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A Study on the Process of a Carbon Reduction Policy Using an Activity-Based Model

Jooyoung Kim[a,*], Seungjae Lee[b], Kwangsik Kim[c], Doyoung Jung[d]

[a]Department of Transportation Planning & Management, Korea National University
[b]Department of Transportation Engineering, University of Seoul
[c]Department of Public Administration, Sungkyunkwan University
[d]Korea Institute of Civil Engineering and Building Technology
jykim@ut.ac.kr

Recently, there has been an increased need for new urban policies in industrialized cities that take action against climate change. In particular, to achieve eco-friendly and efficient transportation systems, carbon-reducing transportation policies should be implemented while managing transportation demand. This study predicts and assesses the effects of a carbon reduction policy in terms of transportation plans, and various responses to policies by users are predicted. The aim is to develop a transportation planning model that improves the effectiveness of a carbon reduction policy. The intention is to provide reasonable support for the decision-making process with regard to the transport policy, and to establish a process for taking into account carbon emissions during the development of future transportation policies. This study used activity-based approach to identify various daily activities of individuals as the decision units of transportation and considers the trip as one of the activities of a continuous daily life. Hence, it is possible to provide analysis results that are suitable for estimating and managing carbon emissions such as introduction of policies for traffic demand management which is a policy for traffic demand management. As a result of simulation, the environmental value of the ‘car-free street’ policy was about 11,548,000 KRW/d, and that of the ‘flexible commuting time policy’ policy was 8,447,000 KRW/d. The proposed carbon reduction policy effectiveness analysis is expected to support decision making concerning carbon reduction policies. Hence, an activity-based simulation of urban transport carbon reduction will help policy-makers support rational decision-making, based on prior experimentation in urban planning and the policy impact on cities.

1. Introduction

CO_2 accounts for the largest portion of greenhouse gases emitted by urban populations, 85 % of which originates from fossil fuel combustion (such as coal, natural gas, and petroleum) as a consequence of human activities. Therefore, to reduce carbon emissions from cities (the centers of human activity) effectively, it is necessary to consider the interaction between human activity and traffic in an integrated manner and propose alternative plans for carbon footprint reductions.
Despite the close relation between human activities and traffic, these two aspects have traditionally been studied separately. Hanpattanakit et al. (2018) estimated the amount of CO_2 emission by tourist transportation through a survey, and Tran (2019) is monitored at the six main stations to analyze the air pollution situation due to transportation activities. As above, traffic demand estimation using an activity-based approach has not been employed in practice, due to the complexity of the model and the limitations in data analysis. However, research has been actively conducted on models in recent years that can analyze the interaction between human activities and traffic, through the development of computer technology and the availability of various data. Furthermore, there is a growing demand for techniques that can evaluate the effects of air pollutants arising from human activities and traffic, and can assess the consequent health effects on humans.
Therefore, the goal of this study is to establish a process to analyze the effect of carbon reduction policy by predicting trip patterns in districts following the implementation of a carbon reduction policy on a microscopic level, by designing and conducting a human activity-based simulation. Using the activity-based model, the

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primary aim of this study is to predict and assess the carbon reduction policy effect on transportation planning. Moreover, the aim is to support the decision-making process, where the effectiveness of the carbon reduction policy can be improved by predicting various responses to policies by users. This is a process in which the carbon emission caused by human activities is taken into account at the stage of traffic policy making.

The four-step model, which is a traditional travel demand model, follows a sequential procedure involving the trip generation, trip distribution, mode choice, and route assignment to forecast travel demand. Based on the underlying assumption that the mechanism governing current transportation system would remain unchanged in the future; these traditional approaches assume that current travel behavior and travel patterns of individuals would also persist. However, when it comes to actual travel demand forecasting, these conventional four-step models, which collect data on the amount of traffic generated within a specific area for a specific time period in order to analyze and predict travel demand, have difficulty taking into account causes or time-specific attributes of such travel. This is because any changes to travel demand would stem from extrinsic factors, namely other social activity structures, rather than from changes in the travel itself. These four-step estimation models have shortcomings in that they fail to recognize the characteristics of individuals, as well as the influence that travelers' attributes have on travel demand, and derivative factors resulting from the involvement of travel demand in traveler activities. Hence, these approaches fail to provide travel characteristics found in activities of travelers, which are deduced through the travelers' decision-making process.

For the activity-based model, on the other hand, successively measured observational data of an individual's daily travel pattern are used, by regarding their various daily activities, as a decision-making unit for the transportation planning to analyze travel behavior. Thus, the model studies the traveler’s daily activity plan, considering travel to be an activity of continuous daily life. In the activity-based model, travel behavior itself is classified into habitual, forced, selective, and avoidant travel, and then analyzed consecutively. It is not viewed as a single behavior simply connecting the travel starting point and destination. The parameters of this model, based on the life cycle of humans, include the length of stay at a particular place, total number of trips during the survey period, and the number of stops made during the travel. Therefore, this model can easily identify the travel pattern of an individual traveler by traffic demand simulation, based on the theory of the Individual Behavior Model. This can be helpful to estimate traffic demand more precisely in the future. In addition, adapting this model to different locations and time is possible, thus rapidly producing results while saving computational cost. Since the model is suitable for rough evaluation of transportation planning, it is assumed to be also useful for the purpose of this study, namely analyzing carbon emissions. However considering specific examples, where the activity-based model has been implemented in practice. For example, Bradely et al. (1998) develop activity-based model and Bowman et al. (1998) develop the demonstration of an activity-based model for Portland. Bradley et al. (2001) suggest activity based micro simulation and Jonnalagadda et al. (2001) development destination and mode choice model of micro simulation for San Francisco. But there is no detailed module composition in the activity-based model and the different analysis procedure is applied depending on the study objective and purpose of the traffic demand model, taking into account the difference with the theoretical methodology and the perspective on the patterns of human activity. Hence, the selection of the simulation platform of the activity-based model is an important issue, because the model requires the analysis of travel distance, travel route, traffic volume, and travel speed of each vehicle for carbon emission estimation and management.

In this study, a travel demand estimation simulation based on an activity-based approach was implemented using MATSim (Multi-Agent Transport Simulation, 2016), and the change in travel patterns of the district unit according to the implementation of carbon reduction policy was predicted and modeled. The MATSim used here is a traffic demand estimation simulation based on activity-based approach theory, which identifies the trip pattern of the individual traveler, enabling a more accurate estimation for future traffic demand (Balmer et al., 2006). The present study developed a human activity-based traffic simulation model considering activity objectives of the traveler and their daily schedule, based on everyday activities. An assessment model was developed, in which the environmental effect of the micro-level traffic policy can be predicted. Specifically, a population synthesizer by Kim and Lee (2016) was used to create an active population for each type of city, and a Korean-version activity-based model was developed, making use of big data such as smart card data, household travel behavior survey data, and the national geographic information system. Furthermore, employing MATSim, the consistency of the newly established was verified by the validation process between the traditional four-step model based on a macroscopic model and the actual data. This paper is organized as follows. In Section 2, the process of carbon emission estimation based on the model is described, and Section 3 discusses the actual implementation of the model to a pilot city and the implementation results for reduced carbon emission based on different scenarios.

2. Methodology of carbon emission estimation

2.1 Micro-level driving data calculation for carbon emission estimation

The MATSim used in this study makes use of the Queue Based Model, and links are modeled by a queue of FIFO (First In, First Out) format. This means that a vehicle in a queue cannot escape from the queue until a certain amount of time associated with the free-speed travel time has passed. Only cars with limited numbers exit the link at a specified time, so there can be no incidence such as overtaking or changing of lanes. The vehicle can be added or removed only at the start and end of the link, as in a queue where the entry and exit of the vehicle is determined either at the start or the end.

For the carbon emission estimation, the data of driving speed and acceleration calculation of individual vehicles are needed, however in the case of MATSim, as a large-scale network dynamic simulation, there is difficulty applying traffic flow simulations due to the computation speed and quantity. MATSim adopts the traffic flow model of the queue theory, and there is a limitation in reflecting the reality arising from the lag time in case of the interrupted flow or additional time required for the deceleration/acceleration in case of continuous flow. Therefore, a technique for calculating micro-level driving data, such as lag time, is needed. In response to such a need, this study aims to calculate data for carbon emission by the hour zone (on the level of second) by utilizing the travel data from individual vehicles and more specifically aims to calculate micro-level driving data in the queue model under the FIFO format. Therefore, the present study calculated micro-level driving data by the following assumptions and network division. First assumption is that to express the actual acceleration/deceleration in the passage of the link, the average vehicle speed entering the link every second and the initial speed of the vehicle is used, and thereby the link travel speed for every second is calculated. Others is the link travel speed is again applied to the agent, and the rate of acceleration/deceleration is estimated in passing the link.

This methodology provides a reasonable way to consider the additional lag time due to the traffic situation for the MATSim program output, as the simulation tool used in this study records the event by agent activity every second and calculates the data. Moreover, as it takes time for agent to enter and exit the link, the travel time increases as the number of links increases, although the total distance remains the same. Therefore, the entry/exit of the link is recorded as an event in MATSim, and the passing time of the link increases temporarily because of the occurrence of events.

To obtain micro-level travel data, in this study, link division criteria were set differently for different road grades, and validation was performed by comparing simulation results with the observed travel speed. From the analysis results, the optimal link division criteria for each road grade were as follows: Highway 500 m, National Road 300 m, Local Road and Local Branch Road 100 m.

2.2 Carbon emission estimation model

In the carbon emission estimation procedure of the activity-based transportation planning model, the database linked with the road traffic carbon emission estimation module (micro-based) includes the mobile emissions source emission factor DB and the vehicle characteristics information DB. The micro-based road traffic carbon emission calculation is a technique for calculating the emission with consideration of instant (seconds) changes in speed, i.e., deceleration/acceleration, and Vehicle Specific Power (VSP), all of which depict vehicle driving characteristics. Compared to the emission estimation methodology based on the mean velocity, this method estimates values closer to the actual emission.

In the calculation of emissions, the micro-based carbon emission factor and the pollutant emission factor are applied. In Korea, the Transportation Institute in the National Institute of Environmental Research conducted research and experiments on several types of vehicles. However, numerous driving experiments must be conducted to properly reflect the characteristics of diverse vehicle types and driving conditions. Therefore, in this study, based on the Motor Vehicle Emissions Simulator (MOVES) developed by the US Environmental Protection Agency (EPA), the emission factor is extracted from MOVES DB, and subsequently the representative emission factor table is estimated by the pollutant and by vehicle type, according to the domestic vehicle categories. The emission factor table is calibrated considering the domestic emission factor standards to prevent errors in the emissions estimation result that originate from the differences in the characteristics of Korean and American vehicles. Specifically, the construction of the micro-based emission factor DB was achieved by the process of emission factor extraction, estimation, and calibration.

- Step 1: Domestic vehicle type is reclassified according to the vehicle type defined in MOVES
- Step 2: Micro-level emission factor of pollutant for the reclassified vehicle type is extracted from MOVES
- Step 3: Emission calculation according to individual vehicle link driving cycle of the road section (link)
  - Step 3-1: Vehicle Specific Power (VSP) calculation
  - Step 3-2: Operating mode (OP-mode) estimation
  - Step 3-3: Emission factor by driving mode of vehicle type is applied for emission estimation

The activity-based carbon emission estimation is a method of calculating emissions based on instant changes in vehicle driving characteristics with respect to speed (deceleration/acceleration) and VSP. Traffic volume, link driving cycle, and vehicle type distribution are required in the vehicle characteristics information DB required for the road traffic carbon emission estimation module (micro-based). Among these, the traffic volume and link driving cycle were obtained and utilized by converting the simulation output data of MATSim, the activity-based transportation planning model. The detailed procedure is given in the two following steps: estimation of emissions of individual vehicles passing through the road section, and estimation of vehicle emissions by road section. The VSP is required primarily to calculate micro-level emissions of individual vehicles. When VSP is defined in the simulation model, the model needs to apply the individual vehicle type information. However, since MATSim has no such function, the vehicle type of the individual vehicle is assigned by calculating the emission factor ratio of the vehicle type using the number of vehicles in the vehicle registration information. The calculation process of VSP per second as the link driving cycle data of each vehicle is as Eq(1) and (2)

$$a_t = v_t - v_{t-1} \tag{1}$$

where v_t is the velocity (m/s) and a_t is the acceleration (m/s^2).

$$P_{V,t} = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t(a_t + gsin\theta_t)}{m} \tag{2}$$

where $P_{V,t}$ depicts the VSP of vehicle V at time t (kW/t); t is the time (s); v_t is the velocity (m/s); a_t is the acceleration (m/s^2); m is the vehicle-based mass (t); A is the rolling resistance (kW.s/m); B is the rotational resistance (kW.s^2/m^2); C is the air resistance (kW.s^3/m^3); g is the gravitational acceleration (9.81 m/s^2) and θ_t is the slope of a road (°).

Here, the values of A, B, C, and m in the formula for calculating VSP are different for each type of vehicle, and passenger cars have the following values: A = 0.15646, B = 0.002, C = 0.00049, m = 1.4788.

In addition, the operating mode (OP-mode) is divided in such a way that the emission rate according to the vehicle driving characteristics was calculated (m/s^2), and VSP was calculated. In the micro-level emission table (by pollutant), the emission coefficient corresponding to the applicable vehicle driving mode was identified, and the emission rate (g/s) for each vehicle was calculated and added, obtaining the micro-level emission of the individual vehicle that passed the relevant road section.

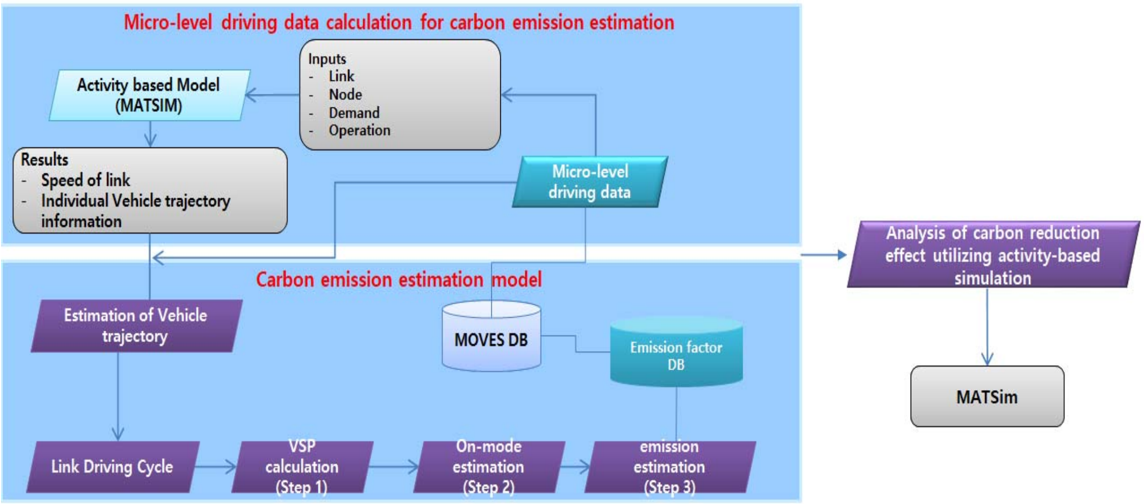

Figure 1: Overview of flowchart on the methodology of carbon emission estimation

3. Analysis of carbon reduction effect utilizing activity-based simulation

The 'car-free street' and the ‘flexible commuting time policy’ scenario were applied. It is assumed that traffic congestion could be alleviated owing to changes in the users’ choice of transportation means, and that the decrease in overall traffic volume with the ‘car-free street’ project and accordingly the transportation convenience of local residents was improved. This sets the ‘car-free street’ as a possible scenario in the pilot city on the ground for the effectiveness of the project. If approximately 2,500 public officials from the Suwon

City government participate in a flexible commuting time policy by delaying the morning commute to avoid peak hours, traffic congestion can be alleviated and additional costs caused by congestion can be reduced. With the positive effect of this system, the analysis of the carbon reduction effect was carried out by adopting the 'flexible commuting time policy' as a scenario.
For the 'car-free street' scenario, network properties of the analyzed area were modified. Vehicles were removed from the link attributes, such that they could not enter the street. Specifically, a vehicle that could not enter the street due to the 'car-free street' project was made to move to an area close to the target area (outside parking-lot) by the activity-based model, and movement from outside parking-lot to the target area was allowed only by walking. In terms of the activity schedule, walking to the outside of the parking-lot and then driving the vehicle was designed for activities occurring within the target area. The analysis results show that about 38% of car-use activities out of the total activities in the target area, in the 'car-free street' scenario were converted to public transportation, and the average traffic speed was improved by 4.23%. In case of the 'flexible commuting time policy' scenario, there was no difference in the existing network, however with regard to the activity schedule, the commuting time of the government official agent in the target area was changed. Specifically, agents who headed for the Gyeonggido Provincial Office, Suwon City Hall, Borough Offices in Suwon City and other public offices, were extracted from the facility, and their time of arrival and departure from the office was rearranged. Consequently, the maximum traffic volume at peak time dispersed, having the distribution effect on the overall traffic volume in space and time and increasing the travel speed by 2.42 % at peak times.

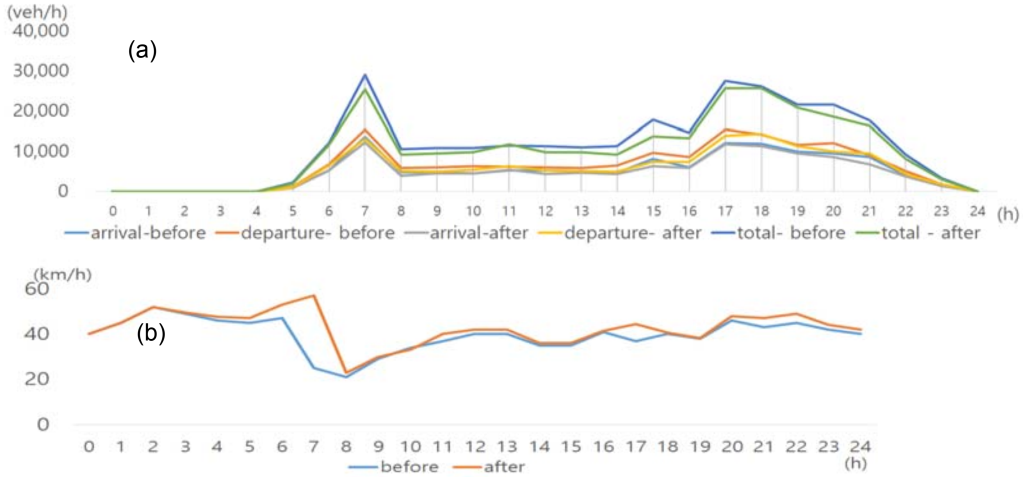

Figure 2: Scenario application results for (a) change in daily travel demand, (b) travel speed for Jeongjo-ro (Janganmun-Paldalmum)

Along with the above-mentioned project, implementing a carbon-reducing traffic policy scenario could decrease emissions of various pollutants and greenhouse gases. To estimate the economic value of improvement in air quality and reduction of greenhouse gas emissions generated by the introduction of this traffic policy, the reduction of greenhouse gas emissions was converted into monetary value. In this study, 521 KRW/kg was applied as the social cost of greenhouse gas emissions, similar to the study of Kim et al. (2017). Resultantly, the environmental value of the 'car-free street' policy was about 11,548,000 KRW/d, and that of the 'flexible commuting time policy' policy was 8,447,000 KRW/d.

Table 1: Environmental value of carbon reduction policy (Unit : 1,000 KRW/d)

Category	BAU Scenario	Car-free street policy	Flexible commuting time policy
Environmental cost	941,432	929,884	932,985
Environmental value	-	11,548	8,447

4. Conclusion

Among the policies implemented to reduce air pollutants resulting in global warming, mobile emissions have been identified as the major contributors. Recently, the Climate Change Information Center (CICC) of the Korea Metrological Administration announced that Korea's annual CO_2 concentration exceeded 400 ppm, which is the psychological bottom line of climate change, and that the rate of increase of CO_2 concentration was more than twice the global average. To solve this problem, it is necessary to develop a policy process to evaluate and manage the carbon reduction effect in advance by implementing a low carbon transportation policy. In this study, we presented a system that can measure the carbon emission reduction effect of the micro-level transportation policy using an activity-based traffic model.

Holistically, this study described the process for integrating human activity-based traffic simulation with the model for carbon emission estimation. In particular, the use of the activity-based model allows consideration of traffic travel behavior and enables analysis of the continuous traffic demand change with time, leading to a more accurate forecast of response behavior to the carbon reduction policy, as well as the calculation of micro-level driving data for the estimation of carbon emissions. The proposed activity-based traffic simulation analyzes the travel of each individual vehicle through travel behavior analysis at the individual agent level. This facilitates the analysis of various scenarios that closely resemble real-life travel patterns. This model is clearly distinctive with regard to this aspect, and by maximizing the advantages of the individual behavior model that are not constrained to the TAZ (Traffic Analysis Zone), it can greatly contribute to the forecast of future traffic demand. The model also provides the basis for a more advanced analysis technique in terms of the collection and treatment of data. Moreover, the proposed carbon emission estimation methodology depicts a model that can estimate carbon emissions in terms of microscopic results according to the predictions of the traffic simulation model, unlike by the usual simplified mean velocity-based analysis. The significance of this model lies in the fact that it enables more accurate estimations of emissions, based on the travel patterns of individual vehicles.

The model presented in this study demonstrates the estimation of carbon emissions based on the prediction of activity-based traffic demand changes following the implementation of a carbon reduction policy, and compares the resulting effects of each policy. Accordingly, we anticipate that this model will enable the predictive analysis of effects of various transportation policies, and thus contribute to the relevant decision making.

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