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Optimisation of toll levels in networks: an optimal toll design framework, using a pattern search approximation algorithm

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Within the world of traffic engineering, road pricing is widely accepted to be a measure that can contribute to the solution of several problems in the present traffic system: congestion, environmental damage, use of unsustainable recourses, use of space, etc. Road users, the government, and neighbours of roads are the most important stakeholders of these problems. Although some successful practical applications of road pricing exist (for instance Singapore, London, Stockholm), no large scale implementation of road pricing exists in the world yet. The Dutch government has decided to implement road pricing in the whole country, starting in 2011. In order to be able to influence the traffic system, this road pricing system will be able to handle time and space differentiation of tolls. An important question that rises from this quality is where and when the tolls should have which particular value. This thesis investigates this question.

A stakeholder analysis for the Dutch context confirms the Dutch government's idea: in the Netherlands, a need for a time and space differentiated fare per kilometre exists. The system must have a predefined maximum value and should be clear and comprehensible for the public. The price needs to be differentiated to the vehicle's environmental characteristics. The differentiated road pricing system can be used to influence the traffic system in order to achieve a range of policy objectives, which are assumed to benefit the society as a whole. For example, the minimisation of total congestion, minimisation of average travel time, or minimisation of vehicle emissions.

In order to gain more insight in the problem of optimal toll design, it is formulated as a mathematical program. The policy objectives are made quantitative in the form of objective functions. In this formulation the value of the objective function depends on the space and time differentiated toll levels. Some of the stakeholders' demands are formulated as mathematical constraints. The problem is formulated as a bi-level problem. The upper level consists of the road authority which aims to minimise an objective function, in this case the average travel time in the traffic system.

Upper level
Optimisation problem
System objective function minimisation
Design constraints

Lower level
Optimisation problem
Individual objective function minimisation: user equilibrium
Constraints: flow conservation, flow propagation, non-negativity.

Solving this mathematical program is not a trivial case, because the traffic model is treated as a black box and one function evaluation takes a lot of computation time. Based on the problem's previously mentioned characteristics, a local search algorithm has been selected to approximate the solution of the optimisation problem, namely pattern search.

Application of different variants of the pattern search algorithm to the case study showed that it is possible to achieve considerable improvements in the value of the average travel time. From all tested variants, one which monitors improvements performed best in terms of average travel time value, within a reasonable computation time. Another variant which adapts a few different tolls at the same time, performed well in terms of computation time, within a reasonable achieved value of the average travel time. The tests also showed that multiple local minima exist, with many of them having approximately the same average travel time value. So by means of the policy objective, these toll settings are roughly the same. Other political arguments, like the expected revenue of these toll settings, can determine which exact toll setting is to be implemented. It cannot be guaranteed that this applies to other networks, but this research gives an indication that when a local minimum is found, the average travel time is close to the optimal value.

The result of this research is a practical modelling framework for the approximation of optimal toll design. Restrictions to computational power make that at this moment it is not yet possible to approximate highly differentiated tolls in big networks with the proposed modelling framework. The approximation of very roughly differentiated tolls on bigger networks seems possible, which is promising when the space and time differentiation will be designed for the Dutch road pricing system.