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Behavioural sensitivity towards emission concepts

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Abstract

Agent-based simulation lends itself to study emergent behaviour when agents respond autonomously, based on their unique and individual attributes, to external interventions. In transport, the vehicle-specific attribute of interest is its fuel efficiency and emissions. While research showed that vehicle-specific emissions can be accounted for in terms of pollutant quantities, this paper aims to demonstrate that the chosen model is sensitive to a vehicle's designated emissions concept. In urban freight or city logistics, such behavioural sensitivity is necessary to evaluate interventions like low emission zones where access is provided to goods vehicles based on their emission category.

Keywords: MATSim; emissions concept; behavioural response; HBEFA

1. Introduction

Macal [11] defines four properties for agent-based modelling and simulation: individuality, autonomy, interactivity and adaptability of the agents. For a model to classify as *agent-based*, not all of the properties are necessarily required. In scenarios where there are high levels of inequality and diversity among the population, the *individuality* property lends itself well to capture and represent reality.

The Multi-Agent Transport Simulation (MATSim) toolkit facilitates the modelling of large-scale transport scenarios of diverse individuals [5]. The toolkit accommodates all the properties stipulated by [11]. In MATSim, the individuals (richly described persons represented as agents) make autonomous decisions about their routing, activity timing, mode or other choice dimensions that the modeller captures using its modular coding infrastructure. An agent has a planned sequence of activities and trips, which is then executed in a queue-based simulation representing the network of transport supply. Since all agents execute their plans simultaneously on the road and transit network, there is interactivity among the agents as they share the capacitated network, jointly causing congestion. Consequently, the agent's experienced plan may differ from the original plan. The iterative nature of MATSim allows agents to score their experienced plans using a generalised cost function, and storing the scored plan in memory. For the next itera-

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tions, agents randomly selects from their pool of memorised plans, favouring those that are expected to yield a lower generalised cost (higher utility). In aiming to maximise personal utility, agents therefore adapt and *learn* from their experience.

The value of the learning property lies in the fact that the model can demonstrate emergent behaviour of complex systems: unplanned for, unrealised, and sometimes counter-intuitive behaviour [2]. Such agent-based simulation can provide valuable insights and decision support to situations that possibly require a counter-intuitive approach [9], allowing researchers and practitioners to study both intended and the unintended consequences of interventions applied on a large scale.

In previous research, MATSim was already adopted to demonstrate its ability to address vehicle-specific emissions [6, 9, 10]. In the mobility simulation of MATSim, each vehicle's movement is coupled with vehicle-specific emission attributes (g/km) of the Handbook Emission Factors for Road Transport (HBEFA), version 3.1, in different traffic conditions [4]. The focus was on the actual pollutant quantities. The purpose of this paper is to take one step back and provide a systematic evaluation of the behavioural sensitivity of MATSim with regards to emission concepts, which is vehicle-specific, from the (updated) HBEFA 4.1 database. The question we aim to answer is: *"can MATSim capture the behavioural sensitivity of agents using different emission concept vehicles?"*

If this is possible, it paves the way to use MATSim to evaluate the effect of, and more likely, the (un)intended consequences of implementing interventions like low emission zones [3, 12]. The paper is structured as follows. Section 2 reviews the MATSim mechanism to account for emissions. In Section 3 we provide the experimental setup to test the behavioural sensitivity of the model. Results are presented in Section 4 before we conclude.

2. Emissions modelling

In his thesis, Kickhöfer [8] identifies the improvements in applied benefit-cost analysis (BCA) when introducing unique agent attributes and preferences in MATSim. His agent-based approach advocates the use of MATSim for several reasons. Firstly, its high degree of modularity and focus on the agent facilitates an individualised behavioural model. Secondly, it provides a mesoscopic traffic flow model: on a scale large enough to consider emergent behaviour and small enough to study a single agent. Calculating externalities like congestion and vehicle-specific emissions requires this type of model. Thirdly, MATSim can handle large networks with several million agents and enables investigation at one second time steps. This allows us to observe traffic scenarios at different times in a day, e.g. peak and off-peak, and over the entire dynamic journey of an agent. Finally, MATSim offers performance functions that capture travel preferences by assigning weights to agent attributes. With this, we can examine the impact of externalities like emission tolls on individual travel decisions.

In [6], the authors develop an approach to link MATSim with emission factors and traffic situations in HBEFA. It calculates time-dependent cold and warm emissions specific to each vehicle type. Its reusability and transferability to other scenarios are among its main features. The code extension (or `contrib` in MATSim terminology), called `emissions`, comprises two main steps:

1. deduction of kinematic characteristics from MATSim simulations: when an agent enters a link (road segment) on the road network, MATSim saves a timestamp and compares it to the time at which this agent exits the link, resulting in the free-flow travel time; and
2. generation of emissions factors identified per (varying) vehicle type, road category and speed limit. MATSim assigns these factors to each agent and link in traverses.

Agarwal and Kickhöfer [1] evaluate the outcome of pricing emissions and congestion, respectively. Their results show agents trading off conflicting objectives: emissions pricing steers drivers towards shorter distances while congestion might steer them towards shorter travel times, which could mean longer distances. A travel intervention applied to a population of agents could produce both intended and unintended consequences.

In these initial studies, emissions are calculated based on the vehicle type but the pricing/intervention is base don the total emissions and not specifically the vehicle type in itself. Also, whenever one applies an intervention to a large case study, the size of the scenario and the various influencing factors, many of which may be case-specific artefacts, can reduce the signal-to-noise ratio. As a result, one may remain with the question: *"is what we observe maybe simply a result of congestion, or is the model really sensitive to the emission characteristics of the individuals?"*

3. Model

To address the concern, we provide in this section a systematic evaluation of the behavioural sensitivity of MATSim as it relates to emissions. The goal is to demonstrate that agents, each with a vehicle with unique emission attributes, respond autonomously to external stimulus in the form of an intervention.

The experiment we set up uses MATSim's small-scale "`equil`" network. The intervention mimics what we see from case studies presented in the literature: emission tolls or carbon tax imposed on a driver population. We apply this approach to agents traversing between their home and work locations along the 23 directional links connecting 15 nodes in the circular network, shown in Figure 1. To create travel demand, we synthesise a population of 1 000

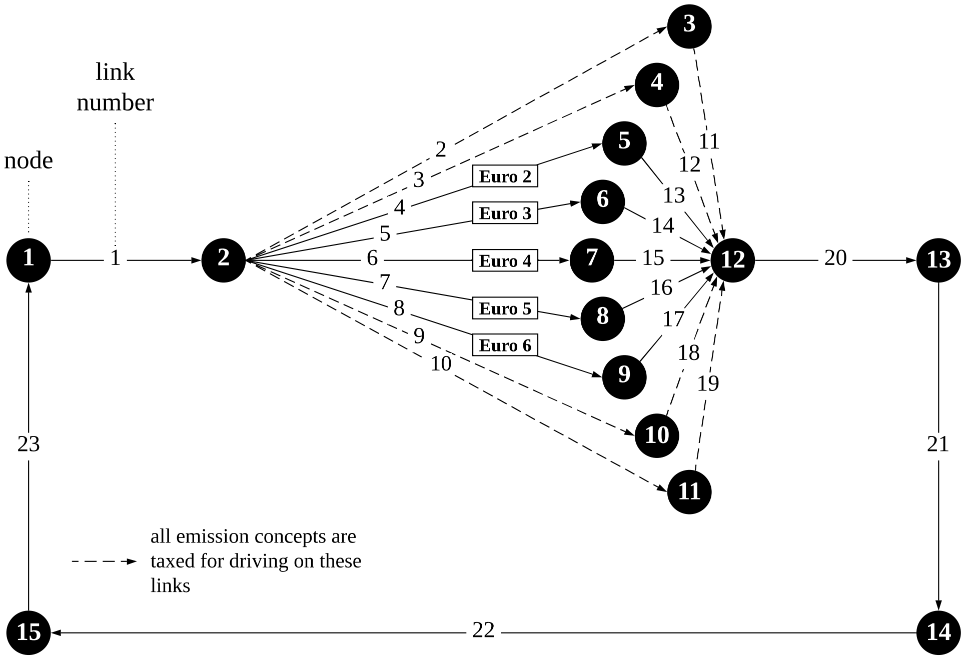


Fig. 1: The `equil` network showing taxed and non-taxed links based on emission profiles

agents with a (single) daily home-work-home activity chain (*plan*). Each initial plan sees an agent leaving their home location, located at node 1, and randomly choosing their route to work, located at node 13, among the nine available route choices, each route equally likely. All agents return to their home location by using the same fixed route via links 21 → 22 → 23. Each agent is assigned a vehicle and each vehicle has a designated vehicle type, which is randomly sampled from a set of five vehicle types. The five vehicle types, again each equally likely to be sampled, represent Euro 2, Euro 3, Euro 4, Euro 5 and Euro 6 emission concepts.

Our intervention restricts each agent (with its unique emission profile) to *one* route among the nine given. We do this by creating only one *non-taxed* route for each emission concept. The Euro emission concepts and their non-taxed routes are as follows (from Figure 1):

- Euro 2: link combination 4 → 13;
- Euro 3: link combination 5 → 14;
- Euro 4: link combination 6 → 15;
- Euro 5: link combination 7 → 16; and

- Euro 6: link combination 8 → 17.

We tax *all* Euro concepts for driving on the upper and bottom two routes, shown as dashed lines, namely link combinations 2→11, 3→12, 9→18, and 10→19.

Upon entering a link in the network, the mobility model verifies the vehicle type of the agent to obtain its assigned emissions concept. If the agent drives a vehicle of which that particular Euro concept is taxed on the given link, we penalise the agent with a cost, which reflects as a negative utility to the agent's score. After the mobility simulation, agents evaluate their executed plans and can *replan* based on this score (total utility gained). Replanning involves either changing the departure time of an activity or choosing another route from home to work. The score also captures utility gained from performing an activity and utility lost from travelling between activities.

The behaviour we intend to produce is that when agents wrongfully drive on taxed routes, they learn and change their behaviour based on the utility lost when executing that plan (travelling on a specific route). Consequently, agents will realise that it is to their benefit to refrain from travelling on taxed links. They will replan after each iteration, choosing different home-to-work routes, until they achieve the maximum attainable score in their current network environment.

4. Results

We execute an instance of the simulation with 1 000 agents for 250 iterations. The vehicle type with its associated emissions profile is assigned proportionally to the population, resulting in 200 agents for each Euro concept (2-5). The only relevant model input parameter is the "tax amount" (negative utility) incurred by an agent travelling on an emission-taxed route. Joubert [7] found that the size of this amount to be of less significance than the mere presence of it. That is, agents' travel behaviour remain the same irrespective of the size of the tax amount. Therefore, we exclude the study of the model's sensitivity based on this parameter.

At the start of the simulation (Figure 2a) the initial travel demand is spread equally across the nine different routes between nodes 2 and 12. As the iteration progress, the emission tax on specific links causes the agents to replan, changing their home-to-work route choice with each successive iteration to avoid taxed links given their specific vehicle types. In iteration 100 (Figure 2b) we already see agents starting to prefer routes associated with a tax exemption for their specific vehicle types.

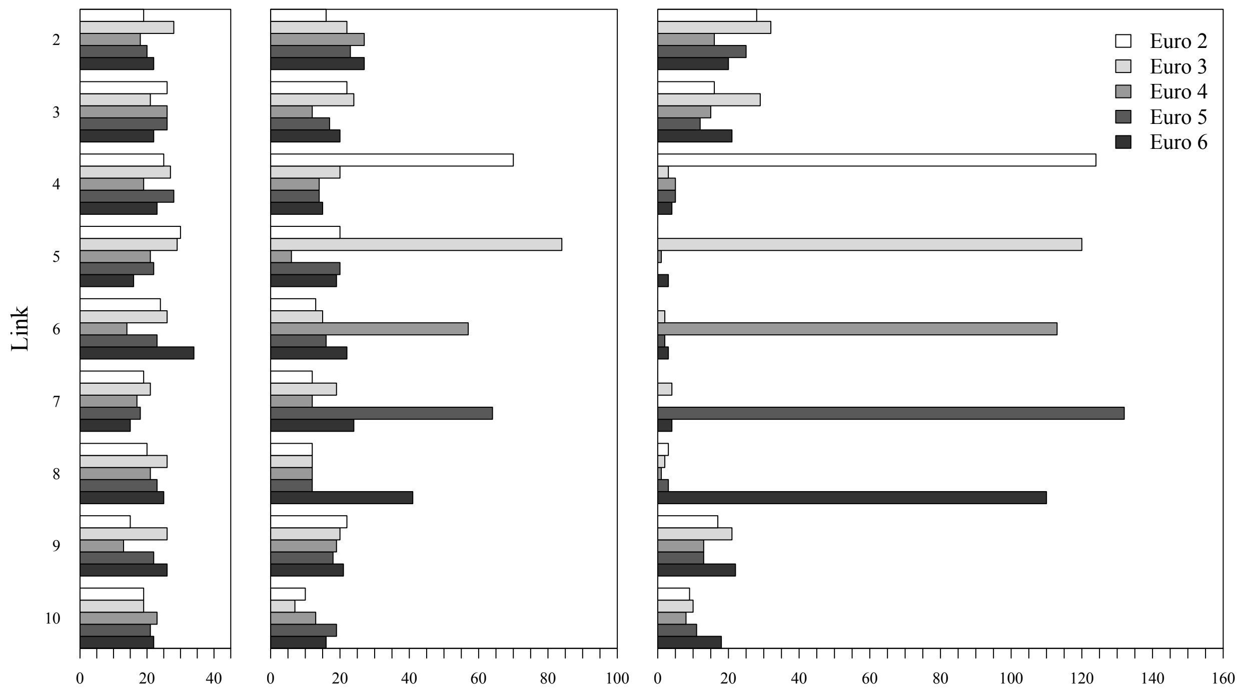
After 250 iterations, the simulation reaches a relaxed state where no agent can make any significant improvements to its score, and maintains its current best plan (route across the network). Note how one type of emission concept dominates the route on which it does not incur the imposed emission tax. This route occupation corresponds to what we set out to produce with our experimental setup in section 3.

5. Conclusion

From our systematic, small-scale experiment, we confirm that MATSim is indeed behaviourally sensitive to the agent's unique attribute (vehicle type). Agents respond to external interventions in an emergent way that maximises their individual utility. Consequently, MATSim is useful to evaluate the impact of interventions, like low emission zones, that targets specific vehicle types. As shown in earlier research, limiting higher polluting vehicles in certain areas may lower the overall emissions in the focal area, but may contribute to higher overall emissions across the larger transport system.

While the network and use case is fairly trivial in this paper, it still captures the behavioural sensitivity. That was indeed the focus. The same behavioural response can be expected in larger use cases. We simply chose a small case study to strengthen the signal-to-noise ratio, which is often overshadowed in large case studies by other behavioural choice dimensions like congestion avoidance through route choice and activity timing choice.

A next step in this area would be to evaluate and study people's willingness to adopt to low-emission vehicles. When carbon tax is implemented (quite bluntly) as part of a fuel levy, for example, people may rather aim for fuel efficiency instead of lower emissions. Acquiring or replacing a vehicle is also a major event for an individual and such longer term choices are not always convincingly accounted for in shorter term traffic and transport models.



(a) Iteration 0 (b) Iteration 100 (c) Iteration 250

Fig. 2: Vehicle counts over consecutive iterations for one simulation instance

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