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Enforcement in free-flow systems: a case study

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Abstract

Sometimes System Dynamics tools are not suitable for solving dynamic problems although on a high level of abstraction they can be modelled as "stock and flow" diagrams. A typical example is the design of an enforcement schema for a free-flow motorway toll system. This case will be used to discuss how to deal with these problems by starting with a "stock and flow" diagram and then proceeding to implement them as an agent-based simulation.

To do this a graphical backcloth must first be designed which models the relationships between the dynamic and static agents in a topologically correct way. Then the dynamic behaviour of the agents must be formulated, which is possible on the agent level but probably would be too complicated on the aggregate level needed for implementation with common System Dynamics software. Based on a behaviour space generated by simulating key combinations of the design parameters, recommendations for a satisfactory enforcement schema are possible.

Pseudo-empirical data produced by the agent-based simulation could be used to calibrate aggregated behaviour equations suitable for modelling with System Dynamics software tools.

The features of the case

In a free-flow motorway toll system the vehicles which are liable for tolling, usually trucks, have to be equipped with onboard units which count the kilometres travelled on the toll motorway. The onboard units are either GPS/GSM- or microwave-based. The microwave-based technology needs in addition to the onboard units toll gantries in every segment of the motorway. Toll enforcement requires special equipment (1) which can detect vehicles whose onboard units are not properly set. Normally two types of enforcement units are deployed: stationary and mobile units. Stationary enforcement units are gantries permanently installed in some of the segments and equipped with sensors and cameras. Mobile enforcement units may either consist of mobile gantries equipped with sensors and cameras or of monitoring vehicles moving along the motorway, again equipped with sensors to detect toll violators.

The designer of the toll system has to decide in which segments of the motorway stationary enforcement units should be installed and also how many mobile units of which type are needed and in what parts of the motorway they should be applied. His decision has to take into consideration the amount of the fine which a toll violation will incur. The amount of the fine influences the risk which will be acceptable to a potential toll violator. A violator's final decision depends on the inconvenience which violating the toll may cause and the expected risk of the toll being enforced. The expected risk will definitely increase if he has been caught violating tolls once and may decrease if not. The risk expected by non-violators may increase if they notice enforcement acts and decrease otherwise. Violators caught by enforcement may influence the expected risk of neighbours.

In a well-defined enforcement system public opinion will rate enforcement as a deterrent. A toll system acts as a sufficient deterrent if the number of violators is below 5 % of all users and does not increase over time. Furthermore, the deterrent effect should be achieved with minimal expenditures for the installation and operation of the enforcement gantries and equipment.

"Stock and flow" model of the case

The case previously outlined may be modelled (2) as shown in the following Figure 1.

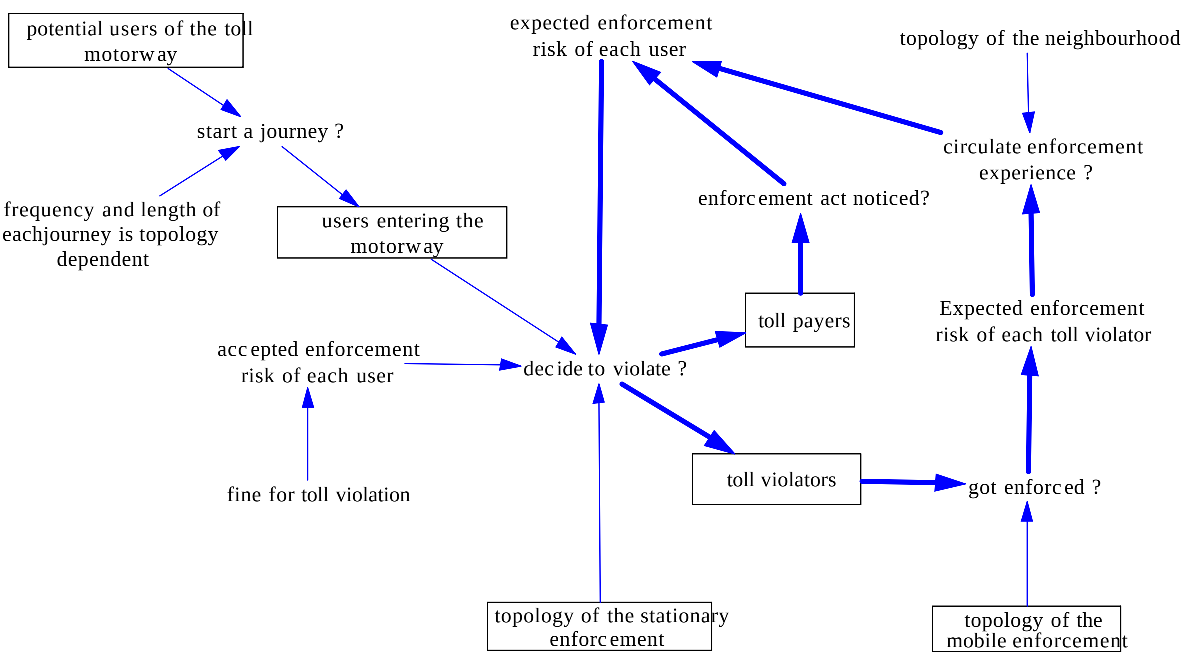

Fig. 1: Toll Enforcement: Top-level "stock and flow" chart

The thick lines define two nested feedback loops driving the number of motorway users who may violate the toll system. The loops display a negative feedback: if violations are not enforced or if motorway users do not notice unexpected enforcement activities at least some of the time, this may increase the number of violators in the future. If an enforcement act is noticed or experienced, the feedback loop will be negative and the number of violators may decrease.

If one tries to implement this model as shown in Figure 1 using a System Dynamics software package one encounters problems which have two causes in common:

- the need to consider topological relationships explicitly;

- the lack of information, or insufficient information, about the behaviour of the components on an aggregated level, even though a fair amount is known on the level of the individual agents.

Without further discussion it can be seen that the topology of the motorway, the distribution of the potential users and the configuration of the enforcement gantries and equipment will have a decisive influence on all flows in the chart. For instance, journey length depends on a truck's home area. The degree of inconvenience experienced by avoiding tolls depends on where a truck starts its journey on the motorway and how many of the stationary enforcement gantries it has to circumvent. The risk of being caught by enforcement depends again on where the journey starts, how long the journey is and what the preferred segments (unknown to the violator) for operating mobile enforcement units are. The efficiency with which experiences with toll enforcement are circulated by a toll violator depends on the number of colleagues a truck driver has in his neighbourhood.

One approach to overcoming these problems at least partly when using a System Dynamics tool would be to split up the users into a set of specific groups depending on their topological positions. In addition one would have to develop stochastic equations which model the behaviour of collectives of truck drivers and reflect the influences of the topology of a specific stretch of motorway and the enforcement units there. This is not only a very demanding task but may bias the problem in such a way that the results gained with the help of the model are misleading. On the other hand, concepts about the behaviour of individuals in comparable situations exist and can be easily adapted, based on episodic or personal experience. Here, as quite frequently, "surface complexity arises out of deep simplicity" (3).

The other approach is to apply an agent-based simulation tool which lends itself in a comprehensive way for modelling topological relationships. It seems that a suitable tool for this purpose is NetLogo (4) which will be applied for the case study in hand. An alternative tool would have been Swarm, a powerful but complicated-to-use collection of C modules now hosted by the University of Michigan.

A simulation model implemented with NetLogo consists of 3 parts:

- Backcloth: a Graphics Window showing the agents, their geometric relationships and the changes during a simulation run
- Program: LOGO-related code which sets up the backcloth and the behaviour of the agents and drives the simulation of their interactions
- Input-Output devices: Buttons, Sliders and Switches to control the simulation and to input values; Charts and Monitors to show the actual state of variables and their development during a simulation run.

Design of the backcloth

The goal of the agent-based simulation model is to study and quantify on a low level of abstraction the influence of different combinations of stationary and mobile enforcement topologies on the number of toll violators. For this purpose a typical stretch of the Austrian motorway system, 150 km long between 2 mid-sized urban areas, each with about 200,000 inhabitants, is modelled. Since January 2004 a free-flow toll system using microwave technology has been in operation on the Austrian motorways and dual carriageways.

The development of an agent-based simulation model starts with the design of the graphical backcloth. First you have to ask who the agents are, what states they may be in during a simulation run and what influences their movement from one state to the next. The diagram in Fig. 1 helps to answer these questions. In our case the agents are the trucks and their drivers using the toll motorway and the toll enforcement installations along the motorway. The states which they may be in are shown too in Fig. 1. The movement of each agent from one state to the next is influenced by some attributes which are either strictly individual to an agent, like the risk a truck driver may find acceptable for violating tolls, or depend on the agent's topological relationship to other agents. For instance, the frequency of journeys and their net lengths depend on the home location of a truck. The circulation of information from one truck driver to his neighbours about enforcement experiences gathered during the last trip depends on the density of truck home locations.

The actual design of the backcloth has to consider two aspects: which topological relationships require geometrically correct modelling and which do not, and how those aspects which are of particular interest during a simulation run can be visualised graphically.

A screenshot of the Graphics Window of the simulation model after the first few time steps of a simulation run is shown in Fig. 2.

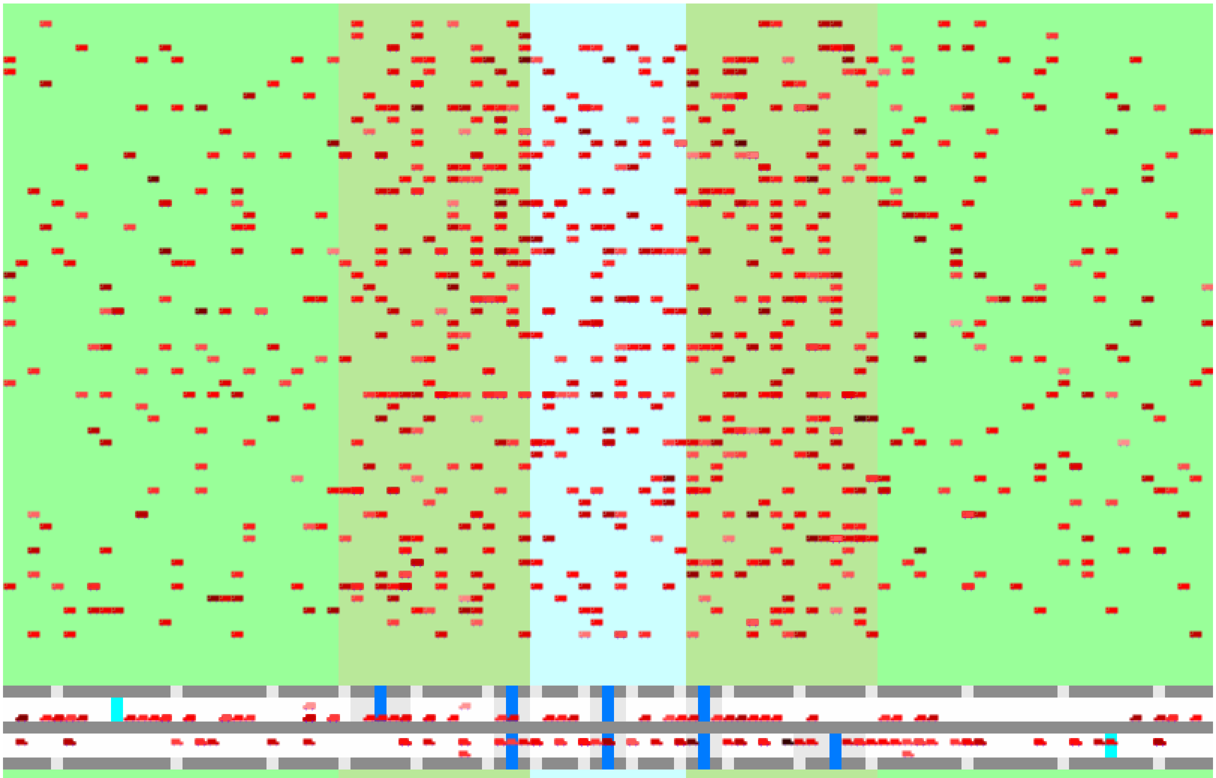

Fig. 2: Screenshot of the backcloth

The graphic consists of 101 x 65 so called patches. It is horizontally divided into two areas. The lower area of the graphic shows the westbound and eastbound directions of the motorway, their lanes and segments. The upper area shows the home locations of the trucks in three differently coloured zones. The light-blue zone in the middle symbolises the core area of the city, flanked on both sides by an industrial belt in khaki. The rest, belonging to the rural and sparsely populated area between the two cities, is shown in green.

The dots in the upper area of the graphic symbolise the trucks, the potential users of the motorway. They are distributed over the zones reasonably realistically: in the industrial-belt area the truck density is high, in the rural and sparsely populated area low. The truck colours symbolise the risk their drivers expect of encountering enforcement if violating a toll on their next journey. Dark-red coloured trucks have drivers with high-risk expectations; drivers of light-red trucks expect a low risk.

The motorway shown in the lower area of the graphic consists of segments with different lengths. The segment lengths are again modelled reasonably realistically and are multiples of patches. Since a patch is about 1.5 km long in reality, a truck travelling at 70–80 kph will take about 1–1.2 minutes to pass a patch. Patches in blue symbolise stationary enforcement gantries, those in cyan mobile enforcement units. The positions of the mobile units change during a simulation run.

When a truck starts a journey on the motorway, it is transferred from its home position vertically down into one of the directions on the motorway. There it moves forward one patch for every time step (tick) until it comes to the end of its journey, from where it is transferred back to its home position. Trucks moving off the left border enter the graphic again at the right border and vice versa.

Trucks on the motorways move either in the right or left lane. Trucks which violate tolls are put into the right lane and trucks which don't into the left lane. The toll violators are hidden when they pass a segment with a stationary enforcement gantry, because they will have to circumvent this segment so as not to get caught. A truck's colour may change during its journey. When a toll-violating truck passes a mobile enforcement unit, the risk expectation of its driver will increase and the truck colour will turn a darker red. The same happens, although to a lesser degree, with a truck which does not violate tolls but passes mobile enforcement units.

A toll violator back in his home location will circulate among his neighbours the experiences gathered during his last journey. As a result the colour of his neighbours' trucks may change in the graphic.

Behaviour of the agents

From a modelling point of view you need to distinguish between two types of behaviour. For the first type statistical data exist which allow formulation of behaviour equations by algebraic means. This kind of behaviour is mostly exogenously forced on to the agent; in our case the start and length of journeys belong here. The second type of behaviour is mainly endogenously driven by the aspirations and similar attitudes of the agents. Agents change their behaviour only after they have had to change their relevant levels of aspiration. This type of agent behaviour is best modelled using simple step functions. Everything in connection with the decision to violate tolls belongs here.

Every time step a number of trucks is selected randomly from their home positions for a motorway journey either on the westbound or eastbound lane. Trucks in the industrial area will start journeys more frequently because there are more trucks in that area than in the other two areas.

The length of a journey is calculated with a random-normal function truncated on the left side with a mean value depending on the area where the truck has its home location. This takes into consideration that short journeys are more frequent than longer ones. The mean journey length is relatively short for trucks starting in the central area and long for those starting in the rural or sparsely populated area. Very long journeys may wrap around the graphic more than once.

The values of some of the parameters, e.g. number of trucks in the areas, topology and length of the motorway segments, number and length of journeys, can be found in or derived from statistical material about the motorways and truck traffic on them. For instance, it is known that in any given normal work hour about 25 % of all truck-driving potential motorway users will be on a journey and that their mean journey length on the motorway will be about 75 km.

Agents accept some risk of being caught for violating a toll. This risk depends on the amount of the fine for a toll violation. It is modelled with a random-normal distribution and stays constant for a truck over a whole simulation run. In addition, every truck or truck driver has a risk expectation of being caught for violating a toll, which at the start of a simulation run has a random-normal distribution but will change based on experiences gathered during a journey. A driver will consider violating a toll only if the expected risk of encountering enforcement is lower than the accepted risk. The decision of a driver to violate a toll depends furthermore on the difference between the number of all segments to be passed in the course of his journey and the number of segments with stationary enforcement gantries which he will have to circumvent so as not to get caught. Only a very absent-minded, silly or reckless toll violator would enter a motorway segment where he knew a functioning stationary enforcement gantry was installed.

During his journey a driver will adapt his risk expectation. He will increase it if he has passed a stationary enforcement unit and may decrease it if he hasn't. Violators increase their risk expectation much more after encountering enforcement than do non-violators. Furthermore, when at their home location again, violators will spread their adapted risk expectation to neighbours who will adapt their risk expectations accordingly, although in a less marked fashion.

Due to the novelty of the toll technique modelled here, only anecdotal or second-hand information is available about the behaviour of the agents involved. Some information may come from records about truck-related violations of traffic regulations on motorways. Other information has to be estimated intelligently using general benchmarks. The design of the behaviour equations and their parameters is based mainly on common knowledge. It is a relatively simple and straightforward task using step functions because the agents in this instance are concrete and not abstract entities. To model this sort of behaviour for a collective of agents, as would be needed if implemented with a System Dynamics software tool, would be a very demanding job indeed.

The process of calibration of the behaviour parameters and the validation of the whole model is supported by the dynamic presentation of the truck movements and the changes in their colours in the graphics window. The development of interesting variables can be followed visually thanks to output monitors and charts. Moreover, the simulation can be stopped at any time to analyse the parameters of individually selectable trucks or patches. But, as always with simulations, it takes time and many trial runs to calibrate the model so that it does not violate known facts and behaves in a plausible fashion.

Generating the behaviour space

The enforcement system for a toll motorway consists of the fines which toll violators have to pay if caught and of devices to prevent and/or to detect toll violations and to identify those who are responsible for the violations. In our case these devices are stationary enforcement gantries and/or mobile enforcement units. For every one of these devices there are several alternatives. An indicator of their effectiveness is the mean percentage of violators after installation and operation over a certain period. To determine the effectiveness of the alternatives or combination of alternatives the behaviour space of the case has to be evaluated.

The Cartesian product of the alternatives for the fines, the stationary and mobile enforcement devices – the so-called dimensions – defines the behaviour space. To reduce the number of simulation runs to a reasonable amount only a few alternatives for every dimension need to be considered.

The amount of a fine can vary between a minimum and a maximum value. Below the minimum, which is about 20 % of the toll charge for the journey, at least 50 % of all drivers would not care if fined after violating a toll. The maximum value for fines must bear a reasonable relationship to the damage done by violating a toll. It should not be above 300% of the toll charge for the journey. Otherwise drivers and related interest groups would start fighting the whole toll system by taking any penalty which is slightly questionable to the courts, and the working relationship with the toll operator would break down. The alternatives "low", "medium" and "high" are considered for the fines.

Stationary enforcement gantries are built and operated in segments where a large amount of traffic on short journeys can be observed or in segments near the national borders where it would be inconvenient for many of the potential violators to circumvent these segments. In our case three alternatives are sufficient: the first alternative is not to have any stationary gantries, the second is to install a few mainly in the core area ("standard"), and a third is to use twice as many as in the second alternative located in the core and the industrial-belt areas ("extended").

Mobile enforcement units are normally more expensive to operate than stationary ones and therefore should be used sparingly. In our case five alternatives are considered. The first alternative is not to use any mobile enforcement units, the second is to operate two in the rural and sparsely populated areas only (called "2 peripheral"), the third is to operate two in the industrial-belt or core areas ("2 central"), the fourth is to operate alternatively two in the rural and two in the industrial-belt or core areas ("2 central or 2 peripheral"), and the fifth is to operate alternatively two in the rural and four in the industrial-belt or core areas ("4 central or 2 peripheral"). This defines a behaviour space with 3 x 3 x 5 = 45 cells. The most plausible and probable values will be applied for those parameters of the behaviour equations which cannot be deduced empirically. The same random seed is used for every alternative.

NetLogo allows running every combination of alternatives unattended for a fix number of time steps or until some condition is met. Here a limit of 5000 time steps is used, which produces reasonably stable values for the mean percentage of violators for every run. By observing the emerging patterns and their colours in the graphic of the backcloth during a simulation run, additional information and unexpected insights may be gained.

In a real-life study with a less idealised backcloth more alternatives and more time steps may be needed to support reliable conclusions.

Fig. 3, which shows the mean percentage of violators for every cell of the behaviour space, gives a superficial impression of the effects of the alternatives and their merits. From these numbers it seems that the deterrent effect of stationary enforcement units is not sufficient and that in some circumstances mobile enforcement units may be enough if they can be operated at reasonable cost and without seriously disturbing the free flow of traffic on the toll motorway. Further evaluation should be concentrated on those cells of the behaviour space which are marked green in Fig. 3. Here is not the place to discuss in detail the results of the simulation runs and their implications for the optimal configuration of enforcement systems.

Mobile Enforcement	Stationary Enforcement	Low Fine	Medium Fine	High Fine
None	None	58.3	53.2	43.5
None	Standard	50.0	45.8	37.3
None	Extended	37.5	33.8	27.4
2 peripheral	None	8.9	6.0	2.5
2 peripheral	Standard	6.0	4.1	1.5
2 peripheral	Extended	5.9	3.6	1.3
2 central or 2 peripheral	None	6.4	3.8	1.2
2 central or 2 peripheral	Standard	5.3	3.4	1.0
2 central or 2 peripheral	Extended	3.7	2.4	0.7
2 central	None	5.3	3.8	1.7
2 central	Standard	4.4	3.0	1.2
2 central	Extended	2.4	1.7	0.6
4 central or 2 peripheral	None	0.6	0.3	0.03
4 central or 2 peripheral	Standard	0.6	0.3	0.03
4 central or 2 peripheral	Extended	0.6	0.3	0.03

Fig. 3: Behaviour Space: Mean Percentage of Violators

Before a final decision can be reached another behaviour space should be evaluated, this time with only one dimension for the alternatives but explicit dimensions for some behaviour parameters. The measures of this space would be needed to test the sensitivity and stability of the results of the most promising alternatives.

Some final remarks

This case study aims to show that a class of dynamic problems exists for which System Dynamics thinking and its tools are suitable for sketching a meta-model but not for implementing it in sufficient detail. It is essential for these problems to provide detailed modelling of topological relationships. Concepts of, experience with and data for their behaviour equations are available only for low-level agents and not in aggregated form. Agent-based simulation software packages like NetLogo, which was used in this case study, are appropriate tools for implementing simulation models to support the understanding of and solution to these problems.

It lies in the nature of agent-based simulation that a great many details have to be taken care of in implementing the backcloth and the behaviour of the agents. Without a System Dynamics meta-model it is easy to get sidetracked and to overlook the dynamic feedback loops.

Agent-based simulation models produce a great amount of detailed data. These data may be interpreted as pseudo-empirics and can be used to generate and calibrate high-level behaviour equations, which could then be used to implement the problem as a standard System Dynamics model. To what extent such pseudo-empirical data are a substitute for real-world data and how statistical sampling theory methods would be applicable requires further study.

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