km/h (speed limit 80 km/h). Truck drivers also adjust their speed, with 0 to 2 km/h.

Because of the reduction of the speed limit during heavy rain, travel times increase to the same extent as to which the speeds decrease. However, the share of vehicles that encounter lower speed limits is small (1.4%).
The traffic safety indicators determined all suggest that the rain algorithm on the A12 Bodegraven – Woerden improves safety. When speed limits were lowered because of heavy rain (during the after measurements), the average speeds were reduced, the highest speeds (V95, the speed above which the 5% fastest vehicles drive) were reduced as well, with 20-35 km/h. There was a lower standard deviation of the speed, and the share of critical headways and times-to-collision was reduced, compared to the before-measurements.

Because the rain algorithm only set lower speed limits when there is heavy rain (which does not happen very often), air quality and noise levels did not change significantly.

It should be noted that the precipitation thresholds in the current algorithm can only be used for rain. As became clear during the winter of 2009-2010, with an unusual large amount of snow for the Netherlands, the algorithm would need to be adapted to also be able to deal with snow. Lower precipitation thresholds are needed, as well as the ability of the algorithm to distinguish between rain and snow.

**Effects of “shockwave algorithm” (SPECIALIST)**

The effects of the shockwave algorithm were analyzed in two ways. Firstly, the same analyses as for the other field trials were carried out (indicators for acceptance, behaviour, throughput, safety, air quality and noise). Secondly, a detailed analysis was made of each of the shockwaves that the algorithm attempted to resolve. It should be noted that not all shockwaves could be resolved by applying a lower speed limit, for instance because the road section where a lower speed limit was needed was longer than the road section selected (and equipped) for the field trial. In those cases, no lower speed limit was imposed by the algorithm.

An important question was whether road users would be prepared to lower their speeds substantially when the algorithm sets a lower speed limit (the normal limit being 120 km/h, and the lower limit 60 km/h). They do...
not actually see the shockwaves, only the flashers warning for congestion (posted beside the lower speed limit).

The evaluation showed that the measure has an effect on driving behaviour. Drivers do indeed reduce their speed, though not to 60 km/h (and not always immediately). There were hardly any changes in the division of traffic over lanes. Depending on the location and traffic volumes, reductions in average speed of 23 to 40 km/h were found. Trucks also lowered their speed, with about 8 km/h (their normal speed limit is 80 km/h).

The average speeds found at locations and during periods that the speed limit was set to 60 km/h varied substantially between locations. At some locations, averages close to 60 km/h were found, but averages of around 80 km/h were also found. The standard deviation of the speed varied from 10 to 19 km/h.

It was also analyzed whether the fastest drivers would reduce their speeds. The data showed that the V95 was reduced in the same way (relatively) as the average speed (from 130 to 100 km/h). This means that even the drivers with a high desired speed are prepared to reduce their speed.

The objective was to reduce the congestion due to shockwaves by changing driving behaviour. The detailed analysis shows that it is indeed possible to resolve shockwaves by applying lower speed limits. Furthermore, the SPECIALIST algorithm did not result in new congestion.

The algorithm intervened on average 1.6 times per day. In 48% of the interventions, it targeted shockwaves; in 52% of the interventions it targeted other types of congestion. The latter type of interventions was unintended. The cause was, in some cases, a malfunctioning loop detector. In other cases, it was difficult to distinguish between (non-propagating) congestion caused by a specific bottleneck and a shockwave that had just occurred. As a quick detection of shockwaves is important, and the algorithm did not worsen the situation (i.e. cause extra congestion) the unintended interventions were deemed acceptable.

The algorithm intervened once for every ten shockwaves, and resolved approximately 80% of them. In total, the number of shockwaves is therefore reduced by 8%. Of the unintended interventions, the congestion was resolved in approximately 40% of the cases. Every shockwave resolved resulted in a reduction of 39 vehicle hours of delay. The other interventions had a smaller effect. The average intervention reduced the amount of vehicle hours of delay by 18; with 1.6 intervention per day, this meant a reduction of 29 vehicle hours of delay per day. It can be concluded that the algorithm can solve congestion (without creating new congestion) and can therefore help to improve throughput.

The shockwave algorithm was able to solve only a small share of the congestion on the A12 Bodegraven-Woerden. The shockwave algorithm reduced the amount of vehicle hours of delay by 1 to 1.5%. Further extension of the algorithm is possible, so that in the future more shockwaves and possible other types of congestion can be addressed.

The other aspects evaluated did not show major effects. There was a slight improvement in the traffic safety indicators (average speed, V95, standard deviation of speed, share of critical time headways and times-to-collision). Because the lower speed limits were only active during very short periods, there were no noticeable effects on air quality and noise levels.

Effects of “80 km zone algorithm”

This field trial was commissioned when it was concluded that introducing a strictly enforced speed limit of 80 km/h for air quality reasons led to extra congestion on some of the sections. On the A12 motorway, near Voorburg, the 80 km/h limit reduced capacity, especially during evening peak hours. Strict enforcement (section control with license plate recognition cameras) led to very little variability in speeds. It also meant that drivers were less inclined to use the left (fast) lane and that they found it difficult to change lanes. This
was partly due to the homogeneity of the traffic flow, and partly due to the strict enforcement. Drivers did not
dare (for fear of a speeding ticket) to accelerate, even briefly, to overtake the vehicle in the next lane before
merging in front of it.

In the evaluation of the 80 km zones, it was suggested that the speed limit should be set to 100 km/h during
peak hours, which should result in more variability in driving speeds and thus higher capacities. Also, it was
proposed to use the same speed limit of 100 km/h in the night, as traffic volumes are very low during that
period and it would increase the acceptability of the 80 km/h limit during the day. It was expected that the
reduction in emissions from resolving the extra congestion would counteract the increase in emissions from
traffic driving faster in the night, so that the net result would be less congestion at the same air quality and
noise levels.

The evaluation showed that the measure was successful in increasing the capacity of the road and reducing
congestion in the evening peak (see table 5.3). The speeds driven increased when the speed limit was
raised, but the average speed stayed well below the speed limit. The increase was the highest on the left
lane; there, speeds were much closer to (and sometimes over) the speed limit. Even though the speed limit
for trucks remained 80 km/h, an increase in average speed was also found for trucks (about 5 km/h).

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Change shortly after introduction</th>
<th>Change after a few months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle hours of delay (evening peak)</td>
<td>-31%</td>
<td>-65%</td>
</tr>
<tr>
<td>Travel times (evening peak)</td>
<td>-18%</td>
<td>-32%</td>
</tr>
<tr>
<td>Capacity (evening peak)</td>
<td>+4%</td>
<td>+8%</td>
</tr>
<tr>
<td></td>
<td>80 km/h limit</td>
<td>100 km/h limit</td>
</tr>
<tr>
<td>Average speed</td>
<td>75 km/h</td>
<td>80-85 km/h</td>
</tr>
<tr>
<td>Highest speeds (V95)</td>
<td>85 km/h</td>
<td>95-100 km/h</td>
</tr>
<tr>
<td>Speed limit compliance</td>
<td>80%</td>
<td>almost 100%</td>
</tr>
</tbody>
</table>

Table 5.3: Overview of effects found on A12 near Voorburg

The congestion in the evening peak hours almost disappeared. Drivers took a while to get used to this
measure; Figure 5.2 shows how congestion decreased over time.

Figure 5.3 shows how the fundamental diagram changed after the implementation of the dynamic speed
limit. The before-measurements (blue dots) were plotted first, then the measurements of the first after-period
(green dots) and then the measurements of the second after-period (red dots). The red dots clearly show
that the 100 km/h limit works either at low traffic volumes (during the night) or at high volumes (during the
evening peak period). Less easily visible is how the maximum traffic flow (an indication for the capacity of
the road section) changes, but it appears that higher volumes can be found for the after-periods (more so for
the second after-period than for the first). This was confirmed by capacity analyses using the Smulders
function, see also table 5.3. The 5-8% capacity lost after the introduction of the static 80 km/h speed limit
was regained entirely by making the speed limit dynamic.
The dynamic speed limit had a clear impact on driving behaviour. During the night, drivers adapted their speed to the higher limit immediately. However, the average speed was, surprisingly, still well below the speed limit (usually below 90 km/h). In the evening peak, it was more difficult to see how drivers adapted their behaviour. When the limit changed from 100 km/h to 80 km/h (in the morning and after the evening peak), drivers clearly reduced their speeds. When the speed limit went from 80 km/h to 100 km/h, drivers only adapted their speed when the traffic situation allowed it, i.e. when it was not too busy. Speed limit compliance was already high (due to the strict enforcement); when the 100 km/h limit was imposed, it was close to 100%.
During the evening peak, with a speed limit of 100 km/h, the share of vehicles on the left lane increased slightly and fewer vehicles used the middle and right lanes. During the night, the lane choice behaviour hardly changed. The dynamic speed limit resulted in more dynamic lane change behaviour, so that the weaving section was used more efficiently.

The user acceptance study showed that:

- Experienced users were less accepting of the fixed 80 km/h limit than occasional users. About half of the drivers said it was acceptable to drive 80 km/h.
- The increased speed limit during peak hours was received with enthusiasm. Drivers understood that this might help reduce congestion.
- Allowing a 100 km/h speed limit during the night increased the acceptance of a lower speed limit throughout the day.

The measure was expected to have both a positive and an adverse effect on the emissions of NO\textsubscript{x} and PM\textsubscript{10}: less emission due to less congestion, but more emissions because of higher speeds. Calculations of the concentrations of NO\textsubscript{x} and PM\textsubscript{10} were carried out. It was found that the increase during the night was very small, because the amount of traffic in the night that encountered a 100 km/h limit was only 3-4% of all traffic on the A12 near Voorburg (the measure was only implemented in one direction). The situation during the evening peak was more complicated. Part of the section studied saw a substantial reduction in congestion, which meant that any increase caused by the higher speed limit was offset by the decrease due to less congestion. Other parts of the section did not have as much congestion and thus saw a small increase in concentrations of NO\textsubscript{x} and PM\textsubscript{10}. However, the increases calculated were smaller than the level of uncertainty of the models used and, in absolute values, very small compared to the air quality limit values.

Other effects analyzed were noise levels and traffic safety. The increase in noise levels was also calculated and measured to be very small (0.2 dB). Conclusions with respect to traffic safety were very hard to draw. The measurement period was too short to analyze changes in the number of accidents. Speed (and variations in speeds) increased, which might suggest an increase of the accident risk. However, it has to be taken into account that the design speed of the road was 120 km/h, and speeds are still well below that. The tentative conclusion is that, based on all the information available, a slight decrease in safety is expected.

![Figure 5.4: Dynamic speed limit strategy depending on the traffic volume.](image)
5.3. Reliability of Results

See section 5.2

5.4. Research Questions Answered

See section 5.2

5.5. Overall Assessment

A comprehensive programme of field trials with several new applications was carried out in The Netherlands. The objective of the programme was to gain more insight into the impact of variable (dynamic), tailor made speed limits on various policy goals. Innovative solutions were developed, e.g. an algorithm using real time precipitation radar data to lower speed limits in adverse weather conditions and the reduction of shockwaves through the application of a dynamic speed limit algorithm.

The results of the field trials in The Netherlands are quite convincing and demonstrate that dynamic speed limits can be applied to achieve various policy objectives, such as improving throughput, traffic safety and air quality. Road users appreciate the dynamic speed limits and adapt their behaviour accordingly. Undesired side effects were shown to be very limited to non-existent.

The evaluation results of the field trials were reported to the Ministry of Transport in The Netherlands in the fall of 2010. Decision-making on further application of dynamic speed limits is ongoing. Further research is needed before dynamic speed limits can be applied nationwide:

- Selection of the sections of the Dutch freeway network for which dynamic speed limits will apply;
- Selection of the algorithms (rain, shockwave, etc.) to be introduced at each section;
- Formulation of boundary conditions to be taken into account, such as legal boundary conditions, enforcement of dynamic speed limits, etc.;
- Determination of systems specifications;
- Research into the business case for dynamic speed limits, including (societal) costs and benefits.

Below the main finding of the evaluation are summarised in terms of contribution to the European objectives.

5.5.1. SAFETY

Based on the data available, dynamic speed limits have no negative up to a positive effect on traffic safety:

- No measurable (negative) impact on traffic safety was found in the FOT to shorten travel time (A1 Naarden);
- A limited (positive) impact was found in the FOT to improve air quality (A58 Tilburg);
- The safety indicators showed a significantly better value in the FOT of dynamic speed limits under rainy conditions (A12 Woerden-Bodegraven);
- The safety indicators showed the same or a slightly better value in the FOT to reduce shockwaves (A12 Woerden-Bodegraven);
- Traffic safety did not change significantly in the FOT to improve traffic flow while preserving local air quality (A12 Voorburg).
5.5.2. Efficiency

Traffic throughput as a result of the dynamic speed limit field trials did change as follows:

- Travel time was reduced by 7% (beneficial for 39% of the road users) in the FOT to shorten travel time (A1 Naarden);
- Average speeds remained significantly (10 to 25 km/h) above the (lowered) speed limit of 80 km/h in the FOT to improve air quality (A58 Tilburg). Note that there was no strict enforcement. Travel time increased by 10 to 15% as a result of the lower speed limits;
- Average speeds reduced by 12 km/h at speed limit 100 km/h (instead of 120 km/h) and 21 km/h at speed limit 80 km/h (instead of 120 km/h) in the FOT to increase traffic safety in rainy conditions (A12 Woerden-Bodegraven). This reduction was higher than speed adjustments road users apply themselves in the rain (3 to 8 km/h);
- 8% of the shockwaves were resolved in the FOT to reduce shockwaves (A12 Woerden-Bodegraven). This resulted in a better throughput without causing new traffic jams, with an average decrease of 39 vehicle hours lost per dissolved shockwave. At the test site this led to a reduction of 1-1.5% of the total lost vehicle hours.
- The average number of vehicle hours lost during the evening peak decreased significantly from 622 to 215 hours in the FOT to improve traffic flow while preserving local air quality (A12 Voorburg).

No hard conclusions were drawn on the contribution of the field trials on the efficiency, e.g. the return on investment ratio. Specific calculations were not made for this reason.

5.5.3. Environment

In the five field trials, the effects on the environment (both air quality and noise levels) were as follows:

- At the A1 Naarden trial (shortening travel time), small increases were found in NO\textsubscript{2} emissions (0.75 µg/m\textsuperscript{3}) and PM\textsubscript{10} emissions (0.1 µg/m\textsuperscript{3}), but these increases were very small compared to the legal limits (40 µg/m\textsuperscript{3}). Noise levels during the day increased by 0.3 dB (0.4 dB for the night period).
- The number of days when the concentration norm of particular matter PM\textsubscript{10} was exceeded was reduced from 24.4 to 22.5 days in the FOT to improve air quality (A58 Tilburg). The traffic contribution of PM\textsubscript{10} and NO\textsubscript{x} emissions appeared to decline by 18%. Dynamic speed limits to reduce airborne pollution will only be effective when the traffic emission as part of the total concentration is relatively high. A limited (positive) impact on noise emissions was found.
- The reductions in PM\textsubscript{10} and NO\textsubscript{x} concentrations were negligible compared to the local background concentrations in the FOT to increase traffic safety in rainy conditions (A12 Woerden-Bodegraven). There was no significant effect on noise levels.
- The reductions in PM\textsubscript{10} and NO\textsubscript{x} concentrations were also negligible compared to the local background concentrations in the FOT to decrease shockwaves (A12 Woerden-Bodegraven). There was no significant effect on noise levels.
- In the FOT to improve traffic flow while preserving local air quality (A12 Voorburg), the air quality remained the same at one location and increased slightly at two other locations. In the latter case, the higher emission contribution was caused by the higher speed limit. The noise level was calculated to increase slightly by 0.1 dB.
6. European Dimension: Transferability of the Results

The following conclusions can be made regarding the applicability of the results of the Dynamax field trials to other similar implementations in the Netherlands and other countries:

- Dynamic speed limits demonstrate to achieve various policy objectives in a quite convincing way. After this evaluation of 2010, plans were tabled by the Dutch government to increase the regular speed limit of 120 km/h to 130 km/h at 8 sections of the motorway (in total 300 km, July 2011). Together with the results from the Dynamax field trials, this new experiment will provide the experience for a governmental decision as to how and under what conditions a dynamic increase of speed limits will be used in the future.

- As the characteristics of traffic management systems used in other countries are different than the ones used in the Netherlands, field trials with appropriate algorithms are recommended there as well to investigate the impact of dynamic speed limits.