VIRTUAL TECHNOLOGY ASSESSMENT FOR VIABLE POLICY OPTIONS

a System Dynamics approach

by

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Abstract

Since 1980 Technology Assessment (TA) has changed in nature from an analytical tool for technology evaluation, which depends heavily on quantitative and qualitative modeling methodologies, into a strategic planning tool for policy making concerning acceptable new technologies, which depends on participative policy problem analysis methodologies. The goal of TA today is to generate policy options for solutions of organizational and societal problems, which at the operational level utilize new technologies that are publicly acceptable; that is, viable policy options.
After a review of some serious flaws in participative policy problem analysis, prototype modeling for computer simulation is advocated as an alternative methodology for complex policy problem analysis. This methodology has been applied to investigate the viability of the Dynamic Traffic Management technology called ramp metering as a policy option for reducing traffic congestion on the Dutch motorway system. For this virtual TA the prototype model has been specified as a System Dynamics model, which has been used in computer simulation experiments that produced positive results.

1. Introduction

Nowadays western societies are changing with a pace not preceded in history as the result of more quickly available technological innovations based on information technology. At the same time, the number and intensity of exchange relations among people and organizations increase vastly and change rapidly due to ever improving communication facilities. Within this context of techno-economic change, the assessment of new technologies is a policy problem that soon becomes a complex problem due to the growing number of interrelated stakeholders acting within continuously changing social networks (see Smits & Leyten, 1991). Consequently, causes and effects of a complex problem can hardly be distinguished from one another because of a multitude of feedback relations. The definition of causes and effects becomes dependent then on each actor's view of the problem. An actor's view is, however, only a partial conceptualization of the complex problem because of his/her limited cognitive information processing capacity (see Simon, 1985). And this view will be highly subjective because only selected aspects of the complex problem, which affect the actor or its position directly, and the goals, which the actor tries to pursue, will dominate within the set of information that is actually processed. This process of problem definition by stakeholders is called framing of the problem situation and is dependent on their risk perceptions. This framing by a stakeholder has a strong influence on his/her choice between options for solutions (see Faber, 1990).

In order to facilitate the solution of a complex problem, the stakeholders and other actors involved should reach consensus about the problem definition in order to create a shared vision of the problem and its possible solution(s). Such a shared vision is a prerequisite for concerted actions. And concerted actions are a prerequisite for a viable solution of the complex problem. For reaching consensus about the definition of a complex problem and its possible solutions among stakeholders and other actors involved various group problem definition techniques are advocated (see a.o: Vennix, 1996; Mayer, 1997).

Results obtained from experimental psychological research into the effectiveness of such techniques demonstrate the poor quality of the resulting common definition of a complex problem made within a group in terms of knowledge elicitation and utilization (see Stroebe & Diehl, 1994). In addition, Vennix (1990) and Verburgh (1994) obtained results from experimental empirical research that undermine the assumption concerning the relationship between the consensus about the definition of a complex problem and the creation of a shared vision of the problem among the groupmembers. After working on a common definition of a complex problem in reality the groupmembers involved showed no adaptation of their initial individual problem definition to the resulting common problem definition. Scheper & Faber (1995) have argued that the concepts related to each other in a model (or a scheme) representing a common definition of a complex problem may mask the problem definition in operational terms (that is, in terms of empirical indicators) or beyond. This problem arises because the meaning attached to each concept or its operationalization may differ between two individual groupmembers as each individual's meaning depends on his/her own individual context in reality (cf. Faber & Scheper, 1999). As a conclusion it can be stated that currently used group problem definition techniques do not produce a sufficient clue for solving complex problems within organizations or society yet.[1]

The question then becomes how to cope with complex problems when group problem definition techniques are not effective yet? This question is the subject of research presented in this paper. In Section 2 prototype modeling as an approach to defining a complex problem and analyzing options for solutions will be discussed. This approach is applied in Section 3 in order to specify a model of the societal problem of massive daily traffic jams on the Dutch motorway system. This model is used to assess the effectiveness of a dynamic traffic management (DTM) technology called ramp metering. This virtual technology assessment is based on a System Dynamics prototype model of macroscopic flows of vehicles on road segments. The results of this virtual technology assessment are presented in Section 4. Finally, conclusions are drawn about prototype modeling in order to define complex problems and its use in computer simulations for assessing the viability of policy options for solutions.

2. Prototype modeling of complex problems.

With respect to many complex problems the stakeholders and actors involved do not differ very much when defining the core characteristics of the problem at hand but do differ greatly when defining the causes and effects of these core characteristics. For example, when the Dutch government experiences a budget deficit, which is reflected in a growing public debt, then the core characteristics are identified soon enough such as extra governmental expenditures on public health (or social security). But as many direct and indirect causes may play a role in the extra expenditures on public health various stakeholders like patients' groups, (associations of) physicians and medical specialists, hospital directors, health security agencies, employers, etc. will stress another (set of) cause(s) in order to avoid receiving the bill (i.e. the negative effects) of reducing these budget-exceeding expenditures. A way out of this impossibility to define the main causes of the core characteristics of the problem is to turn to prior theory formation and (empirical) research in this subject area. On the basis of prior theory formation and (empirical) research the main causes of the core characteristics may be identified together with their feedback relations in order to model the plausible essentials of the complex problem in reality. These essentials do not represent the complex problem in detail but represent already determined general characteristics of the complex problem. The goal of such prototype modeling is to assess viable general policy options for solutions, which may be worked out later in further detail for specific stakeholders in subsequent research. The approach proposed here is to analyze complex problems in a program of nested research projects with a general prototype model at the top and functionally related detailed models of parts of the problem in reality at the bottom. After each layer of more detailed models is completed and is tested for its validity it can de decided to stop modeling (parts of) the complex problem in further detail because a viable policy option has been assessed. This approach is quite different from the group problem definition approach, which produces a single (detailed) consensus model of a complex problem in reality. Furthermore, the resulting models in the prototype modeling approach are not defined by stakeholders and other actors but only checked by them during the last iterations of each modeling process.

As many complex problems are not or only badly documented with (historical) data statistical analysis of the validity of any model in the research program is seldom an option in policy research. By defining a (prototype) model as a simulation model and using this model in computer simulations various tests on the validity of the model can be carried out. These tests comprise checks on the internal consistency of the model via dimensionality analysis, on its plausibility via analysis of the stationary character of time series of forecasts, and on its reliability via sensitivity analysis. When these checks on the validity of the model do not falsify it then the model can be used in computer simulations to analyze (different) policy measures as options for solutions in order to assess possibly viable measures. The insights resulting from such a virtual assessment of viable policy options, which are specified in one or more layers of models with varying degrees of detail, in order to solve a complex problem may be of great value in terms of avoided costs. These costs result from inconsistent policy options, implausible policy options, ineffective and time consuming field experiments, hazardous field experiments, etc. (cf. Shannon, 1975: 11).

It should be borne in mind that every model, which results from a group problem definition program, a prototype modeling program or another modeling activity, is always an abstraction from reality subject to spurious correlation (cf. Faber & Scheper, 1999). Therefore, even with favorable results from statistical tests of the model's validity and the validity of viable policy options for solutions, the validity and viability of actual policy measures when applied in reality is not beyond doubt. Consequently, it is impossible to speak of a valid model and after repeated testing of reliable a model of a complex problem and its solution(s) but only of a worse or better model of the problem. Statistical tests of the accuracy of predictions and forecasts provide only information about the descriptive power of the model and not about the explanatory power of the model (cf. Faber & Koppelaar, 1994: 425). Paradoxically, statistical testing of a mathematical representation of a model is a bad method for assessing its explanatory power but it is the best method available; validation of the explanatory power of a model on the basis of experts' opinions (including the scientific forum) or problemowners' opinions is a worse method because of the large risk of systematic biases in their opinions due to uncontrollable latent groupthink, various contextual conditions, hidden agendas, etc. Summarizing these remarks, it should be stressed that every model of a problem and its solution(s) is only a helpful instrument in sorting out inconsistent and implausible policy options but that successful effects of consistent and plausible policy options can only be assessed in reality after these policy options have been transformed into actual policy measures.[2]

3. Prototype modeling of traffic jams and DTM technology

Traffic jams on roads occur as the result of traffic congestion. Traffic congestion is the situation wherein a growing number of vehicles on a road segment experiences a decreasing speed ultimately until nil. Many causes of the growing number of vehicles on various road segments can be identified as there are many categories of vehicle owners and vehicle drivers who have all their reasons for being on a road segment. And every category will identify one or more other categories of vehicle users as the main cause(s) of traffic congestion. Reducing traffic congestion on road segments becomes a complex problem then. Consensus among various categories of stakeholders about the core characteristics of traffic congestion will be easily reached, namely too many cars driving on the road segment. But consensus about the main causes of too many cars driving on the road segment is much more difficult to reach if it is possible at all. And if a consensus about the main causes is reached then one can never be sure that the identified main causes are also the main causes in reality. A category of stakeholders, whose interests are given the lowest priority by all other categories of stakeholders, runs a large risk of being defined as the main cause. If this is not the case then the same category of stakeholders may end up in the same situation due to (c)overt coalition formation among the other categories of stakeholders before or during the discussions about the main causes of too many cars driving on a road segment. Thus, the political nature of consensus formation within and between various categories of stakeholders concerning the definition of a complex problem may lead to a problem definition based on interests in causal effects instead of magnitudes of causal effects. This is another reason of why prototype modeling has been applied.

Prototype modeling of traffic congestion is focussed on modeling the core characteristics of this complex problem and its main causes, which are identified in the literature on traffic congestion. When studying traffic congestion one is not interested in a single vehicle driving on a road segment but in all cars driving on that road segment. All cars driving on a road segment can be conceived as a flow of cars, which is represented in a so-called macro-scopic traffic model. In order to model the dynamics of flows of cars on successive road segments subject to entries and sorties, the prototype model of traffic congestion has been specified as a SD model.
The SD model contains three interconnected flows of cars on subsequent road segments. Each flow of cars on a road segment is represented by three interrelated characteristics, namely the occupancy rate of the road segment (BG), the average speed of the flow of cars on the road segment (V)[3], and the intensity of the flow of cars on the road segment (I). V=f(BG) and I=BG*V (see Taylor et al, 1996: 40). On theoretical grounds f(BG) is specified as a third-order polynomial function of BG (see Buisson, 1996). This relationship between V and BG has been estimated by means of the OLS method. The input data have been obtained via random sampling

(N=359064) from daily time series of data on BG and V for 4 road segments of the western motorway around Amsterdam covering the period from June 1994 until May 1996 (provided by the Transport Research Center in Rotterdam). The OLS estimates (with t-values) are as follows (cf. Alkim, 1998: 57).

$$(1) \qquad V_t = \underset{(1658.31)}{120.71} - \underset{(-211.32)}{0.84\,BG_t} - \underset{(-21.25)}{0.001\,BG_t^2} + \underset{(59.19)}{8.40*10^{-6}\,BG_t^3} + \varepsilon_t \qquad R^2 = 0.84$$

However, the predicted value of V_t, i.e. $\hat{V}_t$, becomes negative for $BG_t = 200$ (0• BG_t •200) and $\varepsilon_t = 0$. Within the context of simulation such values of $\hat{V}_t$ are theoretically impossible. For this reason, a predictive function for V_t, which contains only powers of BG_t ($\varepsilon_t = 0$), has been calibrated from (1) that sticks as close as possible to (1) and avoids these problems, namely

$$(2) \qquad V_t = 120.72 - 0.8688\,BG_t - 0.000416\,BG_t^2 + 8.71*10^{-6}\,BG_t^3 \quad .$$

As can be derived from above, successive values of BG in time determine the average speed V of vehicles during the same periods of time, and both variables determine the intensity I of the traffic flow. Successive values of BG_t are outcomes of BG_0 and the subsequent changes in BG_t, i.e. ΔBG_t, when $t > 0$. Any change in the number of cars on a road segment with a length of one (or more) kilometer(s), ΔBG_t, is the result of the number of cars entering the road segment, i.e. $BGin_t$, and the number of cars leaving the road segment, i.e. $BGuit_t$; ΔBG_t, = $BGin_t$ - $BGuit_t$.

In the basic SD representation of the macro-scopic traffic model, the traffic flow on three subsequent road segments has been specified as three flow processes changing $BG1_t$, $BG2_t$ and $BG3_t$ with functional connections between $BG1uit_t$ and $BG2in_t$, and $BG2uit_t$ and $BG3in_t$. $BG1in_t$ functions as the initial source of the 3 interconnected flows and $BG3uit_t$ is their ultimate sink. As the occupancy rates $BG1_t$, $BG2_t$ and $BG3_t$ may differ from one another during the same period of time, the average speeds on the three road segments will vary with them so that each out-flow of occupancy rate may have to accelerate (with $2m/s^2$) or to decelerate (with $-6m/s^2$) when becoming an in-flow of occupancy rate for the next road segment during the next period of time (Vermijs & Middelham, 1995: 39). The need for acceleration by an out-flow in order to adjust its average speed to the average speed on the next road segment has a stimulating effect on the amount of out-flow. The contrary happens when there is a need for deceleration.
Additionally, the maximum occupancy rate[4], that is BGMAX = 200, may put a restriction on the in-flow of vehicles onto a road segment; this happens when $BG1uit_t$ > (BGMAX- $BG2_t$) or when $BG2uit_t$ > (BGMAX- $BG3_t$). And as the SD model runs in STELLA II™, which simulates flows with a fixed time period DT, the SD model has been specified to take into account that it may last longer than one DT before an in-flow of vehicles becomes part of the out-flow of vehicles. This depends, of course, on the average speed of the vehicles on a road segment during successive DT's.

In the SD model ramp metering has been specified as a possibly viable general policy option for solving traffic congestion. Ramp metering is a DTM technology based on information technology. Ramp metering has been specified as an additional measure applied to in-flows of vehicles from ramps onto road segments. It is assumed that the additional in-flow of vehicles from the ramp occurs with the same speed as the average speed on the road segment. The additional in-flow of vehicles from the ramp is defined in terms of an extra occupancy rate to be added to $BG2in_t$ or $BG3in_t$. For $BG2_t$ or $BG3_t$ > 73.5[5] ramp metering equals 1 vehicle per 15 seconds, that is, $BG2Rin_t$ or $BG3Rin_t$ = 0.0011 per second. For $BG2_t$ or $BG3_t$ • 73.5 ramp metering varies between intervals of 15 and 4 seconds between subsequent vehicles entering the road segment from the ramp. The actual interval is calculated from the difference between BGOPT = 73.5 and the actual value of $BG2_t$ or $BG3_t$ minus the actual value of $BG2in_t$ or $BG3in_t$; for example, $(BGOPT - BG2_t) - BG2in_t = BG2Rin_t$. And 3600 seconds divided by $BG2Rin_t*V2_t$ equals the length of the interval in seconds between subsequent vehicles entering from the ramp. When the interval is less than 4 seconds the ramp metering is put off. The in-flow of vehicles from a ramp is specified in the SD model as the additional occupancy rate per Δt (in seconds), i.e. $BG2Rin_t$ /(Δt /3600) or $BG3Rin_t$ /(Δt /3600). These theoretical essentials of the traffic flow on a road have been specified in the STELLA II™ model presented in the appendix to this paper.

4. Results from the SD prototype model of traffic congestion and ramp metering

The SD model has been checked on its internal consistency, on the stationary character of the forecasts calculated by the model, and on the sensitivity of the forecasts with respect to changes in initial conditions of the model. The internal consistency of the model was found to be perfect after checking on dimensionality relations. The regression coefficients in the estimated relationship between V and BG represent decelerations of the average speed of a flow of cars in km/h per extra vehicle on a road segment with a length of 1 km. The stationary character of the forecasts calculated by the model also proved to be perfect in all tests with equal sizes of flows of cars on all road segments modeled. The sensitivity of the forecasts to changes in initial conditions of the model can be inspected in figure 10. The source of the model changes BG1 from 1 until 199 vehicles per km and back. BG2 and BG3 react smoothly to these changes in BG1 as is reflected by the intensities I1, I2 and I3 in figure 10. No explosion, implosion or other unexpected disturbance of I2 and I3 was found. This implies that the model can be considered to be reliable.

In order to test ramp metering for its expected effectiveness and the plausibility of its effects, an experimental design for simulation analysis has been developed. In this design the SD model of the through-flow of vehicles on a road (i.e. 3 successive road segments) is used in experimental runs combining four experimental conditions imposed on $BG1in_t$ and three experimental conditions imposed on $BG2Rin_t$ with and without ramp metering. These conditions have been designed to evaluate the effect of ramp metering on the increase and decrease of traffic congestion on a road including control group experiments (or base runs).

The conditions imposed on $BG1in_t$ are: 1) a constant occupancy rate of 1 vehicle per kilometer of the road, 2) a constant occupancy rate of 60 vehicles per kilometer of the road, 3) a constant occupancy rate of 120 vehicles per kilometer of the road, and 4) a fluctuating occupancy rate from 1 until 199 vehicles per kilometer of the road and back. The conditions imposed on $BG2Rin_t$ are: a) a constant occupancy rate of 0 vehicles per kilometer of the ramp, b) a constant occupancy rate of 30 vehicles per kilometer of the ramp, and c) a fluctuating occupancy rate from 0 until 30 vehicles per kilometer of the ramp and back. Combining both sets of conditions results in 12 experiments, of which experiments 1a, 2a, 3a and 4a represent base runs for the varying initial conditions on the road. For the purpose of evaluation, the base runs 1a, 2a and 3a and the experiments 1b and 1c are not particularly interesting. The other 7 experiments must be carried out for A) without ramp metering and B) with ramp metering. Because the results of experiments 4aA and 4aB will be identical 13 experiments have been carried out.

The executed experiments are 2bA, 2bB, 2cA, 2cB, 3bA, 3bB, 3cA, 3cB, 4aA, 4bA, 4bB, 4cA and 4cB in order to assess the theoretical effects of ramp metering on the through-flow of vehicles (INT_i) under conditions that induce traffic jams on three successive segments (i=1, 2,3) of a road. The results of the selected experiments are presented below (for DT = 5 seconds over a period of 3 hours via 2160 DT's).

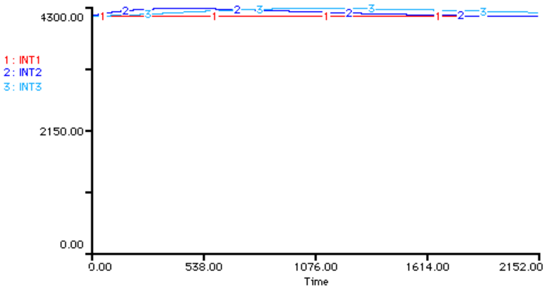

Figure 2. Experiment 2bA

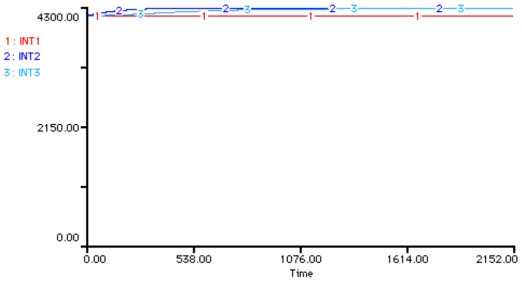

Figure 3. Experiment 2bB

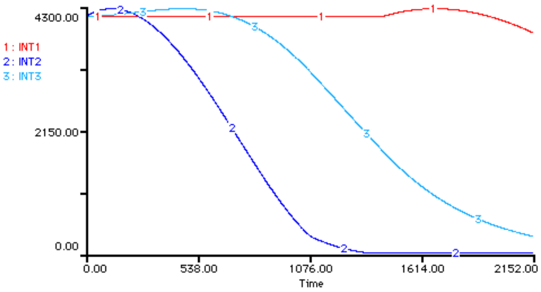

Figure 4. Experiment 2cA

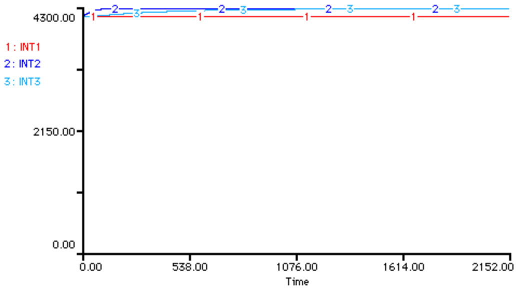

Figure 5. Experiment 2cB

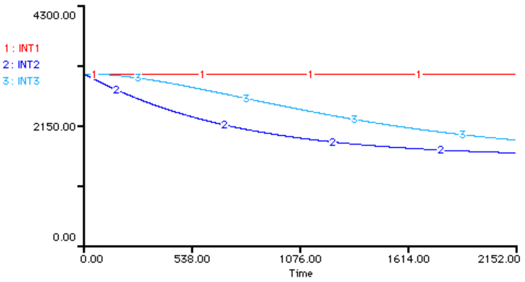

Figure 6. Experiment 3bA

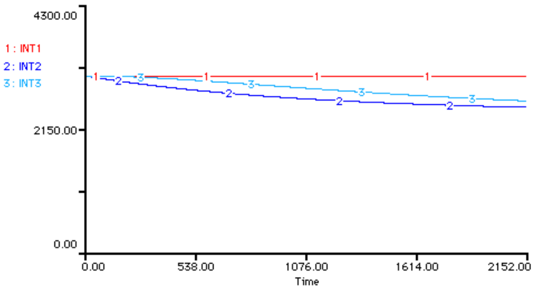

Figure 7. Experiment 3bB

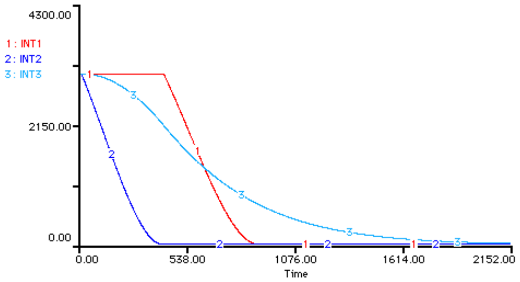

Figure 8. Experiment 3cA

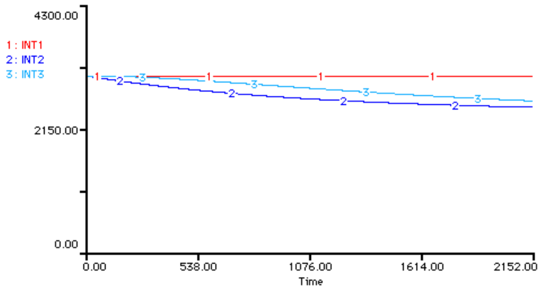

Figure 9. Experiment 3cB

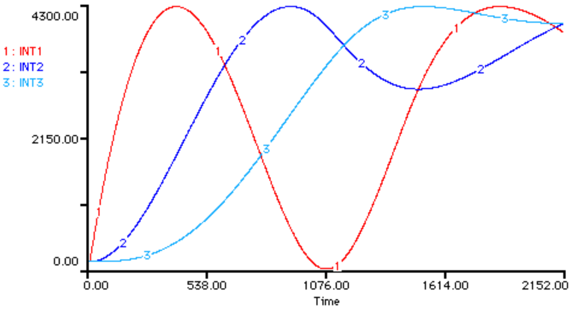

Figure 10. Base run 4a

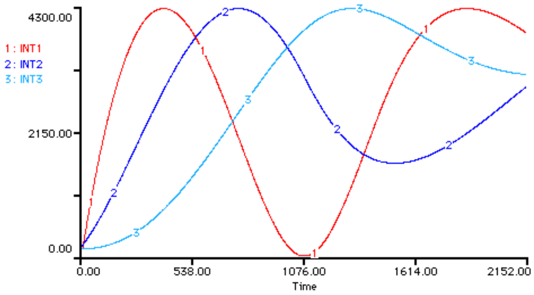

Figure 11. Experiment 4bA

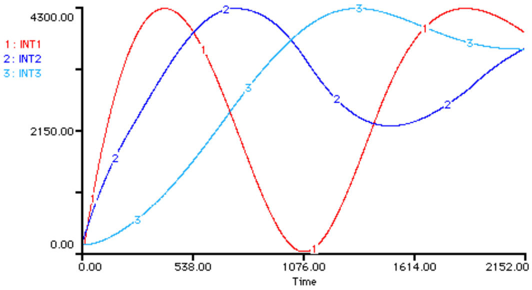

Figure 12. Experiment 4bB

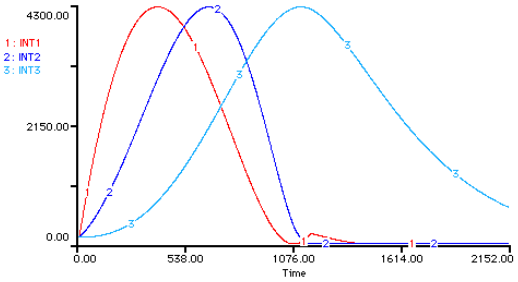

Figure 13. Experiment 4cA

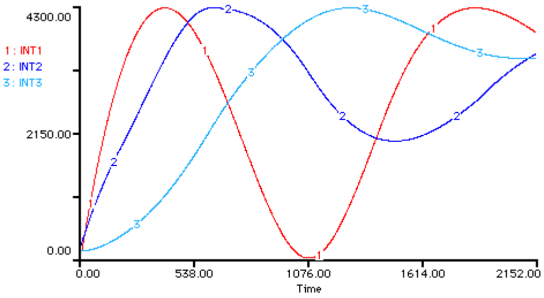

Figure 14. Experiment 4cB

From figures 2, 3, 6 and 7 it can be concluded that in the experiments with constant occupancy rates of the road and constant occupancy rates of the ramp no traffic jams occur. With constant occupancy rates of the road below the optimal occupancy rate of 73.5, the additional in-flow of vehicles from the ramp not even affects the trough-flow of traffic on the road (figure 2). Ramp metering has no impact then on the through-flow of traffic on the road (figure 3). With constant occupancy rates of the road above the optimal occupancy rate, the additional in-flow of vehicles from the ramp creates traffic congestion on the road, which results in less through-flow of traffic on the road (figure 6). Then ramp metering improves the through-flow of traffic on the road (figure 7).

Constant occupancy rates of the road and fluctuating occupancy rates of the ramp result in a complete standstill of the traffic on the road (figures 4 and 8). In these cases ramp metering keeps the traffic on the road going (figures 5 and 9). Turbulence in the in-flow of traffic from the ramp results in traffic jams on the road due to delayed speed adaptations by the flow of vehicles on the road. Ramp metering regulates the turbulence in the in-flow of traffic from the ramp with positive results for the through-flow of traffic on the road.

Fluctuating occupancy rates of the road and fluctuating occupancy rates of the ramp also result in a complete standstill of the traffic on the road (figure 13). Fluctuating occupancy rates of the road and constant occupancy rates of the ramp worsens the through-flow of traffic on the road but not severely (compare figures 10 and 11). In both cases ramp metering improves the through-flow of traffic on the road (figures 12 and 14).

From these experimental simulation results it can be concluded that ramp metering is potentially an effective policy option for solving traffic congestion in general; that is, at the level of the prototype SD model, which represents the traffic dynamics on a road for all categories of vehicle users.

5. Conclusions

If ramp metering is applied to all entries onto those parts of the Dutch motorway system that experience traffic congestion and massive traffic jams every day then the through-flow of traffic on the Dutch motorway system will improve considerably. The price of this improvement will be more traffic on the rest of the Dutch road system as the amount of passenger kilometers traveled by car has grown quickly during the last decade(s) and is also expected to do so in the foreseeable future. Thus, ramp metering will displace traffic congestion from the motorway system to the rest of the road system, where the problem hopefully fades away due to its spatial dispersion.

This result also provides insight into why smoothing shock waves at ramp connections with the main road currently by means of automated speed control installations on large parts of the Dutch motorway system is ineffective especially during rush hours. Automated speed control disperses local traffic congestion at ramp connections to preceding road segments. But when increasing numbers of vehicles occupy subsequent road segments during rush hours then traffic congestion is unavoidable; automated speed control then only delays the occurrence of traffic congestion and traffic jams on roads.

The prototype SD model can also be used to evaluate another at this moment heavily debated DTM technology, namely account driving during rush hours. For this purpose additional information is needed on the shares of various categories of vehicle users in the flow of cars on segments of the Dutch motorway system and information is needed on the expected effects of account driving during rush hours on actual vehicle use of each category of vehicle users. When this information comes available then the prototype SD model must be specified into further detail in order tot take the road use of the distinguished categories of vehicle users into account as well as their cumulative road use for the assessment of the effects of account driving during rush hours on the through-flow of traffic. Then we have a two-layer prototype SD model of traffic congestion.

As a conclusion it can be stated that prototype modeling in combination with computer simulation has been demonstrated to be a powerful alternative to group problem definition techniques, which have been argued to suffer from some serious flaws. Prototype modeling for computer simulation also overcomes some serious flaws in more traditional forms of complex policy problem analysis based on data analysis and/or experts' assessments as mentioned before. Prototype modeling requires almost no data, which is characteristic of most complex problem situations.[6] Nevertheless, it is still possible to test for the validity of the prototype model and its results. This is a clear advantage over validity assessments by experts (or stakeholders) all having their own interests. The same argument holds for the input of information into prototype modeling; prototype modeling relies on reported magnitudes of causal effects and not on communicated interests in causal effects. Future research into prototype modeling for computer simulation will learn us whether or not its acclaimed advantages in complex policy problem analysis hold.

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[1] Opinions of people engaged in group problem definition programs are very favorable about their effectiveness (see Vennix et al, 1993). But the resulting common problem definitions and assessed options for policy solutions are seldom applied in reality for the reasons mentioned. There remains the well-known gap between intentions and deeds of people.

[2] Even then it remains undefined whether the successful effects of policy measures are caused by the measures themselves as predicted by the model or by circumstantial conditions or other factors not considered in the model.

[3] Speed is defined as the space speed and not as the spot speed (see Taylor et al, 1996: 43).

[4] For a road segment of one kilometer and an average vehicle occupancy of 5 meters only 200 vehicles can occupy the road segment.

[5] A BG_t of 73.5 is according to eq. (2) the value corresponding with the maximum intensity of 4270 vehicles. per hour passing through with an average speed of 58.1 kilometers per hour.

[6] If the data on the relationship between V and BG had not been available then a linear relationship between V and BG woolies have been assumed with an intercept equal to the maximum speed allowed on Dutch motorways (120 km/h) and a regression coefficient of -120/200 = -0.6. The results with respect to the effectiveness of ramp metering are not different then.

Appendix: STELLA™ model for experimental ramp metering assessment