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A system dynamics approach to scenario analysis for urban passenger transport energy consumption and CO_2 emissions: A case study of Beijing

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HIGHLIGHTS

- The creation of a Beijing urban transport carbon model using system dynamics.
- The effect of different policies on energy conservation and emission reductions.
- The cumulative effect of different individual policies.
- The optimal sequence of individual policy implementation in comprehensive policy.

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ABSTRACT

With the accelerating process of urbanization, developing countries are facing growing pressure to pursue energy savings and emission reductions, especially in urban passenger transport. In this paper, we built a Beijing urban passenger transport carbon model, including an economy subsystem, population subsystem, transport subsystem, and energy consumption and CO_2 emissions subsystem using System Dynamics. Furthermore, we constructed a variety of policy scenarios based on management experience in Beijing. The analysis showed that priority to the development of public transport (PDPT) could significantly increase the proportion of public transport locally and would be helpful in pursuing energy savings and emission reductions as well. Travel demand management (TDM) had a distinctive effect on energy savings and emission reductions in the short term, while technical progress (TP) was more conducive to realizing emission reduction targets. Administrative rules and regulations management (ARM) had the best overall effect of the individual policies on both energy savings and emission reductions. However, the effect of comprehensive policy (CP) was better than any of the individual policies pursued separately. Furthermore, the optimal implementation sequence of each individual policy in CP was TP→PDPT→TDM→ARM.

1. Introduction

In response to oil shortages, air pollution and climate change, an increasing number of governments have begun to set goals for energy savings and emission reductions (Zhang et al., 2014, 2011a, 2011b; USEPA, 2012). More than half of the world's population currently lives in cities. What is more, their Greenhouse Gas (GHG) emissions accounted for more than 80% of the world's total GHG emissions (Feng et al., 2013). In China, approximately 18% of the population lives in the 35 largest cities, but they brought in vast energy consumption and CO_2 emissions, which accounted for more than 40% (Dhakal, 2009). Therefore, energy savings and emission reductions at the city level played a vital role in the process of fulfilling existing overall energy conservation and emission reduction targets (Chen and Chen, 2012; Zhang et al., 2012; Chun et al., 2011; Li et al., 2010). In addition, energy consumption and CO_2 emissions from urban passenger transport played an important role at the city level; therefore, energy conservation and emission reductions in urban passenger transport became important measures by which to achieve low-carbon development goals (Litman, 2013a, 2013b; Geng et al., 2013; Chiou et al., 2013).

Currently, there are many researchers interested in urban transport energy conservation and emissions reduction measures (AASHTO, 2009; Ross Morrow et al., 2010; Gross et al., 2009;

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Seckin et al., 2013). Substantially, these measures can be divided into two categories: a clean vehicles strategy, which reduces energy consumption and emissions of vehicles or other automotive devices per kilometer using related technical improvements for vehicles or fuel; and a mobility management strategy, which reduces traffic volume through a variety of measures. However, there have been many debates regarding which strategy is optimal overall. Researchers who support a clean vehicles strategy usually think that mobility management is difficult to implement because there is great uncertainty and the potential for great harm to residents' utility and the urban economy (Cox and Moore, 2011; Hartgen et al., 2011; McKinsey, 2007; Moore et al., 2010). Others who support a mobility management strategy argue that the effect of mobility management on energy conservation and emissions reduction is more economical and efficient (TRB, 2009; USDOT, 2010; Gross et al., 2009). The mentioned measures are not absolutely negative or positive in principle. But comprehensive energy conservation and emission reduction policy should include various mobility management policies both in developed countries and developing countries (Litman, 2013a, 2013b). What is more, there is a high-income elasticity of demand for cars in developing countries. It means that car ownership will grow faster in the nearest future (Dargay and Gately, 1999). Thus, the motorization of developing countries will put a strain on global efforts to cut carbon emissions from transport. At the same time, developing countries lack the financial resources and governance system for achieving low-carbon transport target. Fortunately, the mobility management strategy can help cities in developing countries on the path toward a more low-carbon future (Santos et al., 2010). So we primarily analyze mobility management measures.

An urban passenger transport system is typically an open complex giant system that contains several subsystems. In such a complex system, a tiny change in societal, economic or environmental factors can lead to enormous changes to urban passenger transport development or energy consumption and emissions. For these reasons, it is vital for us to comprehend the structures and the relationships between different subsystems of the urban passenger transport system. Consequentially, quantitative analyses of behavioral characteristics and the dynamic mechanisms involved in urban passenger transport have become important areas of investigation.

In the past few years, a large number of studies have delved into the problem of urban transport energy consumption and emissions. These researches can primarily be divided into three types: top-down, bottom-up and hybrid methods.

(1) Top-down methods mainly include CGE, MACRO, GEM-E3, 3Es-Model, and so on. For example, Schafer and Jacoby (2005) analyzed how promoted new automobile technologies enter the automobile market and influence climate change under policy constraints using the CGE Model. Small (2012) assessed the effectiveness and cost of different energy policies for light motor vehicles using the National Energy Modeling System. Rentziou et al. (2012) forecasted urban passenger transport volume, energy consumption and CO_2 emissions based on the simultaneous equations Model. On the whole, top-down methods are good at providing economic analyses, but not do well in describing technology concretely. These methods generally underestimate the potential for technological progress (Nakata, 2004).
(2) The bottom-up approach primarily includes MARKAL, MESSAGE, EFOM, LEAP model, and so on. For example, Pressley et al. (2014) utilized a life cycle assessment methodology to evaluate the conversion of U.S. municipal solid waste to liquid transportation fuels via gasification and Fischer–Tropsch. Contreras, et al. (2009) analyzed the change in hydrogen energy vehicles' market share in road traffic using the MARKAL model. Cortés et al. (2008) developed an object-oriented simulation platform using a Java program to analyze urban traffic network energy consumption and emissions. On the whole, bottom-up methods perform economic analyses poorly, providing useful detailed descriptions of technology. These analyses generally overestimate the potential for economic progress (Nakata, 2004).
(3) Hybrid methods mainly include NEMS, POLES, PRIMES, POLES model, and so on. For example, Messner and Schrattenholzer (2000) analyzed an energy supply situation according to demand changes for different passenger and cargo transport units using an IIASA-CEC E3 model. Hickman et al. (2010) built the transport and carbon simulation model and investigated a series of potential policy packages that could reduce the emission's effect in London. Yang et al. (2009) built Long-term Evaluation of Vehicle Emissions Reduction Strategies and researched how to reach the target of reducing CO_2 emissions by 80% by 2050 in California. On the whole, hybrid methods combine the advantages of top-down and bottom-up methods. Not only are their functions more complete, but they also have a more complex structure. Therefore, they are more suitable to the simulation of complex giant systems.

Past research using hybrid methods normally assumed that the evolution structures of urban transport energy consumption and emissions were known; therefore, they reflected the dynamic process of energy consumption and emissions poorly and had difficulty conveying the uncertain behaviors of the primary issues associated with urban transport systems. Conversely, SD combines qualitative analysis with quantitative analysis and uses system synthesis reasoning to describe these undefined behavioral characteristics, making SD a better choice in dealing with nonlinear, high order complex time-varying systems. For these reasons, we chose the SD model to evaluate urban passenger transport energy consumption and CO_2 emissions in Beijing.

SD was first proposed for the analysis of a complex dynamic feedback system by J. W. Forrester in 1956 (Zhao et al., 2011). Based on computer simulation technology, this visual tool can analyze relationships among various factors, simulate quantitative data and obtain information on the feedback structure, function and behavior of the system. This makes it easier for us to understand the system overall and formulate various relevant policy scenarios to control the system's dynamic evolution mechanism (Yuan et al., 2008).

Currently, SD has been widely applied in various research fields, including societal and economic systems research (Forrester, 1969, 1971), ecosystem research (Saysel and Barlas, 2001), transportation research (Suryani et al., 2010) and so on. For instance, in the field of energy management, SD was widely applied to national energy policy-making and evolution (Ford, 1983; Naill, 1992; Qudrat-Ullah, 2005; Barisa et al., 2015). In addition, SD was also used extensively in energy efficiency assessments (Dyner et al., 1995) and the development of the energy industry (Bunn and Larsen, 1992; Chyong Chi et al., 2009). In the field of transportation, SD was applied to research into the operational management of the public transport enterprise (Bivona and Montemaggiore, 2010), the operational management of roads and infrastructure networks (Fallah-Fini et al., 2010), the usage of low emission cars such as electric vehicles and hydrogen vehicles (Walther et al., 2010), and the relationship between land usage and urban transport (Pfaffenbichler et al., 2010). Recently, Vafa-Arani et al. (2014) built an SD model that included urban transportation and air polluting industries subsystems to research urban air pollution in Tehran, Iran. However, in spite of these findings, there is still little literature in the field of the urban passenger transport energy and