Application of Zonal Crash Prediction Models in Traffic Safety Evaluation of a Fuel-Cost Increase Scenario Using an Activity-Based Transportation Model

Ali Pirdavani, Tom Brijs,
Tom Bellemans, Bruno Kochan and Geert Wets[1]

Transportation Research Institute (IMOB)
Hasselt University
Wetenschapspark – Building 5
B-3590 Diepenbeek, Belgium

Tel: +32(0)11 26 91{39, 55, 27, 47, 58}
Fax: +32(0)11 26 91 99

Email: {ali.pirdavani, tom.brijs, tom.bellemans,

bruno.kochan, geert.wets}@uhasselt.be

Total number of words: 7513 (2 Tables and 2 Figures included)
Date of submission: 4/11/2011

---

[1] Corresponding author

ABSTRACT

Travel Demand Management (TDM) consists of a variety of policy measures that affect the transportation system's effectiveness by changing travel behavior. The primary objective to implement such TDM strategies is not to improve traffic safety; however, their potential in providing traffic safety profits should not be neglected. The main purpose of this study is to evaluate the traffic safety impacts of conducting a fuel-cost scenario in Flanders, Belgium. While travel demand management strategies are usually conducted at an aggregated level, Crash Prediction Models (CPMs) should also be developed at a more aggregated level. Therefore Zonal Crash Prediction Models (ZCPMs) are considered to present the association between observed crashes in each zone and a set of predictor variables. To this end, an activity-based transportation model framework is applied to produce exposure variables which will be used in prediction models. This allows us to conduct a more detailed and reliable assessment while TDM strategies are inherently modeled in the activity-based models unlike traditional models in which the impact of TDM strategies are assumed. Crash data used in this study consist of observed fatal and injury crashes between 2004 and 2007. The network and socio-demographic variables are also collected from other sources. In this study, a selected zonal crash prediction model is developed to predict the Number of Injury Crashes (NOICs) (including fatal crashes) for both the null and a fuel-cost scenario. The results show a considerable traffic safety benefit of conducting the fuel-cost scenario besides its impact on reducing total vehicle kilometers travelled. The expected NOICs decreased by 4.65% whilst a yearly 5.02 billion vehicle kilometers travelled reduction was observed after implementing the fuel-cost scenario; i.e. increasing the fuel cost by 20%.

INTRODUCTION

It is beneficial to know the consequences of TDM strategies, like traffic safety which is an external side effect of TDM. Road crashes are known as one of the negative impacts of growing travel demand. For many years, researchers have attempted to investigate this impact by predicting the Number of Crashes (NOCs) based on the patterns they have learnt from crashes that occurred in the past. Traditionally, this reactive approach consists of different phases such as; identification, diagnosis and improvement of dangerous locations, so called hot spots. From the ethical point of view, this reactive approach is not acceptable because it requires several years of crashes to occur in order to identify and treat safety problems. Thus, providing a more proactive approach which is capable of evaluating road safety at the planning-level is essential. This proactive approach is increasingly being paid attention to by researchers and practitioners in the last few years. Dealing with traffic safety at the planning-level requires the ability to integrate TDM strategies into a crash predicting context. TDM consists of several policies and strategies which aim to overcome transportation problems in different ways; such as changing travel behavior, making transportation systems more efficient or reducing travel demand. In general, TDM strategies are implemented to improve transportation systems' efficiency; however their potential traffic safety benefits should not be ignored. TDM strategies improve transport system efficiency by means of a mode shift (e.g. using public transportation instead of cars, biking for short distance trips or carpooling), a travel time shift (e.g. avoiding traffic peak-hours by leaving home/work place earlier or later), or travel demand reduction (e.g. teleworking). TDM strategies are usually performed and evaluated at a more aggregated level than just the level of individual intersections or road section. However, local TDM implementations like adding capacity to a segment of road may also be conducted. Typically the before/after analysis of such an infrastructure adjustment is carried out locally despite the fact that such an adjustment may have broader consequences. Thus, the impact of adopting a TDM strategy on transportation or traffic safety should be evaluated at a higher level rather than merely the local consequences. Therefore, application of CPMs at a zonal level like Traffic Analysis Zone (TAZ) leads to ZCPM.

Until now, incorporating ZCPMs in TDM strategies has hardly ever been carried out. The main goal of this study is therefore to integrate ZCPMs with a fuel-cost scenario to evaluate the traffic safety effects of conducting such TDM strategy by means of performing a simulation based analysis of the impact of fuel price on the travel demand in Flanders, Belgium. To this end, the FEATHERS (Forecasting Evolutionary Activity-Travel of Households and their Environmental RepercussionS) activity-based transportation model is applied on the Flemish population. This study is an assessment exercise which illustrates the impact of 20% increase in fuel-cost on traffic safety; it is essential to indicate that this 20% increase is not an optimal value.

The structure of this paper is as follows. Initially, we will review the literature. Then the activity-based model which is used in this study will be briefly introduced. In the next sections the data preparation and the fuel-cost scenario evaluation process will be demonstrated. Finally, the results of fuel-cost scenario will be shown followed by the final conclusions.

LITERATURE REVIEW

Travel demand management (TDM) has hardly ever been implemented to improve traffic safety. Its main objectives are usually congestion and emission reduction, decrease travel cost and energy saving by means of reducing travel demand and consequently vehicle distance travelled.

Nevertheless, identifying the traffic safety impacts of applying a TDM strategy, beside transportation system's efficiency improvement and the economic/environmental benefits can strengthen the implementation of such TDM strategy. It is a well known relationship in literature that road crashes are tightly linked to traffic exposure. Therefore, strategies that reduce travel demand or distance travelled, or cause a modal shift to a safer substitute mode (e.g., from car to public transportation) tend to reduce the NOCs (*1*), (*2*).

Lovegrove and Litman (*3*) applied community-based, macro-level CPMs to calculate the road safety effects of three mobility management strategies: smart growth, congestion pricing and improving transport options. They assumed the effect of implementing these strategies on different explanatory variables of the CPMs (e.g., they found that the smart growth strategy will decrease vehicle kilometers traveled (VKT) by 15%). Based on these assumptions the expected NOCs have been calculated for each TDM strategy. The results indicated that mobility management strategies can significantly improve traffic safety. Fuel cost is a major component of each motor vehicle's operating expenses. By increasing the fuel cost as a TDM strategy, people tend to travel less with their cars by using public transportation, shifting towards slow modes (biking and walking), carpooling, etc. Thus, traffic crashes are expected to decrease as a result of a reduction in the number of car kilometers traveled. Fuel-cost has an impact on traffic safety through the changes it made in travel demand. Grabowski and Morrisey (*4*) reported a relatively stable number of fatal motor vehicle crashes despite of new traffic safety laws and vehicle innovations over a period of time. Their explanation was that the price of gasoline declined, which resulted in more vehicle miles traveled and potentially more fatalities. Chi et al (*5*) also investigated the impact of gasoline price changes on different types of crashes at a more disaggregated level for different ages and genders. In their reactive approach, they developed models to predict traffic crashes based on explanatory variables like exposure, gasoline price, alcohol consumption, seat belt usage, etc. It was concluded that increase in gasoline price both has a short-term and intermediate-term effect on reducing total traffic crashes.

CPMs can be categorized in two different levels: the local level (road and intersection) and the regional level (e.g. TAZ). Usually CPMs at the local level aim to predict the safety benefits/detriment of infrastructure improvements. These models are not typically designed to evaluate traffic safety impacts of TDM strategies; thus, application of CPMs at a higher aggregation level will be more practical (*6*). Application of CPMs at the TAZ level has been initially introduced by Levine et al (*7*). In their study a set of both socio-economic and network variables were chosen to predict the NOCs in TAZs. They estimated a linear relationship between different explanatory variables and the NOCs. Recently, the application of ZCPMs became more popular amongst researchers because of their ability to estimate the effect of different TDM strategies on traffic safety.

Several researchers have examined the association of a collection of network infrastructure variables, socio-demographic and socio-economic variables and weather conditions with the NOCs in TAZs (*8-14*). It was found that the number of lanes, road length and road density were significantly correlated with the NOCs. As for the demographic variables, it was found that TAZs with a higher percentage of population under the poverty level and a higher percentage of population in the young and also elderly age groups have the potential of increasing crash risk. It was also found that the traffic safety situation is worse for TAZs with lower income and education levels and a higher unemployment rate compared to relatively affluent TAZs. In another study by Wier et al (*12*) it was shown that traffic volume, population size, the proportion of arterial streets without public transit, the proportion of population living in poverty, and the number of people aged 65+ as percentage of the total population, were significantly good predictors. Moreover, Noland and Quddus (*13*) concluded that TAZs with high employment density had more traffic crashes, while urbanized more densely populated TAZs on which less crashes have been observed. De Guevara et al. (*15*) developed planning-level ZCPMs for the city of Tucson, Arizona. They considered many socio-demographic and network variables in their model construction. They concluded that predictors such as population density, the number of persons younger than 17 years old as a percentage of the total population, the number of employees, the intersection density, the percentage of miles of principal arterials, the percentage of miles of minor arterials and the percentage of miles of urban collectors are significant predictors for the NOCs. Hadayeghi et al (*16-21*) have been working on ZCPMs for several years. In one of their first studies, it was shown that the number of accidents in a TAZ increases when the VKT, major and minor road length, total employed labor force, household population, and intersection density increase and it decreases with a higher posted speed and a higher level of congestion in the TAZ (*17*). Hadayeghi et al (*18*) investigated the temporal transferability of the ZCPMs by applying models constructed on 1996 data to predict the NOCs for each TAZ in 2001 for the City of Toronto. They concluded that the models are not transferable statistically but VKT, socioeconomic and demographic parameters are significantly stable over time. In another research, twenty-three regression models were developed to examine the relationships between several types of transportation planning variables and collision frequency. Models were developed for each planning category individually and in combination with other categories. Comparing the models' performance indicated that the comprehensive models are performing statistically better than individual models. The results showed the potential of planning-level safety models to provide decision support tools for planners to consider safety in the planning phase (*19*). Hadayeghi et al (*20*) conducted the same research but this time they applied Geographically Weighted Poisson Regression (GWPR) instead of taking Generalized Linear Modeling (GLM) approach. The major difference between these two types of models is that GWPR models allow the model coefficient estimates to vary spatially for each TAZ. This very important additional attribute of these models provides some extra information as it takes the spatial location of a crash into consideration.

Lovegrove and Sayed (*22*) concluded that quantifying the relationship between the zonal characteristics such as exposure, network, socio-demographic and TDM variables and crashes at a zonal level provides a predictive tool to predict the NOCs in a TAZ. They have used GLM techniques to develop ZCPMs for both urban and rural areas across the Greater Vancouver Regional District (GVRD). Their results show that increasing signal density, intersection density per unit area and per lane kilometers, arterial-local intersections in rural areas and total arterial road lane kilometers will lead to an increase in the NOCs. On the contrary, an increase in the number of three-leg intersections and local road lane kilometers will decrease the NOCs in a TAZ. Lovegrove and Sayed (*23*) further developed a set of ZCPMs for a "black-spot" study in GVRD. These sets of ZCPMs consist of an exposure variable (VKT) and other network, socio-demographic and TDM variables. The results of this study also confirmed that ZCPMs have the potential to complement traditional reactive road safety improvement programs.

Recently, some researchers constructed ZCPMs by associating the NOCs in a TAZ with trip production/attraction and other network characteristics. Abdel-Aty et al (*24*) identified and prioritized important variables which can be associated with crashes per TAZ by means of the Classification and Regression Trees technique. It was shown that this methodology will be helpful in incorporating proactive safety measures for long range transportation planning. They also developed different ZCPMs for different crash severity levels and concluded that different sets of predictors should be considered based on the type or severity of crashes (e.g. total trip productions and attractions provide better model fit for the total and peak hour crashes while severe crashes were best predicted by different trip related variables) (*25*). Naderan and Shahi (*26*) investigated the possibility of associating travel demand in urban areas with crash frequencies in each TAZ. They developed a series of ZCPMs using the Number of Trips (NOTs) produced/attracted as predictors. They concluded that these models provide the basic tool for evaluating TDM scenarios in urban transportation planning in terms of traffic safety as the application of a specific TDM scenario may reduce trip productions of a specific motive. The drawback of considering only trips as an exposure variable is that the impact of trip time, trip length, route choice, intrazonal traffic and transit traffic on a TAZ will be neglected. The number of produced/attracted trips might be an acceptable indicator of how busy or active a TAZ is or how much people are exposed to dangerous situations, but it always leaves out the effects of through traffic which is just passing through a TAZ neither having their origin or destination in that TAZ.

Although most of the above mentioned studies were trying to demonstrate their potential as a predictive tool at the planning-level, so far not much attention has been paid to application of these models to evaluate the effect of TDM's on traffic safety. There are very few attempts to estimate the road safety benefits of applying a specific TDM strategy. In a study conducted by Lovegrove and Litman (*3*), they assumed the effect of implementing these strategies on different explanatory variables of the CPMs and based on these assumptions the expected NOCs has been calculated for each TDM strategy. For instance, it was concluded that a smart growth strategy of more compact and multi-modal land use development patterns may increase traffic safety by means of reducing crash frequency per capita by 20% and 29% for total and severe crashes subsequently. An et al (*27*) found Vehicle Hours Travelled (VHT), the number of intersections and the number of households with low income level to be correlated with the NOCs in TAZs. After running two add-capacity projects in the Pikes Peak region and applying the results in their developed ZCPMs for the do-nothing scenario and both project scenarios, total crashes for both projects were estimated to decrease 0.1% and 0.06% when compared with the do-nothing scenario.

According to the literature, exposure is the most important predictor of crashes; therefore, having a more informative measure of exposure, is expected to result in a better crash prediction. When a TDM scenario is performed, it basically changes the exposure compared with the null scenario. Thus, it is essential to predict the exposure measure as accurate as possible after implementation of the fuel-cost scenario. Activity-based models help with this as they are able to simulate the scenarios and in this case, they model the decision process of individuals with respect to the changes in fuel price. This is the key advantage of applying activity-based models rather than making educated guesses about the impact of fuel-cost changes on travel demand in order to obtain exposure. In the next section FEATHERS activity-based model is briefly introduced and its contribution to the fuel-cost scenario evaluation process is discussed.

IMPACT OF FUEL-COST ON TRAFFIC DEMAND

Traditionally, travel was assumed to be the result of four subsequent decisions which were modeled separately, also referred to as four-step models. More recently, several researchers claimed that travel has an isolated role in these models and the reason of why people undertake trips is completely neglected. This is why activity-based models have been taken into consideration. The main difference between four-step models and activity-based transportation models is that the latter try to predict interdependencies between several facets of activity profiles (*28*). Hence, activity-based models are designed to keep the linkages between the travel decisions of individual members of a single household, interactions among family members such as the use of household vehicles, sharing household responsibilities or performing joint activities, often affects and in many cases largely determines people's travel. Four-step models that ignore such linkages, misstate people's responses to TDM strategies. It is shown that activity-based models are capable of treating TDM strategies and policy issues whereas four-step models become ineffective (*29*).

FEATHERS Framework

The FEATHERS framework (*30*) was developed in order to facilitate the development of activity-based models for transportation demand in Flanders, Belgium. The scheduling engine that is currently implemented in the FEATHERS framework is based on the scheduling engine that is present in the Albatross system (*31*). Currently, the framework is fully operational at the level of Flanders. The real-life representation of Flanders is embedded in an agent-based simulation model which consists of over six million agents, each agent representing one member of the Flemish population. A sequence of 26 decision trees, derived by means of the CHi-squared Automatic Interaction Detector (CHAID) algorithm, is used in the scheduling process and decisions are based on a number of attributes of the individual (e.g., age, gender), of the household (e.g., number of cars) and of the geographical zone (e.g., population density, number of shops). For each agent with its specific attributes, the model simulates whether an activity (e.g. shopping, working, leisure activity …) is going to be carried out or not. Subsequently, amongst others, the location, transport mode and duration of the activity are determined, taking into account the attributes of the individual (*32*).

Implementation of Fuel-Cost Scenario in FEATHERS

An important asset of activity-based models in this context is their integrated approach towards activities and travel. Due to this approach, it can be taken into account that certain trips, which are linked to activities that are not so flexible (such as e.g. work activities) are less likely to be altered under changing traffic system conditions than others (such as e.g. leisure activities). In addition, activity-based models are not only able to predict a change in the demand for travel, but they also predict shifts between different modes of transport and the reallocation of activities due to the imposed measures. Providing a structured approach to agent-based modeling of activities and travel for individuals, the FEATHERS framework is able to account for TDMs. For instance, in the application of a fuel cost scenario, FEATHERS can predict the impact on the NOTs, modal shift and changes in trip time and length.

However, price changes can have an impact on different facets of travel, affecting the NOTs people undertake, their destination, route, mode, travel time, type of vehicle (including size, fuel efficiency and fuel type) and parking location and duration. Therefore, in order to predict the impact of price changes like fuel cost, the scheduling engine has to be structured to account for those changes. In this scheduling engine, price and cost parameters are incorporated in the decision trees that are concerned with activity selection, timing, trip-chaining, location and mode choices. The extended decision trees or Parametric Action Decision Trees combine conventional decision trees and parametric action assignment rules yielding a model that is sensitive for travel-costs scenarios (*33*). In this study, fuel's cost is assumed to be increased by 20%.

DATA PREPARATION

The study area in this research is the Dutch speaking region in northern Belgium, Flanders. Flanders has over 6 million inhabitants, or about 60% of the population of Belgium. As already mentioned before, an activity-based model within the FEATHERS framework is applied on the Flemish population to derive the in depth information of Flemish peoples' travel behavior and travel demand for a null-scenario (current situation) and some TDM scenarios like increasing fuel-cost, teleworking, etc. FEATHERS produces traffic demand by means of OD matrices. These OD matrices include the number of trips for each traffic mode at different disaggregation levels (i.e. age, gender, day of the week, time of a day and motive). This traffic demand is then assigned to the network to obtain detailed exposure measures at the network level. Exposure measures are then aggregated to TAZ level. This has been carried out at the zonal level comprising of 2200 TAZs. The average size of TAZs is 6.09 square kilometers with standard deviation of 4.78 square kilometers. In addition, for each TAZ a set of variables including socio-demographic and network variables were derived to construct ZCPMs. The crash data used in this study consist of a geo-coded set of fatal and injury crashes that have occurred during the period 2004 to 2007 and were provided by the Flemish Ministry of Mobility and Public Works. Table 1 shows a list of selected variables, together with their definition and descriptive statistics, which have been used in developing the ZCPMs presented in this paper.

FUEL-COST SCENARIO EVALUATION

In this study, different Negative Binomial (NB) ZCPMs were constructed using the explanatory variables listed in Table 1. The models can be categorized into three different groups based on the type of exposure measure that was utilized, i.e. 1) flow-based models, 2) trip-based models and 3) models based on a combination of the two. Flow-based models were constructed by regressing the NOICs in each TAZ on VHT or VKT, as the exposure variables, and the network and socio-demographic variables listed in Table 1. Trip-based models use the same network and socio-demographic variables but use NOTs as the exposure variable. In the third type of models, both flow and trip based variables are included simultaneously as measures of exposure. Coefficients were estimated by using a forward selection procedure and taking one of the exposure variables for the starting point and then additional candidate variables were selected. For model development, 70% of the TAZs were chosen randomly as for the training set and the rest of 30% were restored as for the test set. The analysis results revealed that using the combination of exposure variables provides a better model fit; i.e. the models which simultaneously have both NOTs and VHT/VKT as the exposure variables over perform the flow-based or trip-based models. Based on different statistical tests of goodness of fit the final ZCPM has been chosen. Table 2 provides the final model estimates of the different explanatory variables. This is the model by which the fuel-cost scenario is being evaluated.

TABLE 1 Selected Variables to Develop ZCPMs

	Variable	Definition	Average	Min	Max	SD
	Crash	total NOICs observed in a TAZ (2004-2007)	36.03	0	326	41.58
Exposure variables	Number of Trips	average daily number of trips originating/arriving from/at a TAZ	2765.8	0	18111.4	2869.8
	Motorway VKT	total daily vehicle kilometers traveled on motorways in a TAZ	27471.82	0	946152.8	84669.53
	Other Roads VKT	total daily vehicle kilometers traveled on other roads in a TAZ	26662.85	0	303237.6	28133.04
Network variables	Capacity	hourly average capacity of links in a TAZ	1790.1	1200	7348.1	554.6
	Intersection	total number of intersections in a TAZ	5.8	0	40	5.9
	Urban	Is the TAZ in an urban area? "No" represented by 0 "Yes" represented by 1	0	0	1	-[a]
	Suburban	Is the TAZ in a suburban area? "No" represented by 0 "Yes" represented by 1	0	0	1	-
Socio-demographic variables	Income Level	average income of residents in a TAZ describes as below: "Monthly salary less than 2249 Euro" represented by 0 "Monthly salary more than 2250 Euro" represented by 1	1	0	1	-
	Population	total number of inhabitants in a TAZ	2614.52	0	15803	2582.6

a: Data not applicable.

TABLE 2 Model Estimates for the Final Chosen ZCPM

Coefficients	**Estimate**	**Std. Error**	**z value**
(Intercept)	-4.141e+00	1.724e-01	-24.016
log(Number of Trips)	4.520e-01	2.768e-02	16.330
log(Motorway VKT)	7.744e-03	3.404e-03	2.275
log(Other Roads VKT)	3.132e-01	1.411e-02	22.197
Income Level	-1.071e-01	4.153e-02	-2.580
Capacity	3.894e-04	2.758e-05	14.118
Intersection	2.888e-02	2.473e-03	11.676
Urban	3.520e-01	5.836e-02	6.032
Suburban	9.095e-02	2.949e-02	3.084
Population	2.293e-05	8.628e-06	2.658

For scenario evaluation and by running the activity-based transportation model, OD matrices for the fuel-cost scenario will be derived. To carry out the assignment of car trips to the network, an equilibrium method was selected. The fundamental nature of equilibrium assignment is that travelers will strive to find the shortest path (e.g. minimum travel time) from origin to destination, and network equilibrium occurs when no traveler can decrease travel effort by shifting to a new path. This is an optimal condition, in which no user will gain from changing travel paths once the system is in equilibrium. At this moment, all required variables became available to set up the evaluation task. Now, the final ZCPM is applied to the fuel-cost scenario dataset and consequently crashes are predicted for the fuel-cost scenario in each TAZ. The traffic safety evaluation can then be conducted by comparing the NOICs predicted by the final ZCPM for null and fuel-cost scenario. Figure 1 depicts the conceptual framework of the traffic safety evaluation process.

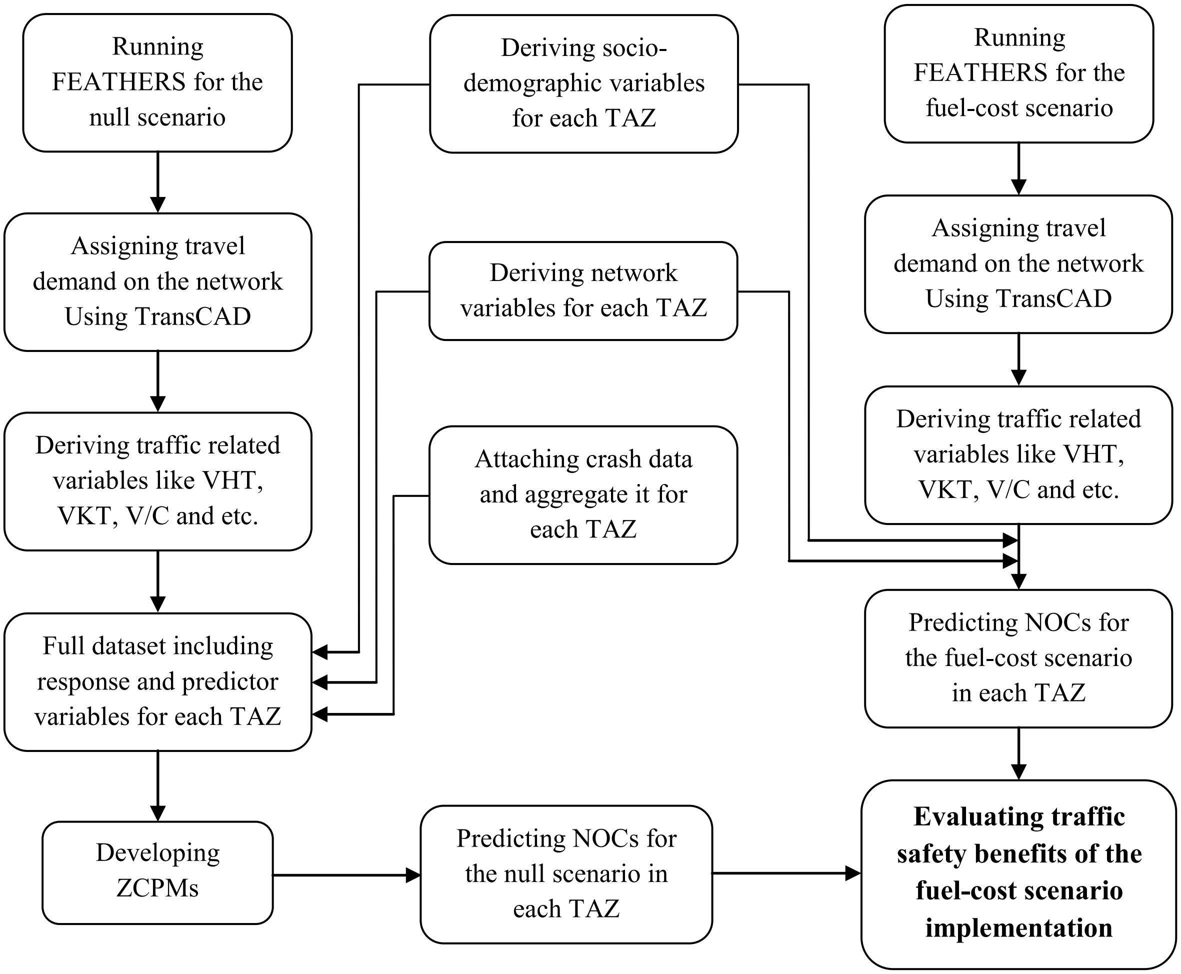


FIGURE 1 Conceptual framework of the traffic safety evaluation process.

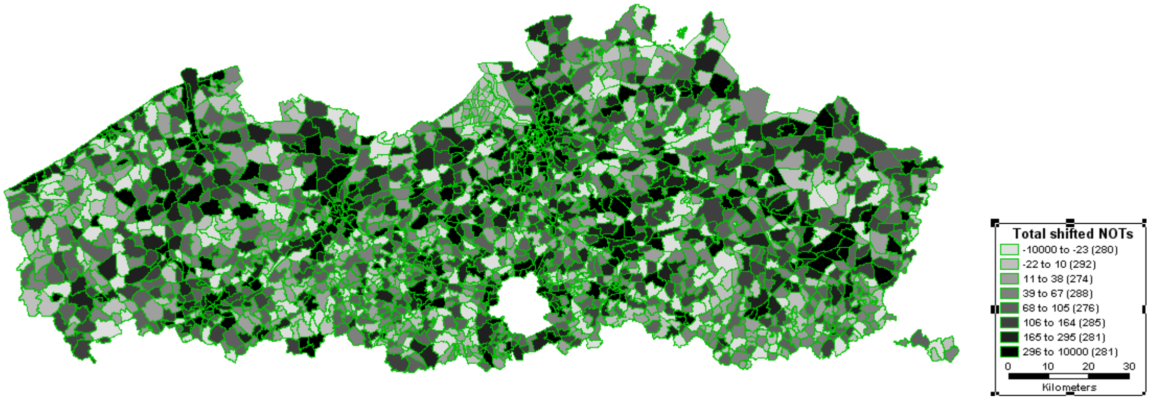
Before describing the traffic safety impact of the fuel-cost scenario, it would be beneficial to have a look at the changes being made to the more traffic related attributes playing a role in the whole chain. As it has been described before, increasing fuel cost will affect and increase the total travel expenses of motor vehicle trips. As a result, people will start comparing the relative costs of travelling and may consider shifting to other available transportation modes. For instance, short distance trips can be substituted by public transportation (e.g. bus or tram) or slow mode (i.e. biking or walking) or long distance trips may be shifted towards a higher use of public transportation (e.g. train) or carpooling.

By comparing OD matrices derived from the activity-based model for both the null and the fuel-cost scenario, it will be possible to perceive any changes in NOTs for different modes and also figure out if there will be any mode shift occurring. The results of these comparisons revealed that conducting the fuel-cost scenario reduces the total NOTs carried out by car (-3.732%) and in contrast, an increase in the NOTs by other modes (Car Passenger by +2.414%, Public transportation by +3.921% and Slow mode by +8.581%) is observed. In addition to the changes observed at the aggregate level, it is also interesting to observe these changes at a disaggregated level, i.e. on the TAZ level. The total NOTs that shifted from car to other travel modes is depicted in Figure 2(a) (darker TAZs represent higher mode shift while brighter TAZs represents lower mode shift). It was observed that urban areas experience higher mode shift while in some particular TAZs like the ones nearby borders less mode shift can be observed. This might be explained as the cross-border public transportation is not a convenient option or in some TAZs there is no cross-border public transportation service available. Thus, many travelers who are travelling across borders prefer to take their car which leads to a higher possibility of having more crashes.

Although the NOTs may represent an acceptable indication of exposure, it neglects the impact of transit traffic which is just passing through a TAZ. As already mentioned before, NOTs do not contain any information about trip time, trip length, route choice, intrazonal traffic and transit traffic; therefore, investigating the impact of fuel-cost scenario on these aspects cannot be practically carried out by considering the changes in NOTs starting or arriving at a TAZ. Thus, other exposure variables which are capable of accounting for the impacts of trip assignment should be taken into account. As a result, inclusion of the flow related variables (VHT or VKT) in the prediction models is essential. The results show that the average values of the VKT and VHT decrease as a result of implementing the fuel-cost scenario. Not surprisingly, the reductions for motorways are higher than for other roads (i.e. reduction in motorway VHT by 16.85%, other roads VHT by 10.34%, motorway VKT by 13.31% and other roads VKT by 9.78%). This can be explained as the majority of long distance trips are carried out on motorways. This is also an indication that the fuel-cost scenario is affecting long distance trips somewhat more than short distance trips. It can also be noticed that the reduction in VHT is slightly more than the reduction in VKT. This also can be explained as the travel time decreases stronger than travel distance due to the secondary rerouting effect of reduced travel demand.

Predictably, in the fuel-cost scenario the total predicted crashes decreases compared to the null scenario. This is the consequence of reduced exposure as the main predictor of crashes. At the aggregated level, the total NOICs is predicted to be reduced by 3827 crashes for a period of 4 years, i.e. 4.65%. The maximal decrease in NOICs is 24 crashes and in the percentage is 19% for a TAZ (these figures are for different TAZs) while the average crash reduction per TAZ is 1.74 crashes. Illustration of changes in NOICs for all TAZs may present a better pattern on how different TAZs are influenced by the fuel-cost scenario. In Figure 2(b), the reduction in the predicted NOICs is displayed for each TAZ. The darker TAZs are the ones which experience the highest reduction unlike the brighter TAZs in which the least reduction is observed. This figure reveals that the reduction of the number of predicted crashes is greater for urban areas and generally trivial for TAZs close to the Flemish borders. By comparing Figures 2(a) and 2(b), a relatively similar pattern can be noticed. It can be described by the fact that in the TAZs on which more trips are shifted towards a safer traffic mode, there will be fewer crashes expected to occur.

(a) Total shifted NOTs from car to other modes in each TAZ after fuel-cost scenario implementation



(b) Total NOICs reduced in each TAZ after fuel-cost scenario implementation

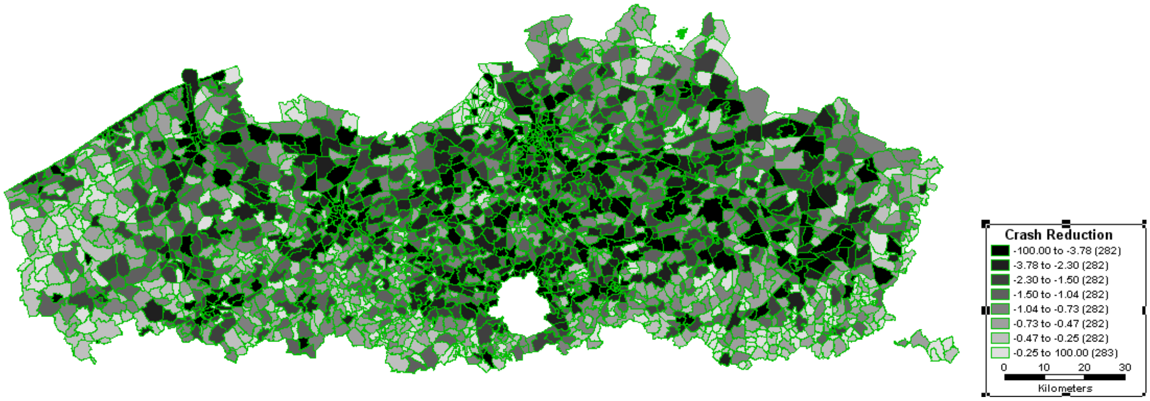


FIGURE 2 Graphical representation of the fuel-cost scenario impact.

CONCLUSIONS

In this study a zonal crash prediction modeling approach has been integrated into the fuel-cost scenario to assess this TDM strategy's impact on traffic safety. This has been carried out by applying an activity-based travel model's outputs. Based on the results the following conclusions can be drawn:

- Activity-based transportation models provide an adequate range of in-depth information about individuals' traveling behavior. The advantage of activity-based transportation models is that the impact of applying a TDM strategy will be accounted for each individual throughout a decision making process. They provide more reliable information as TDM strategies are inherently modeled in these models unlike traditional models.
- Unlike previous studies which have usually followed a reactive approach in evaluating traffic safety benefits of conducting a TDM strategy, in this study a proactive methodology has been followed. This has been carried out in an assessment exercise by assuming a 20% increase in the fuel price

- Sole use of NOTs originating/destining from/to a TAZ for crash prediction and consequently evaluating the safety impacts of a TDM strategy will result missing some important information about the characteristics of reduced trips; i.e. NOTs, as an exposure variable, is not sensitive to trip time, trip length and route choice. Thus, other exposure variables which are sensitive to the impacts of trip assignment should be taken into account. This has been carried out by assigning the traffic demand to the network using an equilibrium assignment and by computing exposure variables that are sensitive to the assignment like VHT and VKT.
- The results of the comparison analysis revealed that the fuel-cost scenario implementation has many impacts like travel demand reduction, crash occurrence reduction, VKT and VHT reduction and mode shift. Fuel-cost scenario causes a reduction of 5.02 billion VKT per year, almost 11.57% of total yearly VKT in Flanders. Total NOICs is predicted to be reduced by 3827 crashes for a period of 4 years (an average of 957 fatal and injury crashes per year) after implementing the fuel-cost scenario.
- Considering the reduction of the NOICs in TAZs under the fuel-cost scenario, it was revealed that the maximum crash reduction was observed in urban areas (cities) unlike TAZs near Flemish borders. It can be concluded that in cities the possibility of finding a substitution mode for cars are higher than other areas. In contrast, the TAZs nearby the borders are usually lacking good public transportation services. Therefore it is expected not to see many trips shifted to other safer modes than car and consequently having a more stable traffic safety situation in these TAZs despite conducting a fuel-cost scenario.
- Aside from the evaluation of traffic safety benefits, investigation on the changes in other modes' travel demand showed that in some TAZs there are not much trips carried out by public transportation or slow mode. This doesn't allow the modal shift from car to the other modes in these TAZs. It could be beneficial if these TAZs are considered to be investigated more specifically to check whether they are lacking proper public transportation services or bike route infrastructure.

This paper presents a new extension in application of ZCPMs incorporated into TDM strategies. The results show the ability of ZCPMs as a reliable predictive tool which can be used in the planning-level transportation projects. Although there are some clear benefits (e.g. traffic safety improvement or VKT reduction) being noted by conducting the fuel-cost scenario, but it would be beneficial if this study will be extended to include other TDM strategies to present a comprehensive package.

REFERENCES

(1) Litman, T. Mobility Management Traffic Safety Impacts. Presented at 85th Annual Meeting of the Transportation Research Board, Washington D.C. USA, 2006.

(2) Litman, T. *Evaluating Mobility Management Traffic Safety Impacts*. Victoria, BC, Canada: Victoria Transport Policy Institute, 2004.

(3) Lovegrove, G. R. and T. Litman.Using Macro-Level Collision Prediction Models to Evaluate the Road Safety Effects of Mobility Management Strategies: New Empirical Tools to Promote Sustainable Development. Presented at 87th Annual Meeting of the Transportation Research Board, Washington D.C. USA, 2008.

(4) Grabowski, D. C. and M. A. Morrisey. Gasoline prices and motor vehicle fatalities. *Journal of Policy Analysis and Management*, vol. 23, no. 3, 2004, pp. 575-593.

(5) Chi, G., A. G. Cosby, M. A. Quddus, D. Levinson, and P. A. Gilbert. Gasoline Prices and Traffic Safety in Mississippi. Presented at 90th Annual Meeting of the Transportation Research Board, Washington DC, United States, 2011.

(6) Tarko, A. P., M. Inerowicz, J. Ramos, and W. Li, “Tool with Road-Level Crash Prediction for Transportation Safety Planning. In *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2083, no. 1, 2008, pp. 16-25.

(7) Levine, N., K. E. Kim, and L. H. Nitz. Spatial analysis of Honolulu motor vehicle crashes: II. Zonal generators. *Accident Analysis & Prevention*, vol. 27, no. 5, 1995, pp. 675-685.

(8) Amoros, E., J. L. Martin, and B. Laumon. Comparison of road crashes incidence and severity between some French counties. *Accident Analysis & Prevention*, vol. 35, no. 4, 2003, pp. 537-547.

(9) Aguero-Valverde, J. and P. P. Jovanis. Spatial analysis of fatal and injury crashes in Pennsylvania. *Accident Analysis & Prevention*, vol. 38, no. 3, 2006, pp. 618-625.

(10) Huang, H., M. Abdel-Aty, and A. Darwiche. County-Level Crash Risk Analysis in Florida. In *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2148, no. 1, 2010, pp. 27-37.

(11) Noland, R. B. and L. Oh. The effect of infrastructure and demographic change on traffic-related fatalities and crashes: a case study of Illinois county-level data. *Accident Analysis & Prevention*, vol. 36, no. 4, 2004, pp. 525-532.

(12) Wier, M., J. Weintraub, E. H. Humphreys, E. Seto, and R. Bhatia. An area-level model of vehicle-pedestrian injury collisions with implications for land use and transportation planning. *Accident Analysis & Prevention*, vol. 41, no. 1, 2009, pp. 137-145.

(13) Noland, R. B. and M. A. Quddus. A spatially disaggregate analysis of road casualties in England. *Accident Analysis & Prevention*, vol. 36, no. 6, 2004, pp. 973-984.

(14) Quddus, M. A. Modelling area-wide count outcomes with spatial correlation and heterogeneity: An analysis of London crash data. *Accident Analysis & Prevention*, vol. 40, no. 4, 2008, pp. 1486-1497.

(15) de Guevara, F. L., S. P. Washington, and J. Oh. Forecasting crashes at the planning level. A simultaneous negative binomial crash model applied in Tucson, Arizona. In *Transportation Research Record: Journal of the Transportation Research Board*, 2004, pp. 191-199.

(16) Hadayeghi, A. Use of Advanced Techniques to Estimate Zonal Level Safety Planning Models and Examine Their Temporal Transferability. University of Toronto, 2009.

(17) Hadayeghi, A., A. Shalaby, and B. Persaud. Macrolevel Accident Prediction Models for Evaluating Safety of Urban Transportation Systems. In *Transportation Research Record*: *Journal of the Transportation Research Board*, vol. 1840, no. 1, 2003, pp. 87-95.

(18) Hadayeghi, A., A. S. Shalaby, B. N. Persaud, and C. Cheung. Temporal transferability and updating of zonal level accident prediction models. *Accident Analysis & Prevention*, vol. 38, no. 3, 2006, pp. 579-589.

(19) Hadayeghi, A., A. Shalaby, and B. Persaud. Safety Prediction Models: Proactive Tool for Safety Evaluation in Urban Transportation Planning Applications. In *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2019, no. 1, 2007, pp. 225-236.

(20) Hadayeghi, A., A. S. Shalaby, and B. N. Persaud. Development of planning level transportation safety tools using Geographically Weighted Poisson Regression. *Accident Analysis and Prevention*, vol. 42, no. 2, 2010, pp. 676-688.

(21) Hadayeghi, A., A. Shalaby, and B. Persaud, Development of Planning-Level Transportation Safety Models using Full Bayesian Semiparametric Additive Techniques. *Journal of Transportation Safety & Security*, vol. 2, no. 1, 2010, pp. 45-68.

(22) Lovegrove, G. R. and T. Sayed. Macro-Level Collision Prediction Models for Evaluating Neighbourhood Traffic Safety. *Canadian Journal of Civil Engineering*, vol. 33, 2006, pp. 609-621.

(23) Lovegrove, G. R. and T. Sayed. Macrolevel Collision Prediction Models to Enhance Traditional Reactive Road Safety Improvement Programs. In *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2019, no. 1, 2007, pp. 65-73.

(24) Abdel-Aty, M., C. Siddiqui, and H. Huang. Zonal Level Safety Evaluation Incorporating Trip Generation Effects. Presented at 90th Annual Meeting of the Transportation Research Board, Washington D.C. USA, 2011.

(25) Abdel-Aty, M., C. Siddiqui, and H. Huang. Integrating Trip and Roadway Characteristics in Managing Safety at Traffic Analysis Zones. Presented at 90th Annual Meeting of the Transportation Research Board, Washington D.C. USA, 2011.

(26) Naderan, A. and J. Shahi. Aggregate crash prediction models: Introducing crash generation concept. *Accident Analysis & Prevention*, vol. 42, no. 1, 2010, pp. 339-346.

(27) An, M., C. Casper, and W. Wu. Using Travel Demand Model and Zonal Safety Planning Model for Safety Benefit Estimation in Project Evaluation. Presented at 90th Annual Meeting of the Transportation Research Board, Washington D.C. USA, 2011.

(28) Davidson, W. et al. Synthesis of first practices and operational research approaches in activity-based travel demand modeling. *Transportation Research Part A: Policy and Practice*, vol. 41, no. 5, 2007, pp. 464-488.

(29) Vovsha, P. and M. Bradley. Advanced Activity-Based Models in Context of Planning Decisions. In *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1981, no. 1, 2006, pp. 34-41.

(30) Janssens, D., G. Wets, H. J. P. Timmermans, and T. A. Arentze. Modelling Short-Term Dynamics in Activity-Travel Patterns: Conceptual Framework of the Feathers Model. Presented at the 11th World Conference on Transport Research, Berkeley CA, USA, 2007.

(31) Arentze, T. A. and H. J. P. Timmermans. ALBATROSS – Version 2.0 – A learning based transportationoriented simulation system. EIRASS (European Institute of Retailing and Services Studies)." TU Eindhoven, NL, 2004.

(32) Kochan, B., T. Bellemans, D. Janssens, and G. Wets. Assessing the Impact of Fuel Cost on Traffic Demand in Flanders Using Activity-Based Models. Presented at the Travel Demand Management TDM, Vienna, Austria, 2008.

(33) Arentze, T. A. and H. J. P. Timmermans. Incorporating Parametric Action Decision Trees in Computational Process Models of Activity-Travel Behavior: Theory and Illustration. *Advanced OR and AI Methods in Transportation*, 2005, pp. 567-572.