Capacity Building for Sustainable Transport. Optimising the energy use of traffic and infrastructure
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5 CONCRETE model: optimisation of network capacity

5.1 Introduction
The CEMENT module (Construction Efforts to Minimise the Energy Need of Transport) has been established in chapter three. It elaborates on the situation of a single road segment with a predominantly constant traffic intensity. Chapter four upgrades the CEMENT module with some feedback effects. The theory of chapter three has been evaluated in chapter four for a single road segment and in a setting of a road corridor, a several segments comprising chain.

This chapter presents the foundation of the COntrol of Network Capacity to REduce the Transport Energy use, the CONCRETE model. The chapter deduces mathematically road improvement strategies in section 5.2. It develops a numerical model of the theory in section 5.3, which is validated in sections 5.4 and 5.5. A side question in the validation, answered in section 5.5, is whether the network system will behave as a complex system or just as a complicated system. Each road segment has a specific optimal state (i.e. optimal capacity). The network itself has also a specific optimal state (i.e. optimal capacities in an optimal configuration). In a complex system, the systems behaviour cannot be explained by reduction methods alone. The similarity between the energy-capacity characteristics of the individual road segments and the energy-capacity characteristics of the road network is a proxy of the non-complexity of the system. If the system exhibits complex behaviour, the transition paths towards an optimal network configuration are more difficult to generalise and several transition paths might appear possible. Multiple transition paths would be at odds with the theory of optimal control that, by definition, provides a single optimal transition path.

5.2 Theory
5.2.1 System definition
Chapter four (and appendix 4.5 in more detail) defines the link between road segments that together form a road trajectory. To explore the results of a linkage in the road improvement analysis, this section looks at a road trajectory that consists of two independent road segments. The segments are indicated by subscripts 1 and 2. Thus, the respective segment capacities (in vkm/h) are $x_1$ and $x_2$. Mathematically, the additions to the model are represented in equation (5.1) for a road system consisting of two road segments:

$$ F = F_1 + F_2 $$

$$ x = x_1 + x_2 $$

$$ \frac{\partial F}{\partial x} = \left\{ \begin{array}{l}
\frac{\partial F}{\partial x_1} = \frac{\partial F_1}{\partial x_1} + \frac{\partial F_2}{\partial x_1} = \frac{\partial F_1}{\partial x_1} \\
\frac{\partial F}{\partial x_2} = \frac{\partial F_1}{\partial x_2} + \frac{\partial F_2}{\partial x_2} = \frac{\partial F_2}{\partial x_2}
\end{array} \right\} = \min \left( \frac{\partial F_1}{\partial x_1}, \frac{\partial F_2}{\partial x_2} \right) < 0 \quad (5.1) $$

In words: the total fuel consumption (MJ/h) is the sum of the fuel consumption of the individual road segments. As the road capacity definition (vkm/h) includes the length of the road segment, the total road capacity is the sum of the road capacities of the

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80 Many authors comment on the difference between complex systems and complicated systems, see e.g. [Kaneko, 1998; Cilliers, 2000].
individual road segments as well. The theory dictates that the capacity of the road segment has to change as fast as possible to the optimal capacity. For arguments sake, an infinitesimal improvement of capacity will either belong to road segment 1 or to road segment 2. The choice which road segment is to be improved, is now dictated by the theory; the beneficial change in fuel consumption as a result of the improvement should be as large as possible, or the derivative of $F$ to $x$ (which is negative) should be as low as possible. This description is sufficient if the road segments are independent. If they are not independent, the interdependencies of traffic intensity might become relevant. The latter interdependencies are also important if the transport system concerned incorporates more than one modality.

Chapter three describes the development of a single road segment in terms of capacity $x$ and marginal energy benefits of road development $\Psi$. These variables obey the following differential system \(^81\) (repeat of equations (3.22), (3.23) and (3.25) respectively):

$$\dot{x} = \begin{cases} 
-\delta x & \Psi < \alpha \\
-\delta x + a & \Psi > \alpha \\
-\delta x + [0, a] & \Psi = \alpha 
\end{cases}$$

$$\dot{\Psi} = (\rho + \delta)\Psi + \frac{\partial F(x)}{x}$$

This system is at rest if $\frac{\partial F(x)}{\partial x} = -\alpha(\rho + \delta)$

The characteristics of the two-segment-model include:

$x = x_1 + x_2$

$F(x) = F_1(x_1) + F_2(x_2)$

$\Psi = \Psi_1 + \Psi_2$

From the independency of the two segments, it follows that

$$\frac{\partial F(x)}{x} = \frac{\partial F_1(x_1)}{\partial x_1} + \frac{\partial F_2(x_2)}{\partial x_2}$$

Therefore, it shows that $\Psi = \Psi_1 + \Psi_2$, notably:

$$\dot{\Psi} = \dot{\Psi}_1 + \dot{\Psi}_2 = (\rho + \delta)\Psi_1 + \frac{\partial F_1(x_1)}{\partial x_1} + (\rho + \delta)\Psi_2 + \frac{\partial F_2(x_2)}{\partial x_2} =$$

$$(\rho + \delta)(\Psi_1 + \Psi_2) + \frac{\partial F_1(x_1)}{\partial x_1} + \frac{\partial F_2(x_2)}{\partial x_2} = (\rho + \delta)\Psi + \frac{\partial F(x)}{\partial x}$$

---

\(^81\) This description includes the parameters: $a$ (maximum construction effort), $\alpha$ (energy costs of capacity improvement), $\delta$ (road wear rate), $\rho$ (time discount parameter) and $F(x)$ (vehicular fuel consumption).
The matrix representation $x = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$ makes the differential system rewrite as:

$$
\begin{pmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{pmatrix} = \begin{pmatrix}
-\delta x_1 \\
-\delta x_2
\end{pmatrix} (\Psi_1 < \alpha) \text{ and } (\Psi_2 < \alpha)
$$

$$
\begin{pmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{pmatrix} = \begin{pmatrix}
-\delta x_1 + a \\
-\delta x_2
\end{pmatrix} (\Psi_1 > \alpha) \text{ or } (\Psi_2 > \alpha) \text{ and also } \frac{\partial F}{\partial x_1} < \frac{\partial F}{\partial x_2}
$$

$$
\begin{pmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{pmatrix} = \begin{pmatrix}
-\delta x_1 + a \\
-\delta x_2 + [0,a]
\end{pmatrix} (\Psi_1 > \alpha) \text{ or } (\Psi_2 > \alpha) \text{ and also } \frac{\partial F}{\partial x_1} > \frac{\partial F}{\partial x_2}
$$

for all other cases

$$
\dot{\Psi} = (\rho + \delta)\Psi + \frac{\partial F(x)}{\partial x}
$$

5.2.2 *System behaviour*

An infinitesimal improvement of the network capacity is supposed to take place either at segment 1 or at segment 2. The theory states that this improvement should occur at the segment where the highest net energy benefit will be achieved. Essential for achieving the optimal state for the entire network is that the rules that govern this system enable a transition path towards the optimal state. Figure 5.1 illustrates this convergence and shows the direction in which the road network changes given a certain starting position.
The behaviour of the system in the distinctive regions $A$, $B_1$, $B_2$, $C$ and $D$ is, as the regions are defined in figure 5.1:

$A$: road segment 2 has too much capacity, while the capacity of road segment 1 is insufficient. Construction will take place on segment 1, until the system meets the vertical dotted line.

$B_1$: both segments have insufficient capacity, but the energy gain of construction on segment 1 is larger than the possible energy gain at segment 2. Construction will continue at segment 1 until the equilibrium line is reached.

$B_2$: as $B_1$ with the energy gain of segment 2 being larger than that of segment 1. Construction on segment 2 will continue until the equilibrium line is reached.

$C$: as $A$ with segment 1 having too much capacity and segment 2 being insufficiently developed. Construction will take place on segment 2, until the dotted line is reached.

$D$: The capacities of both segments are too large. No construction takes place and the system moves in the direction of the rest point of the entire road network.

From the graph, it is now clear that the system will move towards the equilibrium regardless of the starting position; and the equilibrium is a rest point of the entire system. The equilibrium line of figure 5.2 represents the situations in which improvement of one road has the same effect on total energy use as a similar improvement of a second road. The CEMENT module can numerically calculate this line. Figure 5.2 shows the case in which the transport demand on road segments 1 and 2 are respectively 1500 and 2000 vkm/h and considered fixed throughout the day.

\[
\frac{\partial^2 F}{\partial x^2} > 0 \text{ for all } x.
\]

Figure 5.2 Graphs of equal preference in the case of fixed traffic intensities.

The line of equal preference appears to have two features. The line of equal preference can be approximated be a straight line and the line of equal preference includes the point \((x_1; x_2) = (y_1; y_2)\). Figure 5.3 shows that these properties are enhanced if the CEMENT module uses the distributed approximation on traffic intensities. An explanation of the features is given by the function $F$ that describes the fuel.
consumption of the vehicles on a road segment. Chapter three shows the following formulas:

**Formulas describing the energy use of vehicles**

The fuel consumption of the vehicles is described by:

\[
F(x(t), y(t)) = y(t) \cdot \{-0.730 \cdot (1 - 9.29 \cdot e^{-0.0101 \cdot v_x(t) \cdot y(t)}) - 1.86 \cdot 10^{-6} \cdot v_x(t) \cdot y(t)^3\}
\]

in which the velocity is dependent on the traffic system being in forced-flow or free-flow mode:

\[
v(x, y) = \begin{cases} 
  v_{\text{opt}} + \sqrt{\left(v_{\text{max}} - v_{\text{opt}}\right)^2 \cdot \ln\left(\frac{x}{y}\right) \cdot \ln^{-1} \left(f_{\text{max}}\right)} & \text{for } 0 < y < x \\
  v_{\text{opt}} + \frac{\ell_w y_{\text{opt}}}{2c} \left(\sqrt{x^2 + \frac{4c}{v_{\text{opt}} \ell_w} \left(y^{-1} - x^{-1}\right)} - x^{-1}\right) & \text{for } x \leq y < \frac{v_{\text{opt}} \ell_w}{c}
\end{cases}
\]

The fuel consumption \( F(x, y) \) is the product of the energy use per vehicle \( g(x, y) \) and the total number of vehicles \( y \): \( F(x, y) = y \cdot g(x, y) \). Furthermore, the energy use per vehicles is uniquely determined by the velocity \( v \). Thus, the formula for the fuel consumption rewrites as: \( F(x, y) = y \cdot g(v(x, y)) \)

![Figure 5.3 Graphs of equal preference in the case of distributed traffic intensities.](image)

**Figure 5.3 Graphs of equal preference in the case of distributed traffic intensities.**

Literature gives several descriptions for the relation between the velocity and the capacity and traffic intensity. One of those is the frequently applied BPR function [Bureau of Public Roads, 1964]. It gives the travel time \( t \) on a road link as function of travel time in free flow mode \( t_l \), the capacity \( x \) and traffic intensity \( y \), and two parameters \( \alpha \) and \( \beta \): \( t = t_l \cdot \left(1 + \alpha \left(\frac{x}{y}\right)^\beta\right) \). See also figure 4.20 on page 125. In line with the BPR function, the velocity of the vehicles can be regarded as function of the ratio \( x/y \), as well as its derivative \( \partial v/\partial x \). This unspecified function is denoted \( f(x/y) \). The fuel consumption formula now becomes: \( F(x, y) = y \cdot f(v(x, y)) \). It is possible to show that the line of equal preference is a possible outcome:
This is consistent with the straight line. However, for very congested roads, thus \( x << y \), the CEMENT module does not determine the velocity (and thus fuel consumption) by the ratio \( x/y \). For that reason, figure 5.2 does not show a straight line for low capacity values. Nevertheless, the CEMENT module can use the approximation of the straight line of equal preference to determine on which road the improvement will take place. Instead of a time-intensive comparison of the derivatives, the choice is as following:

Construction will take place on road 1, if \( \frac{x_1}{y_1} < \frac{y_1}{y_2} \)

Construction will take place on road 2, if \( \frac{x_1}{y_1} > \frac{y_1}{y_2} \)

In other cases, construction takes place at both roads, or at neither road.

### 5.2.3 Energy benefits of road trajectory improvements

This section models a network that consists of two road segments, both with a traffic intensities of 2000 vkm/h. The road segments have capacities of 1000 and 1500 vkm/h. An optimised network is a network with constant intensity/capacity-ratios for all road segments. From the values mentioned, it follows that the initial network considered in this section, is not optimised. Figure 5.4 shows the graph \( y \) as function of the total network capacity \( x \). The behaviour between 2000 and 3000 vkm/h is a result of the systems need to move from the initial non-optimal state at \( x = 2500 \text{ vkm/h} \) to the state in which \( x_1/y_1 = x_2/y_2 \) or \( x_1 = x_2 \) since the traffic intensities on both roads are equal.

The graph in figure 5.4 corresponds to the capacity of the entire network, given the initial state of the system. Figure 5.5 shows the development of the single-road capacities. The latter graph clearly demonstrates that the system moves as fast as possible to the optimal configuration \( (x_1=x_2) \).
Figure 5.4 The marginal energy benefits of infrastructure improvement $\gamma(x)$ under the condition of the unbalanced starting condition.

Figure 5.5 Change in single-road capacities as function of network capacity.

This section explained the behaviour of the CONCRETE model, using algebraic descriptions. The conclusions of this section should also appear in more complicated models, thus in a CONCRETE model consisting of more, and not linearly aligned, CEMENT modules. The non-linear alignment requires a routing module. Both the complicated character of the CONCRETE model and the routing module therein are incentives to evaluate the CONCRETE model in an algorithmic setting.
5.3 Algorithmic implementation

5.3.1 CEMENT module

The systems behaviour in a multi-segment network optimisation is described in section 5.2. Figure 5.6 shows the algorithmic implementation in the CONCRETE model. The algorithm starts with a specific network configuration. To improve the network capacity, for every road segment the theoretical energy benefit of a capacity improvement on the network is calculated. The road segment with the highest net energy benefit is then upgraded. To diminish the network capacity, the capacity of the road segment with the least energy benefit is downgraded. A resulting chart of the energy benefits as function of the total network capacity (see e.g. figure 5.14) will show, however, that the starting network configuration might not be reached if one starts from scratch (zero network capacity). This is an implicit result of the starting network capacity being unbalanced. However, the chart is more explicit on the optimal network configuration, given the starting conditions.

5.3.2 Routing module

The possible complexity in the system might arise in the interaction between traffic flows and available capacities. To determine the traffic flows over the network, the cars are assumed to use the fastest route to travel from their origin to their destination over the network. Figure 5.7 shows the algorithm to compute the traffic flows over the network. The two main ingredients for the algorithm are the network configuration and the origin-destination matrix. The latter matrix tells how many cars want to move from a specific origin to a specific destination. The algorithm starts with an empty (i.e. without cars) road network. The first cars (first batch) of each origin-destination relation are allocated on the network. Under the conditions that all speed limits are equal and no travel delays exist that are unrelated to the traffic intensity (e.g. traffic lights), this first batch will use the shortest and thus energetically optimal route
available. Only later batches might encounter travel delays on the shortest route due to
the already allocated traffic volumes, and might decide to use other routes. The first
run of this algorithm produces an initial network occupation.

After the initial run, the algorithm is repeated
once. For every batch, the
shortest route is
determined. In this
second run, every batch
will encounter a non-
empty network.
Particularly the first
batches of the series
might choose a different
route. The greater the
difference between the
desired network state and
the actual network state
(the more unbalanced the
network is compared to
the origin-destination
matrix), the larger the
difference between the
traffic allocation of the
first algorithm run and
the second algorithm run.

The effects of more than
two algorithm runs on the
traffic allocation are
negligible: the traffic
allocation per road
segments varies no more
than two batch sizes for
up to twenty consecutive
algorithm runs.

The effect of the first
algorithm run on the
traffic allocation is shown
in the next figures, in
which the traffic
allocation of the second
algorithm run is shown in italics: Figure 5.8 shows the network configuration with the
assumption that 4000 veh/h travel from origin $A_1$ to destination $B$ and 6000 veh/h
travel from $A_2$ to $B$. One can envision the network by supposing a crowded inner-city
road between junctions 4 and 6 (4→6), a city bypass running from junction 2 to 6 via
5 (2→5→6) and a rural road running from junction 1 to 6 via 3(1→3→6). All speed
limits are set to 120 km/h except for the rural road. Two runs are made: one with road
segment capacities indicated by the bold capacity data in figure 5.8, and one with
capacities indicated by the italic capacity data. The corresponding traffic flow charts are respectively figure 5.9 and figure 5.10.

Figure 5.8 Network configuration with distances (route signs), speed limits other than 120 km/h (speed signs) and capacities (boxes).

Figure 5.9 Computed traffic flows with road capacities written in bold in the boxes of figure 5.8.

Figure 5.10 Computed traffic flows with road capacities written in italics in the boxes of figure 5.8.
5.4 **CONCRETE model: validation of coupled CEMENT modules**

The traffic allocation algorithm is in this section combined with the optimisation routine. After each upgrade of the road network, the traffic flows are reallocated. Figure 5.11 shows the interaction of the traffic allocation loop (routing module) within the road improvement loop (CEMENT module). The output of the CONCRETE model is compared to the expected systems behaviour as described mathematically in section 5.2. Therefore, this section validates the algorithmic CONCRETE model within the definition of section 4.1: determining whether the simulation computer program performs as intended.

Figure 5.11 Schematic overview of the interaction of the routing and CEMENT modules.
In order to validate the systems behaviour, the case of a single road is used as an input for the CONCRETE model: a bidirectional single road of two serially aligned road segments, a trunk road and a motorway, with capacities of 10 000 vkm/h and 40 000 vkm/h. The traffic intensities are 4000 veh/h in one direction and 6000 veh/h in the other direction, see figure 5.12. The system described (figure 5.12) is initially in a non-optimal state. As section 5.2.2 clarified, the system aims for equal ratios of traffic intensity and road capacity. Figure 5.13 shows the analysis graphs for improvement. The system starts at a network capacity of 100 000 vkm/h (left hand side) and moves towards the right. The capacities of the four road segments are shown by the rising graphs on the left axis, and the energy benefits are shown by the declining graph on the right axis. The equal ratios of capacity and intensity being achieved, given the initial capacities, are identifiable in figure 5.13 by the paring of the solid and dotted lines. From that moment onwards ($x > 148 000$ vkm/h), all road segments have equal i/c-ratios. The system will continue to improve until the marginal energy benefits equal the costs, which occurs at a network capacity of $x = 160 000$ vkm/h.

![Figure 5.12 Road segment capacities and traffic intensities for the system under study.](image)

![Figure 5.13 CONCRETE diagram of the single road network of figure 5.12.](image)

The figure is completed for capacities below the initial state of the system by reducing the capacity of the road segment with the lowest marginal energy benefit. Still, the graph has to be ‘read’ from left to right as it considers only improvement of capacity. At extremely low network capacities ($x < 30 000$ vkm/h), the validity of the CONCRETE model is compromised as entire road segments disappear. Conversely, at very high capacities the CONCRETE model might suggest expanding one particular
road until infinity, which is not visible in figure 5.13 (figure 5.17 is an example of the latter phenomenon).

Figure 5.14 Complete CONCRETE diagram of the network of figure 5.12.

5.5 CONCRETE model: validation of routing module

The CONCRETE model is applied on the network of figure 5.8, notably with the bold (moderately balanced) capacities. The traffic flows associated with those capacities were shown in figure 5.9. The network configuration is easily adjustable, as illustrated by the textbox containing the input files for the CONCRETE model.

First, the CONCRETE model runs assuming invariable traffic flows: the traffic flows remain unaffected by the changes in segmental capacities. Figure 5.15 shows the marginal energy benefits and the four regions in which the graph can be distinguished.

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82 The technical explanation is that at a certain high capacity, the marginal effect of capacity expansion on fuel consumption on one road segment is less than the marginal effect on other road segments, due to the already high capacity. It is a self-reinforcing effect. In other words paraphrased, the expansion of a 16-lane highway to a 17-lane highway will probably have little effect on the velocity and thus fuel consumption of the traffic, but the expansion from a single-lane road to a 2-lane highway will have a significant impact and velocity and fuel consumption.
Figure 5.15 Marginal energy benefits of the network of figure 5.8 under fixed traffic flow conditions. The four regions correspond to specific system states, as explained in the text.

Part by part, the meaning of figure 5.15 is as follows: The initial network capacity is 308 000 vkm/h; in the range from 308 000 vkm/h down to 160 000 vkm/h (region II), the capacities of the individual segments are balanced out with respect to the traffic intensities. From 160 000 down to 45 000 vkm/h, the network has a non-optimal but balanced configuration (capacity/intensity ratio equal for all segments), while at capacities lower than 45 000 vkm/h, the CONCRETE model boundaries are violated (both region I), see also figure 5.16.

Figure 5.16 The ratios of capacity versus intensity cf. figure 5.15. The change in trend of the marginal energy benefit curve (black curve), which marks the transition between region I and region II, corresponds with the condition of equal i/c-ratio’s for all road segments (grey curves).
From the initial capacity of 308 000 vkm/h onwards, the road segments with the most unbalanced capacity-intensity ratio are improved first. Initially, it concerns the rural road from junction 1 via 3 to junction 6 (1→3→6) and the urban road between junctions 4 and 6 (4→6). Later, the road between 2 and 6 (2→5→6) is suggested to improve as well (region III). From 410 000 vkm/h onwards, the CONCRETE model suggests to improve only the road from 1 to 4, as capacity improvement of that road constitutes the least damage (region IV).

![Figure 5.17 The ratios of capacity vs. intensity for the regions III and IV, cf figure 5.15.](image)

The optimal state of the network is reached when the marginal energy benefits equal the marginal energy costs. It is assumed that the road network is situated in isotropic surroundings. The marginal energy costs for all road segments are equal and set at α=0.01 TJ·h/vkm. The optimal network capacity, given its initial condition, is 357 000 vkm/h, see also table 5.1.

<table>
<thead>
<tr>
<th>Road segment</th>
<th>Traffic Intensity (veh/h)</th>
<th>Initial Capacity (veh/h)</th>
<th>Optimal Capacity (veh/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1→3</td>
<td>2 467</td>
<td>2 000</td>
<td>3 300</td>
</tr>
<tr>
<td>3→6</td>
<td>2 467</td>
<td>2 000</td>
<td>3 313</td>
</tr>
<tr>
<td>1→4</td>
<td>1 533</td>
<td>4 000</td>
<td>4 000</td>
</tr>
<tr>
<td>2→4</td>
<td>3 467</td>
<td>4 000</td>
<td>4 650</td>
</tr>
<tr>
<td>4→6</td>
<td>5 000</td>
<td>4 000</td>
<td>6 750</td>
</tr>
<tr>
<td>2→5</td>
<td>2 534</td>
<td>6 000</td>
<td>6 000</td>
</tr>
<tr>
<td>5→6</td>
<td>2 534</td>
<td>6 000</td>
<td>6 000</td>
</tr>
<tr>
<td>Network</td>
<td>357 000</td>
<td>308 000</td>
<td>(vkm/h)</td>
</tr>
</tbody>
</table>

The general tendency of the CONCRETE model, to move towards equal capacity/intensity-ratios is adequately demonstrated by figure 5.16 and figure 5.17. In general, the CONCRETE model, like the CEMENT modules, strives for an optimal application for the energy resources. The behaviour of individual car drivers, however, is optimised on travel time, cf. figure 5.7.

Figure 5.18 shows the energy benefit graph of the network under study, with the notion that the traffic flows are recomputed after each change in capacity. Figure 5.19 shows the i/c-ratios. The convergences shown validate the CONCRETE model run to
a great extent. The ratios on the routes $1\rightarrow 3\rightarrow 6$ (rural) and $2\rightarrow 5\rightarrow 6$ (bypass) drop to zero as the intensities do; the i/c-ratios on the other routes converge.

![Figure 5.18 Marginal energy benefit graph, with variable traffic flows. The optimal network state is reached after a capacity improvement of 135 000 vkm/h, as indicated by the arrows. Note that it is determined by the intersection of the marginal energy benefit graph and the marginal energy costs of 0.01 TJ·h/vkm.](image)

![Figure 5.19 Ratios of intensity versus capacity, i.e. the data values of figure 5.20 divided by the data values of figure 5.21.](image)

Figure 5.19 shows the road segment capacities and figure 5.21 shows the traffic intensities on the road segments. An essential difference between the improvement schemes of the case with variable traffic flows (figure 5.20) and with fixed traffic flows concerns the traffic that uses the detour routes ($1\rightarrow 3\rightarrow 6$ and $2\rightarrow 5\rightarrow 6$). In the
optimal configuration, about 70% of the initial traffic intensity on the rural road remains, while no traffic remains in the optimal network state on the bypass 2→5→6.

Figure 5.20 Capacity changes of the road segments in the network of figure 5.8 under the condition of variable traffic flows.

Figure 5.21 Traffic intensities on the road segments as function of the network capacity change.

Figure 5.21 shows interesting behaviour of the system. In the first stage of the capacity improvement, until an increase of 50 000 vkm/h, the city road 2→4→6 is improved. It attracts the traffic from the bypass 2→5→6 until none remains on the latter. At that point, the marginal energy benefits of the improvement of the rural road 1→3→6 are larger than those of the improvement of the city road 1→4→6. As construction activities take place on the rural road, more traffic is attracted from the city road towards the rural road. After 80 000 vkm/h improvement, it becomes more beneficial to improve the urban road 1→4→6. The latter situation does not change, until finally all the traffic flows over the city road and none use the rural road or
bypass. An inefficient temporary improvement of the rural road is the result, as indicated by the shaded area.

Figure 5.22 The differences in marginal energy benefits for the two situations. The grey graph results from traffic flows that do not change after alteration of the capacities. The black graph corresponds to the situation wherein the traffic flows do change after alteration of the capacities.

Figure 5.22 shows the impact of changing traffic flows on energy benefits of capacity improvement. In the case of changing traffic flows, over most part of the range shown in figure 5.21, traffic is slowly diverted from the rural road (1→3→6) to the city road (1→4→6). Furthermore, between network capacity changes of 20 000 vkm/h and 50 000 vkm/h, the traffic is lured away from the energy-intensive bypass (2→5→6) towards the city road (2→4→6). Finally, between an improvement of 160 000 vkm/h and 190 000 vkm/h, the traffic is diverted from the rural road with a quicker pace.

5.6 Conclusion

The CONCRETE model is expanded to include two distinctively different optimisations: an energy optimisation in the CEMENT module and a travel time optimisation in the routing module. First, it includes a capacity improvement routine that optimises the energy use. Second, it includes the traffic flow allocation routine that optimises the travel time of cars. In isotropic conditions, the theoretically fastest route (and thus shortest if speed limits are equal) should be improved. The effect of induced traffic, the attraction of traffic from other routes over this improved road, leads to greater road segment capacities on the short routes. Other roads would, at least theoretically, have to be abandoned in the systems studied in this chapter. In essence, greater capacities do not strictly induce traffic, as they can also counteract any prior diversion due to congestion of traffic. Inducement is shown to have a significant impact on the optimal segmental capacities. One should therefore not only be concerned with the actually occurring traffic volumes, but also with anticipated inducement effects. However, the CONCRETE model does not autonomously reach the optimal network configuration due to the non-optimal behaviour of car drivers in energy terms.
The results show that the rural road is upgraded temporarily and unwarrantedly. It is a direct result of not taking into account the future traffic flows while determining the energetically most beneficial capacity change. The optimal control method, as presented in chapter three assumes a constant future traffic flow or transport demand. The results presented in this chapter are therefore in compliance with the optimal control method. This chapter rather emphasises that changes in future traffic flows as well as the interaction between construction efforts and traffic flows are to be included in the analysis, if one attempts to formulate an optimal construction strategy.

Construction works which are governed by contemporary criteria lead to a non-optimal construction strategy. The aim of achieving the largest marginal energy benefits of capacity change per segment is not necessarily the most optimal construction strategy for the entire network. Therefore, a fundamental difference exists between the application of the optimal control strategy on a road corridor and the application of the optimal control strategy on a road network. Chapter six elaborates on the discrepancy and its consequences in a broader context.