A Hybrid Micro-simulator for Determining the Effects of Governmental Control Policies on Transport Chains

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Abstract. A simulation-based tool is described which will be used to investigate how the actors in a transport chain are expected to act when different types of governmental control policies are applied, such as, fuel taxes, road tolls, vehicle taxes and requirements on vehicles. The simulator is composed of two layers, one layer simulating the physical activities taking place in the transport chain, e.g., production, storage, and transports of goods, and another layer simulating the different actors' decision making processes. The decision layer is implemented by a multi-agent system where each agent corresponds to a particular actor and models the way it acts in different situations. The simulator will be used for analyzing the costs and environmental effects, and will in this way provide guidance in decision making regarding control policies. In addition, it will be possible for companies to use the simulator in order to determine cost-effective strategies given different (future) scenarios.

1 Introduction

This paper describes a simulation-based tool with the aim to investigate how the actors in a transport chain are expected to act when different types of governmental control policies, such as, fuel taxes, road fees, vehicle taxes and requirements on vehicles, are applied. The policy making is driven by a desire to attain a sustainable environment (by reducing emissions, noise, accidents, and so on) and to achieve sustainable economical development. From a societal perspective, the simulator will be used to analyze the total costs and environmental effects of a transport chain and in this way provide guidance in decision making regarding control policies. The intention is that such analyses will complement those made using existing macro-models. In addition, it will be possible for businesses to use the simulator in order to determine cost-effective strategies given different (future) scenarios.

In the next section we further motive the need for the type of tool suggested and review some related work. We then describe the problem domain, the structure of the simulator, and a small case study. A discussion and pointers to future work concludes the paper.

P. Davidsson et al. (Eds.): MABS 2004, LNAI 3415, pp. 236 – 247, 2005.

2 Background

The importance of being able to predict the effects of governmental control policies can be illustrated by the *marginal cost principle*. According to this principle, the external costs of transports, such as, emissions, road wear, congestion, noise, accidents etc., should be internalized. It has been argued that the current fees and taxes for heavy transports do not correspond to the actual external costs caused by these transports [5]. To apply the marginal cost principle it is necessary to change some taxes, fees, or regulations. But in order to know which action(s) to take, it is important to have deep knowledge regarding the effects of these actions, i.e., how the different actions will change the behavior of the actors involved in transport chains. This is important in order for policy makers to take a long term perspective supporting sustainable growth of trade and industry. From the perspective of the actors in a transport chain, they need to develop strategies for acting given different future implementations of control policies.

2.1 Existing Simulation Models for Transport Systems

Traditionally, the effects of control policies have been studied using *macro-level* models, such as SAMGODS (SAMPLAN) [9], ASTRA [1] and SISD [6]. These models are taking a societal perspective and are based on aggregated course-grained data on the national level. A problem with these models is that they do not take the logistical processes into account, e.g., choice of carrier type and inventory strategies, and thus fail to model the level where the decisions regarding the actual transports are taking place. Models that take logistical aspects into consideration are for example SMILE [10], GoodTrip [2] and SLAM [6]. However, these models cannot take specific properties of individual transport chains into account. Due to (increased) cooperation between actors in transport chains (e.g., producers, customers, transport operators), there exists a significant flexibility of how to carry out their operations given different control policies. We believe that more precise predictions regarding the effects of control policies can be achieved using micro-level models, i.e., transport chain level models, that capture also the decision making of the actors in the logistical processes.

2.2 Multi Agent Based Simulation for Policy Making

As Multi Agent Based Simulation, MABS, and other micro simulation techniques, explicitly attempts to model specific behaviors of specific individuals, it may be contrasted to macro simulation techniques that are typically based on mathematical (equation-based) models where the characteristics of a population are averaged together and the model attempts to simulate changes in these averaged characteristics for the whole population. Thus, in macro simulations, the set of individuals is viewed as a structure that can be characterized by a number of variables, whereas in micro simulations the structure is viewed as emergent from the interactions between the individuals. According to Parunak et al. [7] "…agent-based modeling is most appropriate for domains characterized by a high degree of localization and distribution and dominated by discrete decision. Equation-based modeling is most naturally applied to systems that can be modeled centrally, and in which the dynamics are dominated by physical laws rather than information processing." Obviously, transport systems fulfill all the characteristics of domains appropriate for agent-based modeling.

As an example of an application of MABS for policy making, consider Downing et al. [4], who have used it in the context of climate policy and climate change. A prototype agent-based integrated assessment model was proposed for water issues like drought, flood etc. where the social relations that support the effectiveness of exhortation are described. Downing et al. argue that MABS is well-suited for this purpose since agents represent the behavior of different actors, here policy makers and households, and the interaction between the agents can therefore be described and evaluated. Also, since MABS can represent different grains, couplings to macro-models can be done.

3 The Problem Domain

The general area investigated is decision support for public policy makers in the area of transportation and traffic. In particular we study the question: What would the consequences be in a transport chain[1] given a certain policy? We envision a simulation-based decision support system were a policy maker is able to experiment with different types of fees, taxes, requirements on vehicles, etc. and get feedback from the system regarding the predicted effects of these policies.

The consequences of public control policies on transport chains are closely connected to the decisions made within the chain, such as, choosing mode of transportation, carrier size, when to transport, which quantities to transport. These decisions are made by different actors at different levels in the chain and may have implications on the system which are rather hard to anticipate.

In general a transport chain can be organized in a number of different ways with respect to the owner of the products at different locations and to the decision makers organizational belonging, e.g., the transport could be carried out by either the seller, buyer or third party logistics operator. The decision making in transport chains is subject to both short- and long-term planning implying that the time dimension of the decisions needs to be considered when modeling the transport chains. We will assume that the decision makers (actors) are cost minimizers locally with only minor exploration of potential cost savings achievable by cooperation in the transport chain. This appears to be rather typical in transport chains today, e.g. a customer orders a certain quantity to be delivered at a particular time and date. However, we also plan to incorporate market-based cooperation between the simulated actors allowing for a behavior which approaches a system optimal behavior. This represents the ongoing development in transport chains, e.g. negotiations of when and of which quantities to deliver to the customer occurs in order to reduce costs of production and transportation.

[1] We avoid the term supply chain, since it implies indirectly that a customer view is taken, i.e. to supply a customer, rather than a system view. Also, our focus is on transports, whereas production and consumption provides the context in which the transports take place.

The input to the simulator is:

- the transport tasks, i.e., a sequence of customer requirements
- the available transport resources and their characteristics, such as costs, capacity, and environmental performance
- the available production resources and their characteristics
- the available infrastructure, e.g., road and rail networks
- the location of producers, customers, storages, etc.

Given this task, the user of the simulator will be able to experiment with different control policies, by varying a number of parameters corresponding to different taxes, fees, regulations etc.

The output will then include (among other things):

- performed transport operations
- the estimated external costs (including environmental costs)
- society revenue (from taxes, fees, etc)
- the internal costs
- customer satisfaction measured in terms of reliability of deliveries and quality of products.

4 The Simulator

We have chosen a hybrid approach, where an agent-based approach has been used to simulate the decision making activities, and a more traditional object-oriented micro-level approach has been used to simulate the physical activities. This is illustrated in Fig 1 and further described in the remaining part of this section.

4.1 Physical Simulator

The physical simulator is based on the description of the production and distribution network suggested by Davidsson and Wernstedt [3]. It simulates the physical level of the production and distribution of commodities, whereas the decisions for what to produce, where to store the commodities, fleet management, etc. are simulated by the decision making simulator.

There are four basic types of entities in the simulator that makes up the production and distribution: nodes, links, transport carriers and commodities. A *node* is a producer, an internal distribution node, or a customer, and has the following attributes:

- production capacity for each commodity,
- production level (dynamic, i.e., the value may change during the simulation),
- storage capacity (volume) for each commodity type,
- inventory level (dynamic),
- load time for each carrier type, and
- unload time for each carrier type.

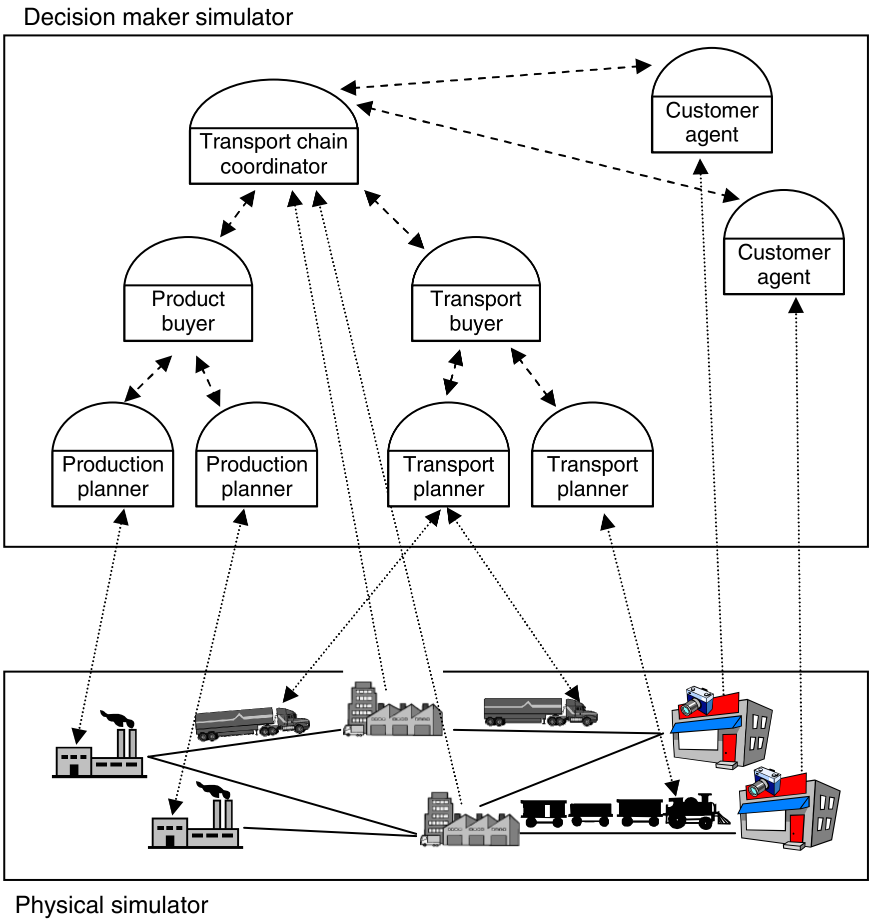

Fig. 1. The two layers of the simulator.

A *link* connects a pair of nodes in the distribution network and acts as a distribution channel for the transport carriers. A link has the following attributes:

- connected pair of nodes,
- mode of transportation,
- length, and
- average distribution speed.

A *transport carrier* is an entity that performs a transport along a link and has the following attributes:

- carrier type (Each type is associated with a particular mode of transportation.),
- volume capacity for each commodity type,
- location (dynamic),
- load (dynamic),
- maximum speed,

– delay probability distribution,
– transport cost, and
– environmental performance.

A *commodity* is produced at nodes and transported via links by transport carriers and have the following attributes:

– commodity type (based on storage requirements),
– production cost,
– production time,
– mass,
– volume, and
– quality (dynamic, based on age).

The activities in the physical simulator can be controlled during run-time through a number of commands. There are commands available to start a production batch, load and unload commodities from a transport carrier, initiate a transport or consume commodities. Commands that are sent to the simulator are placed locally at the target entity in a first-in-first-out queue.

The available commands, their constraints and expected outcomes are:

– *Manufacture(n, c, s).* Adds a new command to the command queue of node *n* to start a new production batch of commodity *c* of size *s*. The command is executed if the node has the required production capacity. The time until the batch is completed is determined by the production time. When the batch is completed the new commodities are placed in storage at *n*.
– *Load(v, c, s, n).* Adds a new command to the command queue of transport carrier *v* to load the quantity *s* of commodity *c* from the storage of node *n*. The command is executed if the transport carrier is located at node *n*. It then requests the commodities from the node which returns the commodities (if available) and the time it takes to load them.
– *Unload(v, c, s, n).* Adds a new command to the command queue of transport carrier *v* to unload the quantity *s* of commodity *c* to the storage of node *n*. Works similar to the Load command with the difference that a request to unload is sent to the node.
– *Dispatch(v, e).* Adds a new command to the command queue of transport carrier *v* to initiate a transport using link *e*. The command can only be executed if the carrier is at either of the nodes connected by *e*, and is not un/loading.
– *Consume(n, c, s).* Adds a new command to the command queue of the node *n* to consume quantity *s* of commodity *c* from the storage of node *n*.

In addition, it is possible to read the attributes of all entities.

4.2 Decision Making Simulator

We have identified a number of important roles in a transport chain, which are described in Table 1.

Table 1. The modeled roles of a transport chain

Decision maker	**Decisions and actions**	**Based on**	**Goal**
Customer agent	Makes requests of products with respect to quantities, time of delivery (or time window), and quality level.	Anticipated customer demand and inventory levels at customer.	Mediate customer requirements in the most accurate way that is possible.
Transport chain coordinator	Decides how much should be bought from producers and how much should be taken from storages. Makes requests to product and transport buyers.	Requests from the customer agents, intermediate inventory levels, and transport and production opportunities.	Satisfy the customer requirements at the lowest possible cost.
Product buyer	From which producer should the products be bought? Makes request of production to production planners.	Requests from transport chain coordinator. Bids from producers (production planners), including prices, deadlines, quality of product etc.	Satisfy the product requirements at the lowest price possible (given the constraints).
Production planner	What is the best bid that the producer can provide? Gives production orders to the producer.	Production capacity, storage levels (at the production site).	Minimize production costs.
Transport buyer	From which transport operator should the transport be bought? Makes request of transports to transport planners.	Requests from transport chain coordinator. Bids from transport operators (transport planners), including prices, quality of transport, etc.	Satisfy the transport requirements at the lowest price possible (given the constraints).
Transport planner	What is the best bid that the transport operator can provide? Assigns tasks to transport carriers (fleet management).	Status (availability, position, etc) of the transport carriers controlled by the operator.	Minimize transport costs.

There are many possible mappings between organizations and the different decision making agents. In the extreme case, all decision makers belong to the same organization for a transport chain, e.g., petroleum companies. Another extreme, is where all decision makers belongs to different organizations. Also, intermediate arrangements exist such as one of the real world cases in the project. Below, some mappings between agents and organizations are suggested:

- The customer agent might be a retailer or a producer, with the goal to buy a desired quantity of goods to the lowest price delivered at a desired time. However, this agent can typically accept (to a reduced price) to receive the products earlier than required and hence store the product until needed.
- The transport chain coordinator might, for example, be a planner within a larger company or a third or fourth party logistics operator.
- The product buyer is often connected to the organization which hosts the transport chain coordinator. However, it can be independent, for example, in case the transport chain coordinator is a third party logistics operator.
- The production planner belongs typically to the producing company.
- The transport buyer might belong to different type of organizations, for instance, the transport buyer might belong to the same organization as the customer or as the transport chain operator.
- The transport planner typically belongs to the organization owning and controlling the transport carriers.

As a case study we have selected a transport chain within the food industry consisting of: Karlshamns AB, a producer of fats and oils, the transport operator FoodTankers, and a typical buyer of bulk products from Karlshamns AB, Procordia Foods. A number of the decision making agents, i.e., the transport chain coordinator, product buyer, production planner, and transport buyer, are all associated with Karlshamns AB. The customer and the transport planner agents are associated with Procordia Foods and FoodTankers, respectively.

The suggested hierarchical design of the decision maker simulator allows for the study of different levels of cooperation. It allows for modeling the extreme (but rather common) case, where the agents have pure local objectives (local cost minimizer) with virtually no sharing of information. Further, the design allows for the other extreme case, where the agents are fully cooperative with the objective of minimizing total cost of the system. In order to approach system optimality, however, an optimization mechanism needs to be applied for guiding the decision agents. In Persson and Davidsson [8], an example of such a mechanism is outlined for a similar problem setting.

The decision making simulator primarily models operational decisions. Strategic decisions, such as buying or selling of vehicles, increase or decrease of storage capacity, are not explicitly modeled. However, these decisions may indirectly be accounted for by the user of the simulator, or directly in a more advanced version of the simulator by extending the decision domain.

5 A Simple Case Study

In order to illustrate the usage of the simulator we have chosen to describe a very simple case study. The scenario consists of a producer of fluids (density 1000 kg/m^3) in Karlshamn, situated in southern Sweden, a customer in Fredrikstad situated in southern Norway, and no internal distribution nodes. There are two transport operators available, one using trucks and one using rail. We focus on the transport selection task, assuming that sufficient amount of products and carriers are available to meet the demands of the customers. Details of the two *links* that connects the two nodes and the three different *transport carrier* types used in the case study are given in Table 2 and 3 respectively.

Table 2. The links of the transport chain

	Link A	**Link B**
Nodes	Karlshamn, Fredrikstad	Karlshamn, Fredrikstad
Mode	Road	Rail
Length (km)	540	600
Average speed (km/h)	72	14

Table 3. The attributes of the transport carrier types. The cost and environmental performance for trucks depends on the load [empty, full]. The values for rail are based on proportions of the size of the average freight train set in Sweden which is 535 tonnes (according to the Swedish Network for Transport and Environment, see www.ntm.a.se)

	Truck	**Rail_27**	**Rail_50**
Mode	Road	Rail	Rail
Volume capacity (m^3)	30	27	50
Max speed (km/h)	90	90	90
Probability of delay	0	0	0
Cost (€)	[665, 680]	1005	1764
Env. perf.: CO_2 (g/km)	[754, 891]	143	265

Further assumptions and characteristics of the studied scenario are given below.

- A time horizon 52 weeks is considered.
- Two customer orders are generated per week. The time and the quantity of the order are randomly generated. The quantities are generated to match an ideal size of a truck, which is 30 tonnes with a probability of 0.5 or of a rail freight carriage of either 27 or 50 tonnes, with a probability of 0.25, respectively.
- In the scenario, the effects (costs and environmental performance) of returning the truck or the rail freight carriage to the producer have been ignored. This has been ignored in these initial experiments since the effects are highly dependent on the possibility to take on other loads on the return trip which is not modeled explicitly.
- It is assumed that the train carriage is transported using diesel engines for 30% of the distance and electrical engines for 70% of the distance, since only parts of the railway network are electrified.
- It is assumed that products can be loaded directly into and directly from the different types of vehicles (train and truck) at both the customer and the producer.

We have chosen to study the effect of using kilometer taxation on heavy trucks, since this governmental control policy is under discussion for implementation in Sweden. In Figures 2 and 3, the results have been plotted for different levels of kilometer taxation. We study the effect on the total cost for the customer, tax income, and emitted carbon dioxide. As expected, the cost is increasing for increasing kilometer taxation. The tax income is not zero for zero kilometer taxation, since a fuel tax is associated with the diesel of €0.55 which applies both for trucks and diesel trains.

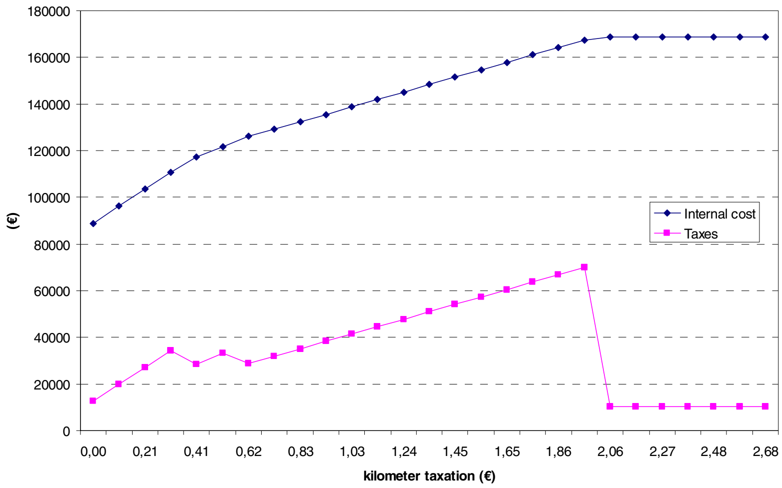

Fig. 2. Internal costs and taxes for different values of kilometer taxation

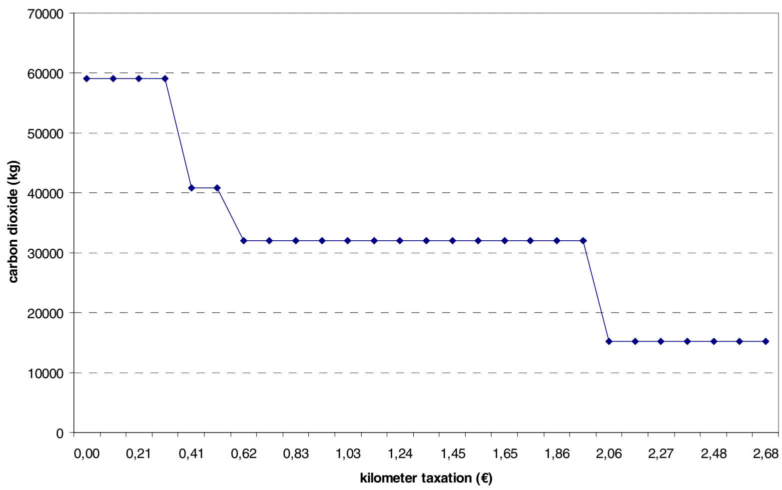

Fig. 3. Carbon dioxide emissions

In Figure 4, the transition from using only trucks and to using only train is illustrated. Using only trucks is competitive up to a kilometer taxation of €0.38; and in order to make only trains competitive a kilometer taxation of €2.0 is required. These breakpoints will naturally shift if the cost for moving vehicles back to the producer is fully considered.

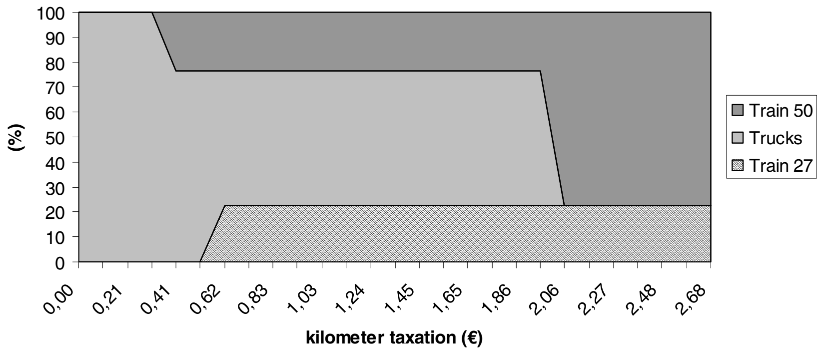

Fig. 4. Percentage of the three carrier types for different kilometer taxations

6 Conclusions and Future Work

We have outlined a hybrid micro-level simulator which is currently being developed. It models the physical activities as well as decision making activities taking place in transport chains. We will use this simulator in order to study the effects of different governmental control policies. This is done in several steps with increasing complexity:

1. Consider only the transport selection issues (focusing on the decisions made by the Transport buyer), assuming that sufficient amount of products and carriers always are available.
2. Considering also fleet management issues (focusing on the decisions made by the Transport planners), but still assuming that sufficient amount of products always are available.
3. Considering also production planning (focusing on the decisions made by the Production planners), but assuming that transports and production are independently planned.
4. Consider cooperation between producers and transporters (focusing on the decisions of the Transport chain coordinator and its interaction with the production and transport buyers).

Once step four is completed, different levels of cooperation between actors can be studied. Hence the effects of governmental control policies can be studied in relation to the level of cooperation.

A number of characteristic scenarios will be studied using the simulator. In-depth case studies will be made on a set of transport chains involving FoodTankers and Karlshamns AB (see below). Validation of the simulation model will be carried out partly through these case studies, and partly though close cooperation with SIKA (the Swedish Institute for Transport and Communications Analysis). SIKA has much experience in the area and access to vast amount of data concerning the Swedish transport and traffic systems. As they also are a potential user of the simulator, they are participating in the requirements analysis.

Acknowledgements

This work is carried out within the project "Effects of Governmental Control Policies in Transportation Chains: A Micro-level Study" (see `www.ipd.bth.se/stem`), which is mainly financed by VINNOVA, the Swedish Agency for Innovation Systems. Further, the Swedish Knowledge Foundation is in part supporting this research, via the project "Integrated Production and Transportation Planning within Food Industry" (see `www.ipd.bth.se/fatplan`) Two companies are primarily involved in the case study, FoodTankers which provides services in the form of tanker transport, and Karlshamns AB which is one of the world's leading producers of vegetable oils and fats. In addition, the project is supported by an expert committee including experts from SIKA and the Swedish Environmental Protection Agency (via the MiSt research programme).

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