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ORIGINAL PAPER

Oil vulnerability in the greater Toronto area: impacts of high fuel prices on urban form and environment

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Abstract The rising cost of fossil fuel is a recognized phenomenon, but its impact at the household level is still widely unknown. Understanding how the socioeconomic impacts of rising fuel prices might be distributed across urban areas is a critical issue that is necessary for sustainable urban transportation planning. This study has refined the vulnerability index for petrol expense rises (VIPER) framework [previously proposed by Dodson and Sipe Urban Stud 44(1):37–62, (2007)] by incorporating travel survey data to better represent households' car dependence. Through this modified VIPER framework, we seek to understand how the socioeconomic impact of rising fuel costs will be distributed across the greater toronto area. The findings of this research reveal a pattern in the distribution of oil vulnerability that depicts a three-ring configuration: expanding outwards from the lowest oil vulnerability in the urban core (1st ring), followed by the highest oil vulnerability in the city's inner suburbs (2nd ring), and a transition to a lower oil vulnerability in the suburban areas (3rd ring). Such results reveal the need for transportation and land use policy measures that tackle the transportation-related social and economic disadvantages due to high fuel prices in the future. The transportation and land use policy measures referred to in this paper focus on the reduction in private automobile use. Therefore, those measures aimed at mitigating oil vulnerability may also have the environmental benefits of reducing greenhouse gas emissions and preserving greenfields.

Keywords Oil vulnerability · Automobile dependence · Rising oil prices · Urban spatial analysis

Introduction

The continued rise of global oil prices has generated concern over its social and economic impact. Highly automobile-dependent cities such as sprawling urban regions of North America are most likely to be affected. To date, there has been little research on the links between transport costs, socioeconomic status, urban socio-spatial differentiation, and household risk related to rising fuel costs. We believe this is an issue that deserves serious consideration given the uncertainty of fuel prices and the negative social and economic impacts of high fuel prices on urban residents. Of critical importance is how the impact of rising fuel prices is distributed across the urban areas, as it is important to evaluate the ability of households to sustain future shocks of high oil price.

This study focuses on the spatial analyses of oil vulnerability across the greater toronto area (GTA). It reports an empirical analysis of spatial oil vulnerability in the GTA using a methodology for assessing the vulnerability of households to rising oil prices. In 2007, Dodson and Sipe conducted a study to assess the spatial distribution of oil vulnerability in Australian cities. They developed a framework called vulnerability index for petrol expense rises (VIPER), a locational measure that assigns average relative values of oil vulnerability. Oil vulnerability is estimated empirically based on variables drawn from the Australian census, including socioeconomic indices, household motor vehicle ownership, and journey-to-work data. Our study refines this VIPER framework using travel survey data in conjunction with socioeconomic variables

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obtained from the census. The travel survey data, which includes percentage of all trips by car, is considered appropriate for representing households' car dependence.

The research findings reported in this paper raise questions about the ability of households in the GTA to sustain the impacts of rising oil prices. Regarding higher oil prices, it asks: Do sprawling urban regions subject certain socioeconomic groups to greater risks than others? Increasing oil prices can have a drastic impact especially if they are not planned for, and if policy decisions do not keep pace with changes in oil supply and price.

This study's findings may provide tools for decision makers by identifying areas of the GTA that may be most impacted by rising oil prices. We argue that infrastructure planning and decisions on where to direct infrastructure investments should take the impact of rising oil prices into consideration. In order to mitigate this impact, investments may be directed to provide greater mobility options that reduce automobile dependence. For instance, when meeting transport demand, more effective investments can be made by providing greater public transit services to oil-vulnerable areas of the GTA rather than building extensive highways that may exacerbate oil vulnerability. The same infrastructure investments to reduce oil vulnerability can also mitigate some of the negative environmental impacts of car dependence, such as greenhouse gas emissions (GHG) and the degradation of greenfields. For instance, it is widely recognized that the transportation sector, specifically private automobiles, is a significant producer of GHG emissions. High-quality public transit can have the effect of reducing the number of private automobiles on the road and thus reducing the GHG emissions per person. Also, improving public transit service to mitigate oil vulnerability in the suburbs, rather than extending the road and highway network, can preserve greenfields on which they would be built. For instance, it is widely recognized that urban sprawl, which is characterized by a high degree of automobile dependence, has two main concerns: the rate at which it consumes greenfields; and the air pollution caused by automobile usage (Williams 1999; Newman and Kenworthy 1989a). Furthermore, the American Farmland Trust reports that about 400,000 acres of prime farmland is being lost to sprawl every year in the USA alone (Gillham 2002). This includes the destruction of natural habitat of several species, which have consequently become endangered (Gillham 2002). In terms of air pollution, a study of 89 global studies by Kenworthy (2003) revealed that the private transport CO_2 emissions per capita in Canada is 2,348 kg/person, whereas public transport CO_2 emissions per capita are 74 kg/person. For (Newman and Kenworthy 1989b), reducing car dependence requires not only re-urbanization to increase densities, but also transport policies that limit construction of new roadways and reallocating resources to promote active transportation and public transit. According to the American Public Transportation Association (2008), public transportation use reduces CO_2 emissions by more than 37 million metric tonnes every year in the USA by reducing travel on roadways and supporting more efficient land use patterns. People who use public transportation reduce their carbon footprint and conserve energy by eliminating travel that would otherwise have been made using private vehicles (American Public Transportation Association 2008). Therefore, the use of public transport to reduce oil vulnerability may also have the added effect of mitigating GHG emissions and preservation of valuable farmland, by reducing the usage of automobile and curbing the outward suburban expansion.

The paper is arranged as follows: a literature review on the issue of rising fuel prices to highlight the social and economic impacts on urban regions with a focus on the GTA; establishing the methodology for assessing the GTA's spatial distribution of oil vulnerability; and conducting an empirical analysis on the socioeconomic impact of higher fuel prices. The paper concludes with a discussion on key observations and recommendations for further research. The research throughout this study was carried out in 2013 at the University of Toronto's Department of Civil Engineering.

Throughout this paper, reference is made to car dependence and vulnerability, which can be explained as:

Car dependence

The reliance on an automobile for daily trips, including work and nonwork trips, due to lack of other viable transportation options. Other transportation options, such as walking and public transit, are not feasible due to the physical separation of activities consistent with low-density urban sprawl. The dispersal of employment, retailing, and service facilities creates a dispersed pattern of trips that are long and not pedestrian friendly (Barton 1992). Also, low densities impact public transit route catchment areas such that the dispersed activities are poorly serviced (Barton 1992). These factors contribute to dependence on the automobile. Conversely, Mees (2000, 2010) argues that even low-density areas can be serviced with excellent public transit service provided that a central authority is responsible for the seamless integration of public transit modes and coordination of scheduling.

Oil vulnerability

The concept of oil vulnerability in this research paper is contemplated at the household scale. Oil vulnerability considers the level of socioeconomic impacts that fuel

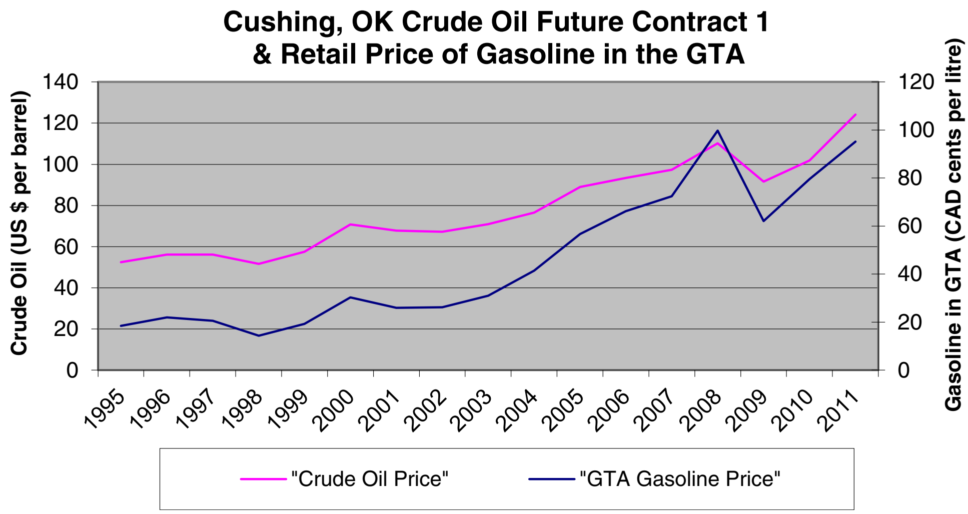

Fig. 1 Cushing, OK crude oil future contract 1 (Dollars per Barrel) and retail price of gasoline in the GTA (Cents per Liter) (Energy Information Administration 2013 & Statistics Canada 2012a)

costs have on a household. Socioeconomic effects of fuel costs can include impacts on household finances, consumption patterns (Dodson and Sipe 2008), and the ability to physically access goods and services outside of the home. The assignment of oil vulnerability to one household is relative to the level of oil vulnerability of all households throughout the GTA, save and expect those not captured by this study.

Issues of rising fuel prices

The continued rise in the price of international oil is a phenomenon that cannot be ignored. This trend has significantly affected Canadian oil prices. Further, predicting this trend is extremely difficult. As the OPEC President explains, "not only must one take into account the fundamental factors, like supply and demand, but one must also anticipate the nonfundamentals, like geopolitical tensions and possible supply disruptions" (Newman 2008). The following is a review of scholarly analyses that shed light on the topic of rising fuel prices.

Dodson and Sipe (2007) discussed this phenomenon on both the international and national scale. Similarly, Fig. 1 presents the international price of crude oil from 1995 to 2011 as well as the average annual price of regular unleaded gasoline at self-service filling stations in the GTA over the same time period. Crude oil prices impact gasoline prices at the local level, and as shown in Fig. 1, both variables have generally been rising over the time period shown.

The issue of rising oil prices is highly complex, and there are numerous debates surrounding the topic. Within this debate, there are scholars who identify possible causes of rising oil prices. For instance, Dodson and Sipe (2007) argue that overall global economic growth has created an increase in demands for oil, with especially high demand in China and India; while on the supply side, increased oil prices have been caused by supply interruptions.

Statistics Canada (2012b) explains that crude oil prices are established in the global market and determined by supply and demand factors, though there are other factors that affect supply and demand and thus contribute to determining the price of oil. These other factors that contribute to the final retail price of gasoline for Canadians include taxes and refinery and marketing margins. However, the price of crude oil established in the global market has the greatest impact on Canada's retail gasoline prices. Statistics Canada (2012a) has recorded historical average retail prices of gasoline for various urban centers. The data indicate that all of the urban centers have seen some increase in the retail price of gasoline at self-service filling stations. For instance, as shown in Fig. 1, the GTA has seen an increase from 52.4 cents per liter in 1995 to 124.1 cents per liter in 2011 (Statistics Canada 2012a).

Contemplating the potential impact of rising oil prices at the local level is relevant given Canada's current reliance on fuel. (Neilson 2006) conducted a global survey of consumers that reveals 83 % of Canadians have a vehicle for which fuel must be bought. The survey also reveals the most common methods of coping with rising oil prices are using private vehicles less, combining trips, reducing nonessential living expenses in order to compensate for higher fuel prices, and using public transit instead of driving.

World oil production and oil prices

Closely related to the issue of rising oil prices is the debate of future world oil production. World oil demand is expected to grow in the future, and if sufficient quantities of new oil cannot be brought into production to meet this demand, the peaking of world oil production will have occurred (Hirsch et.al. 2005). In a 2002 study, Colin J. Campbell predicted that oil will peak around the year 2010. Also, examining the year 2000 base case scenario revealed that the lack of spare capacity was the reason for increased oil prices (Campbell 2002). The price of oil did not rise as much as expected mainly due to the economic recession, which reduced the demand for oil and subsequently reduced the pressure on oil prices. Campbell (2002) explained that as the economy builds strength and moves out of the recession, demand for oil will be restored and will rise until it reaches the "ceiling of capacity." Campbell (2002) predicts that at the point of peak oil, the price of oil is expected to reach an all-time high, thus forcing the economy back into recession. In addition to Campbell's prediction, (Hirsch et al. 2005) compiled a list of peak oil analyses, which shows that many of the projected peak oil dates also cluster around 2010.

Alternatively, recent statistics produced by BP indicate that the total world oil production has generally increased from 2001 to 2011 (BP 2012). BP projects that between the years 2010 and 2030, the growth of world energy consumption will increasingly be met by nonfossil fuels. The supply from the Americas is expected to increase, by \$8 million barrels per day, as advances in drilling technologies unlock unconventional resources such as Canadian oil sands and US shale oil. Railsback (2012) claims that one measurement that paints a clearer picture of the current oil production scenario is the depth of drilling. Railsback (2012) recognizes that increase in the depth of giant petroleum discoveries in the past 15 years is assisted by technological advances, which have facilitated this type of exploration. The explanation of this is simple; drilling deeper preceded the increase in the price of petroleum by more than a decade.

The most revolutionary new development in the natural gas industry has been the improvement in techniques available to extract gas from shale rock (Gjelten 2012). In the past decade, energy companies in the USA have found it economically possible to extract shale gas through the process of fracking, otherwise known as hydraulic fracturing. The recent drop in gas prices, from May 2008 to July 2009, can be attributed in part to an increase in unconventional supplies, including shale gas. Shale gas accounted for only one percent of US gas output in 2000; however, fifty percent by 2035 is projected. The large increase in shale oil output in the USA has resulted in considerable price differentials between oil and gas (Asche et. al. 2012). To the extent that oil and gas are substitutable, market forces will encourage the price difference to iron out. Two hypotheses exist about how gas prices are set in deregulated markets. One view is based on gas-to-gas competition and implies that prices are primarily supply and demand for gas (Asche et. al. 2012). The other view argues that consumers are seeking energy and that a significant amount of substitution exists between various energy bearers (i.e., gas and oil), which means that prices will follow paths that will coincide over time (Asche et. al. 2012).

This research paper recognizes the above debate of peak oil and its impacts on oil prices and considers the scenario of rising oil prices. As such, we consider the following policy implications rising oil prices may have:

Fuel efficiency and fuel tax policies

Frankel and Menzies (2012) propose how to reduce oil use in the transportation sector through a complementary approach of increasing fuel economy and raising fuel taxes. Although this approach is based on American statistics, it is the result of a global trend of rising oil prices and therefore is relevant to this discussion. Their recommendation to increase the fuel economy of vehicles is based on the basic concept that if cars and trucks require less fuel to travel, households' financial burden from rising fuel costs will be less severe and vulnerability to this trend will be reduced. Frankel and Menzies (2012) explain that policies aimed at curbing the amount of energy used for transportation, as opposed to reducing travel distances, are accepting the dominance of the automobile and are attempting to "civilize" it. The corporate average fuel economy (CAFE) program is cited as an example of a "civilizing" policy. This program requires automobile manufacturers to achieve a certain miles per gallon (mpg) average. A similar example is Canada's excise tax of fuel-inefficient automobiles. A tax is placed on automobiles that have a weighted average fuel consumption rating of 13 or more liters per 100 kilometers. This tax is paid by the vehicle manufacturer at the time the automobile is delivered to a purchaser (Canada Revenue Agency 2007). These types of policies can work in conjunction with mandatory, federally regulated GHG performance standards that require manufacturers to rethink how automobiles are made and use fuel. Other attempts of mitigating the negative environmental impacts of the transportation sector include finding feasible alternative fuels that are renewable and more sustainable, as described by (Rasaafi et al. 2006).

The debate surrounding the value and effectiveness of mandatory fuel efficiency policies raises the issue that motorists are expected to drive more if the net fuel cost to operate a vehicle is reduced. Frankel and Menzies (2012) describe this as the "rebound" effect and claim that most estimates of this effect suggest that when real fuel costs decrease by 10 %, there will be a corresponding increase of 1–3 % in vehicle miles of travel (VMT). While improving vehicles' fuel efficiency is a policy implication that may be acceptable to consumers, because it does not require significant sacrifices in the affordability, utility, and performance of vehicles, it may nonetheless lead to some negative environmental sustainability implications. As explained by Abbaspour and Soltaninejad (2004), the deterioration of air quality in most major cities of the world, including Tehran, is largely caused by vehicular air pollution.

Gusdorf and Hallegatte (2007) suggest that cities made more compact by preexisting transportation taxation are better suited than sprawling cities to deal with increases in transportation costs. If a transportation tax is implemented, transportation costs are higher, which makes locations far from the central business district less desirable than those close to the central business district (Gusdorf and Hallegatte 2007). This in turn causes the city boundary to shrink. Using microeconomic modeling, Gusdorf and Hallegatte (2007) show that cities with preexisting high transportation tax levels are less vulnerable to changes in energy costs. Their findings provide insight into policy tools for mitigating vulnerability of cities to higher fuel costs.

Land use and transportation planning policies

Adaptations are required in order to reduce dependence on oil. As Krumdiek (2007) explains, adaptations are alternatives to fuel that essentially reduce demand. They are dependent on urban land use and transportation infrastructure. Land use and transportation infrastructure are highly reflective of policy decisions and funding investments at various levels of government. Adaptability to rising oil prices and constrained fuel supply is severely limited by choice of destination, occupancy, mode, and living arrangements (Krumdiek et al. 2010). These factors are all dependent on urban form, infrastructure, and the built environment. Decisions, expressed through government policy directives, concerning the management and direction all of these factors have led to the current situation, which is characterized by auto-dependant suburbs and a lack of public transit.

In the GTA, much of the city center's outward expansion has occurred in typical suburban fashion. Development patterns beyond the city center are typically low density, and there is a distinct separation of land uses. The implications of this land use pattern are significant given the effect rising oil prices have on auto-dependent culture. Reliance on the automobile is built into the urban fabric of a large portion of the GTA. Krumdiek et al. (2010) recognize the relationship between urban form and oil, and their comparison of Hong Kong and Houston shows the correlation between urban density and per capital fuel use. Hong Kong has an urban density of 32,035 persons per square kilometer and an annual fuel energy use of around 5000 megajoules per person (Krumdiek et al. 2010). Conversely, sprawling Houston has an urban density of less than 1,000 persons per square kilometer and an annual fuel energy use of more than 60,000 megajoules per person per year (Krumdiek et al. 2010). City Cooper et al. (2002) reviewed similar evidence and concluded that if distance traveled and fuel consumption are to be reduced, policies must promote densification, urban compaction, and public transport.

In Newman and Kenworthy (1989a) seminal paper, we are presented with the relationship between car dependence and urban densities. They found that a city's density is the primary factor that determines automobile dependence and that car use declines where densities exceed 30–40 persons per hectare. It appears that Newman and Kenworthy (1989b) argument for the reurbanization of the suburbs, as a tool to reduce auto-dependence and gasoline consumption, has informed much of the current policy planning framework. Reurbanization would be achieved in part by infill development to increase densities above the car dependence threshold. For (Newman and Kenworthy 1989b), reducing car dependence also requires new transport policies that move away from satisfying the needs of the automobile, for instance, limiting construction of new roadways, and instead reallocating resources to promote rail, walking and bicycling.

Recently, there have been policies enacted to curb the trend of outward surburban development, such as the Growth Plan for the Greater Golden Horseshoe (Ministry of Infrastructure 2006). Created by the Ontario government, this policy is a planned intervention that establishes density targets and limits for all future development, thereby forcing a degree of intensification through infill development. While this policy may be a step in the right direction, further policies guiding urban form may need to be introduced.

Decisions regarding planning for transportation and the methods used to meet transport demand are typically made under conditions of low cost and abundant oil (Krumdiek et al. 2010). Since World War II, transportation policies and investment focused on the automobile and worked to meet transport demands through expanded road infrastructure, especially in the newly formed suburban areas. Conversely, the GTA's dense city center is less dependent on the automobile due to the accessibility and quality of the public transportation system. While improved public transportation in areas of high fuel dependency may appear to be an effective policy, the issue is not as straightforward. Generally, governments have subsidized public transit in order to provide mobility options for those who do not have access to cars and to reduce traffic congestion; however, the effect of public transportation on saving energy is questioned. Frankel and Menzies (2012) explain that tripling transit ridership levels in the USA would only produce a small reduction in the national VMT and that motivating people to use public transportation or nonmotorized forms of travel such as cycling or walking in an automotive-friendly environment cannot be achieved simply by providing transportation infrastructure. Public transportation must be supplemented by increased demand for public transportation use, which economists say will be motivated by the financial burden of higher fuel prices (Frankel and Menzies 2012).

Furthermore, Mees (2000) argues that it is indeed possible to have excellent public transit even in low-density areas. This point is demonstrated by comparing the relative performance of the transit systems in Toronto, Ontario and Melbourne, Australia. Despite having very similar characteristics in population, urban form, and density, Toronto outperforms Melbourne in transit by a large margin. This is because Toronto's centralized planning by a single authority has produced an integrated public transport system, whereby the various modes are not in competition with one another, but rather work together to collect and distribute passengers in a seamless fashion (Mees 2000). For example, bus services should not compete with rail systems. Mees (2000) critiques Melbourne's early transit system policies, which were market driven whereby busses were operated by legions of small private firms. This in turn created competition amongst public transportation modes as opposed to competition directly with the automobile.

Materials and methods

This paper considers the connection between oil vulnerability and automobile dependence. The assumption is that the use of automobiles requires the purchase of fuel. Therefore, it can be said that those who are reliant on the purchase fuel to support their car dependence are more impacted by rising fuel prices and thus more oil vulnerable.

Dodson and Sipe (2007) looked at the oil vulnerability of Australia's urban regions, implemented an analytical approach to assess the potential exposure of households to adverse socioeconomic outcomes arising from increased fuel costs. To do so, a locational measure of oil vulnerability was generated, which the authors called the VIPER. VIPER assigns average relative values of oil vulnerability at the local level, allowing comparisons to be made between various districts within the urban region.

Our study uses a refined version of the VIPER framework—termed "the modified VIPER"—to assess the socioeconomic oil vulnerability of the GTA to rising oil prices. In order to represent car dependence, Dodson and Sipe (2007) used the journey-to-work (JTW) mode as revealed by the Australian census. The issue is that the use of JTW may under-represent car dependence since the JTW mode share for car travel tends to be lower than the mode share of car travel for all trips. For this reason, in the modified VIPER index, we utilized travel survey data to determine the percentage of all trips by car. This is considered a refinement in VIPER framework as it is more representative of total car usage. The travel survey data are combined with census data to produce a composite index for representing oil vulnerability. In our analysis, we seek to understand how the socioeconomic impacts of rising fuel costs will be distributed across the GTA's urban landscape. Dodson and Sipe's (2007) VIPER framework and our modified VIPER framework are described below.

Dodson and Sipe's (2007) VIPER framework is comprised of three variables obtained from the 2001 Australian Census that are combined to provide a composite value of oil vulnerability. Oil vulnerability was then mapped geographically at the census collection district (CCD) level. It is important to note that VIPER determines the average oil vulnerability of households within the CCD, as opposed to the specific oil vulnerability of each household. The three variables used to determine oil vulnerability are:

- Socioeconomic index for areas (SEIFA).
- Household motor vehicle ownership.
- Car dependence for the journey to work (JTW).

The three variables used in the VIPER were grouped into different categories based on the 10th, 25th, 50th, 75th, and 90th percentiles for each of the Australian cities under study. Values (or ranks) ranging from 0 to 5 were assigned to census districts depending on which percentile they fell within. In order to combine the variables into one composite index, each of the three variables was assigned weights. The VIPER was divided into two equally weighted sets of variables. The first was comprised of SEIFA, while the second included car ownership and journey to work. The final VIPER values for the CCDs reflected the sum of the rankings of the three variables.

Similar to the VIPER framework, our modified VIPER framework evaluates the average oil vulnerability of households within a given census tract (CT) rather than the specific oil vulnerability of each household. The modified VIPER is comprised of four variables obtained from two sources, the 2006 Canadian census and the 2006 transportation tomorrow survey (TTS) (Data Management Group 2008). The data obtained from these two sources match geographically. The four variables used to determine oil vulnerability in the GTA are as follows:

1. Private households by median household income in 2005 (HDMED) (obtained from Canada's census).
2. Prevalence of low income after tax in 2005 for total persons in private households (PHDLIA) (obtained from Canada's census).

Table 1 Modified VIPER percentile categories and corresponding ranks

Percentile	Household median income (HDMED) Rank	Prevalence of low income (PHDLIA) Rank	Proportion of households with 2 or more cars Rank	Proportion of trips made by cars Rank
91–100	0	5	5	5
76–90	1	4	4	4
51–75	2	3	3	3
26–50	3	2	2	2
11–25	4	1	1	1
0–10	5	0	0	0

3. Proportion of households with two or more vehicles (obtained from TTS).
4. Proportion of all trips by car (obtained from TTS).

For each of the four variables, values corresponding to all CTs were determined. For example, in the case of variable three, the proportion of households with two or more vehicles (in %) was determined for each CT. Similar to the approach used by Dodson and Sipe (2007), the CTs were sorted into different categories based on the 10th, 25th, 50th, 75th, and 90th percentiles. Ranks, ranging from 0 to 5, were then assigned to each CT based on which percentile group the CT's values fell within. The relationship between the ranks and the percentile groups was not the same for all four variables. For example, CTs in higher percentiles for household median income (HDMED) yielded lower oil vulnerability ranks. However, CTs in the higher percentiles for prevalence of low income (PHDLIA) yielded higher oil vulnerability ranks. This relationship between ranks and percentile groups for all four variables is depicted in Table 1. Essentially, the modified VIPER index is divided into two equally weighted sets of variables, the socioeconomic variables, which include the HDMED and PHDLIA, and the car dependence variables, which include car ownership (portion of households with two or more cars) and trips by car (percentage of all trips made by car). Each of the four variables is allocated a weight of five, resulting in a 20-point scale. A CT with the best possible score would receive zero points, meaning that it is the least vulnerable CT to rising oil prices. The worst possible scoring is 20. Overall, the scores provide a range of oil vulnerability values that were then mapped using GIS software (ArchGIS).

Modified VIPER: socioeconomic variables

For the most part, the modified VIPER framework is based on the original VIPER. The approach is generally the same, but the variables and weights used in the two VIPER frameworks are significantly different. For example, Dodson and Sipe (2007) used the Socioeconomic Index for Areas (SEIFA), which is a composite measure that includes multiple social and demographic factors such as occupational status and age. Statistics Canada does not provide a variable comparable with SEIFA. In an effort to compensate for this, our modified VIPER uses two variables from the census, HDMED and PHDLIA. The HDMED variable represents the median household income in 2005, and PHDLIA represents the prevalence of low income after tax in 2005 for total persons in private households. While there is a strong correlation between these variables, there are important differences. HDMED is strictly related to income levels, whereas PHDLIA considers income in relation to spending for basic human necessities such as food, shelter, and clothing. PHDLIA identifies those who spend 20 % more of their after-tax income than the average on food, shelter, and clothing (Statistics Canada 2006). For this study, it is important to capture persons who are in straitened circumstances as they represent an oil-vulnerable portion of the population. Using both variables in this study, we aim to build a more composite measure of socioeconomic status.

Establishing the scores (or ranks) for the HDMED and PHDLIA variables is straightforward. The HDMED values (expressed in dollars) and the PHDLIA values (expressed in percentages) for the CTs were obtained directly from the census (Statistics Canada 2006). Based on the values for each variable, the percentile of each census tract was calculated and a rank was assigned to each CT based on the framework indicated in Table 1.

The assumptions made in the selection of the variables used in the modified VIPER are similar to those made by Dodson and Sipe (2007). In using the HDMED variable, it is assumed that households in census tracts with higher median incomes are more capable of absorbing the costs of rising oil prices than households in census tracts with lower median incomes. It follows that the greater a household's median income, the less vulnerable that household is to the socioeconomic impacts of increased fuel prices. Conversely, in using the PHDLIA variable, it is assumed that households with a low income are less capable of absorbing the costs of rising oil prices. It follows that the greater a CT's prevalence of low income, the more vulnerable its households are to the socioeconomic impacts of increased fuel prices. Hence, as the percentiles of the HDMED increases, the corresponding oil vulnerability rank decreases. Conversely, as the percentiles of the PHDLIA increase, so too does the corresponding oil vulnerability rank.

Modified VIPER: car dependence variables

The original VIPER used a car ownership variable (households with two or more cars) that is also applied in our modified VIPER. In our model, household car ownership data for the GTA were obtained from the 2006 TTS. Using the online TTS website, a query was entered to search for the number of vehicles in households for each CT (Data Management Group 2008). We took the sum of all households in each CT with two or more vehicles and divided by the total number of households in each CT. This provided the values for car ownership (proportion of households with two or more vehicles) used in the modified VIPER. Once the car ownership values were determined, percentiles were calculated to sort the CTs into relative categories and ranks were assigned to CTs based on percentile groups.

The proportion of households with two or more vehicles is an indicator of the demand for automobile travel. Similar to the study by Dodson and Sipe (2007), the assumption made in using this variable is that a household's car ownership level is related to its needs for automobile travel. It follows that the greater a household's car ownership, the higher that household's dependence on oil.

The key distinguishing feature of modified VIPER is its use of travel survey data to determine the trips by car variable (percentage of all trips made by car). The original VIPER used the journey-to-work mode as revealed by Australian Census data. This is not an ideal indicator of travel preference relative to other sources of data. Furthermore, as acknowledged by Dodson and Sipe (2007), the "Census JTW mode share of car travel tends to be lower than the share of all trips taken by car." The TTS travel survey provided us with access to better data on the mode share of car travel for all trips made by persons, not just for journeys to work. This represents a refinement to the VIPER framework as it is a stronger indicator of dependence on car travel.

Using the online TTS website, a query was entered for the primary travel mode of trips. Results indicated the number of trips with a primary mode of travel as auto passenger, transit excluding GO rail, school bus, bicycle, taxi passenger, auto driver, walking, GO rail only, joint GO rail, motorcycle, or other. The data provided by the TTS were collected and/or calculated by the Data Management Group for each day for each person 11 years old and older in households surveyed in 2006 (Data Management Group 2008). We took the sum of all trips made by car and divided by the total number of trips. This provided the trips by car values (percentage of all trips made by car) used in the modified VIPER. Once these values were determined, percentiles were calculated to sort the CTs into relative categories, and corresponding ranks were assigned to CTs based on which percentile groups they fell within. In using the trips by car variable, an assumption was made that overall use of automobiles for all trips made by persons is directly related to their need for travel by automobiles. Therefore, a higher percentage of trips made by car represents a higher oil vulnerability.

Combing travel survey data with census data

As stated earlier, the key defining feature of modified VIPER is its use of travel survey data in conjunction with census data. The advantage of using the TTS data is that it contains a variety of information on households' mode of travel for various types of trips. For this reason, the trips by car variable is an ideal indicator of households' car dependence, as it considers the mode share of car travel for all trips and not just for the journey to work. However, combining the travel survey data with census data was not straightforward. The 2006 TTS provides important travel survey information but is coded to the 2001 census tracts (CTs). On the other hand, the 2006 census data provide socioeconomic data corresponding to the 2006 CTs. This raises the concern that there may be minor discrepancies in mapping when combining the two sources of data as the census tracts have changed slightly from 2001 to 2006. We note that for the most part, the 2001 census tracts matched closely with the 2006 census tracts. In fact, 88 % of the GTA's 2006 census tracts matched the 2001 census tracts. For the remaining 12 %, we interpolated average oil vulnerability values by spatially assessing the oil vulnerability of adjacent census tracts. Finally, the four variables were combined, and the oil vulnerability ranks of each variable were added together to provide a final modified VIPER score for those CTs. The final scores were then mapped to provide a spatial analysis of the distribution of oil vulnerability across the GTA.

Testing for co-linearity

The initial presumption regarding choice of variables might be that the two socioeconomic variables are highly correlated. In order to test for colinearity, correlation coefficients were calculated between all variables in the modified VIPER index. The results indicate a high degree of colinearity between the two socioeconomic variables ($r = -0.71$). Despite this strong linear relationship, both variables were included in the VIPER framework because, together, they capture the heterogeneity that exists in the census tracts. For example, a spatial GIS map of the HDMED reveals a relatively high household median income for census tracts located in and around the inner city core. However, the GIS plot of the PHDLIA variable reveals that these same census tracts

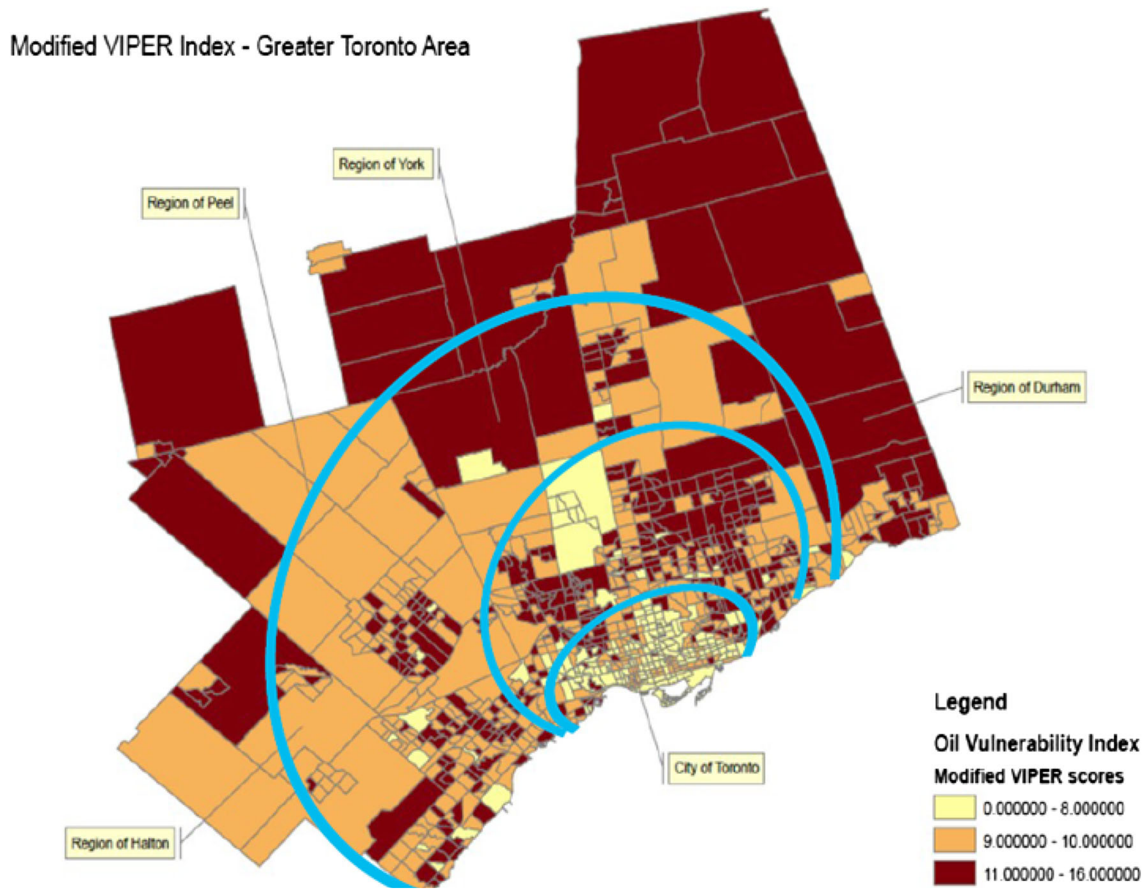

Fig. 2 Modified VIPER Results for GTA

actually have a relatively high prevalence of low income. This is perhaps a common feature of many North American cities that are characterized by significant wealth disparities especially in the inner core of the city. Therefore, using both socioeconomic variables in the modified VIPER index allows us to capture the heterogeneity of the census tracts.

Results and discussion

The degree of oil vulnerability was determined for census tracts across the GTA, and the results are presented in Fig. 2. Presenting these results geographically helps to identify spatial patterns associated with levels of oil vulnerability. When observing the GTA as a whole, there is a general pattern observed: A low vulnerability core surrounded by an area consisting mainly of high vulnerability pockets, which is again surrounded by an area consisting mainly of medium vulnerability pockets. These three areas can be described as rings, which generally coincide with the GTA's urban core, its inner suburbs, and the outer suburbs.

This study recognizes that a distinctly urbanized region exists within the GTA. Rural areas are generally located around the northern and northeastern edge of the GTA and, for the purposes of this study, are not considered as part of the spatial pattern of oil vulnerability. This study does not assess these rural areas in depth, and it suffices to observe that they operate within a different system of daily activities. Much of the GTA is connected to the urban core, and these rural areas encounter very different socioeconomic factors and have their own relationship with the automobile.

The first ring, which can be geographically defined as the urban center of the GTA and generally falls within the municipal boundaries of the City of Toronto, has the lowest oil vulnerability scores within the study area. For the most part, census tracts in this ring score an 8 or lower on the modified VIPER scale. The area immediately surrounding this ring generally consists of Toronto's inner suburbs and is defined here as the second ring. The census tracts in the second ring have the highest modified VIPER scores in study, with scores predominantly between 11 and 16. Expanding outwards from this area of highest oil vulnerability is the third ring, which is comprised of typical North

American-style suburban developments. Moving to this third ring, a drop in modified VIPER scores is observed and as a whole, this ring achieved the second lowest modified VIPER scores in the study area. The majority of census tracts in the third ring have modified VIPER scores of 9–10. It is important to note that within all of the rings identified, there is a degree of variation in scores.

In the GTA, the city center has the lowest oil vulnerability but this does not coincide with the highest median household income. In fact, the first ring has a highly uneven distribution of income levels that includes pockets of the highest and lowest income levels. There is an overall decrease in median household incomes from the first ring to the second ring as the majority of lower-income households in the GTA fall within the second ring. This decrease in median household income coincides with an increase in oil vulnerability scores in the second ring. Finally, the observed decrease in oil vulnerability as one moves from the second ring to the third ring coincides with an increase in median household income.

Significant differences are observed when comparing this study with the results of the original VIPER model. In the study of Australian cities (Dodson and Sipe 2007), there is an observed continuous increase in oil vulnerability as one moves away from the urban center or central business district toward suburban areas. This pattern exists in the GTA as you move from the city center (the first ring) to the immediate surrounding areas (the second ring). There is a change in urban form similar to that observed by Dodson and Sipe (2007), with a decrease in density as it transitions into more suburban development. What is different about the GTA is that this pattern of increasing oil vulnerability stops after the second ring. Unlike with Australian cities, the results of this study depict a decrease in oil vulnerability in the third ring, which contains the most suburban areas of the three rings identified. Finally, another transition in the level of oil vulnerability occurs in this study beyond the third ring. The rural areas of the GTA, located the furthest from the city center, have high oil vulnerability scores, which is similar to the results found by Dodson and Sipe (2007). Understanding why certain census tracts received specific oil vulnerability scores and the patterns these scores have created are discussed in this paper.

Conclusion

When considering the results of this study, it is necessary to understand the variables used to evaluate oil vulnerability, including socioeconomic and car dependence factors. To provide insight into the results, these variables are analyzed in conjunction with the observed characteristics of the GTA, such as levels of public transportation services, urban form, and the spatial distribution of wealth. A significant socioeconomic factor in this study is median household income. It is important to examine the differences in oil vulnerability across the GTA while considering the spatial distribution of economic factors, such as median household income, because it reveals that each socioeconomic group will be affected differently by rising oil prices. When comparing the spatial distribution of median household income and oil vulnerability, we begin to identify some interesting relationships.

Households with higher incomes are likely more equipped to deal with the financial burden created by rising oil prices. It would follow that they receive the lowest oil vulnerability score. This was the case in the study by Dodson and Sipe (2007) and for the most part occurred in central business districts. The GTA is similar to the results presented by Dodson and Sipe (2007) in that the city center does achieve the lowest oil vulnerability scores; however, it does not have comparatively higher incomes, but rather has a wide range and highly uneven distribution of income levels. Given this, we must consider other factors such as car dependence in determining low oil vulnerability in the first ring.

Beyond the factors used in this study to determine car dependency, including car ownership and number of trips by car, it is important to note quality of public transportation. Although this study did not evaluate the distribution of public transportation services across the GTA, we recognize the superior service that exists within the first ring relative to the level of service across the rest of the study area. The results identify the areas of lowest oil vulnerability, which we can conclude, coincide with areas that have the highest quality public transportation, especially in terms of accessibility. This suggests that public transportation plays an important role in determining oil vulnerability. It follows that greater access to public transit means households would require a car less for daily transport needs. Additionally, the urban form of the first ring is dense with a balanced mix of land uses. Unlike suburban developments, this type of urban form lends itself to other forms of nonautomobile transport, including cycling and walking. Shorter travel distances allow for transport needs to be met by modes other than the car, therefore reducing reliance on fuel and decreasing oil vulnerability. The discussion of the quality of public transportation in suburban areas raises important issues of transport policy and transit investment. Mees (2000, 2010) presents an important argument for the provision of high-quality public transit to the suburbs that does not rest on the need for higher urban densities. Mees (2000) praised Toronto's public transit system and argued that its success is the result of integrated service by a single transit authority. In this context, we must recognize that the study area of our research expands beyond Toronto's public transit system that Mees (2000) endorsed. Areas in the third and parts of the second ring are serviced by four different pubic transit systems, all of which are operated by their own transit authority. Recognizing that Toronto acts as a central business district for the GTA and that many trips originating in the second and third rings will terminate there, transportation policies for this region as a whole should consider the argument for a coordinated network approach that Mees (2000, 2010) presents.

In the GTA, households in the second ring benefit from a dense urban form and higher-quality public transportation service relative to their neighbors in the third ring and beyond. Despite this, households in this second ring have higher oil vulnerability scores than those in the third ring. The increase in oil vulnerability scores was expected from the first to the second ring due to an overall decrease in public transportation service. However, the second ring's higher oil vulnerability scores in relation to the third ring lead us to place greater significance on socioeconomic factors in determining oil vulnerability in this area of the GTA. The GTA is similar to the Australian cities studied by Dodson and Sipe (2007) in that socioeconomic status generally decreases as one moves away from the city center. Notably, a large proportion of lower-income households in the GTA fall within the second ring. While the initial pattern of outward decreasing socioeconomic status is apparent, the Australian cities studied differ in that the lowest income households are located furthest from the city center. Finally, when comparing the GTA's lowest income households, located just beyond the city center, with their Australian counterparts, located furthest from the central business districts, we consider the GTA's lower-income households to be less oil vulnerable due to their closer proximity to the region's city center. Therefore, it can be said that Toronto's lower-income households are not subject to transport disadvantages as much as their Australian counterpart since households in the second ring benefit from a relatively higher transit service.

The findings of this study revealed that the second ring (inner suburbs of Toronto), which contains a large portion of the lower-income households in the GTA, has comparatively the highest oil vulnerability. This suggests that lower-income households face the greatest socioeconomic impact from rising oil prices. In fact, this is consistent with studies which suggest that lower-income families spend a greater portion of their household budget on transportation fuel. Great Britain's Energy and Climate Change Committee reported on the weekly household expenditure on fuel by income group. According to the report, in 2008, lower earners on average spent a higher portion of their total weekly expenditure and their total weekly disposable income on fuel than higher earners, thereby making it more difficult for them to meet the increased costs associated with rising fuel prices (Energy and Climate Change Committee 2009). Low-income households spent 5.8 % of their disposable household income on transportation fuel, while higher-income households only spend 3.9 % (Energy and Climate Change Committee 2009). This point is a validation of the VIPER index as it demonstrates that households living in oil-vulnerable areas will suffer the most from rising fuel prices.

The results of this research show a decrease in oil vulnerability as one moves further away from the city center (from the second ring to the third ring). We can conclude that this phenomenon occurs despite the decrease in public transportation service and a lower population density, which create greater car dependence. However, on a socioeconomic level, households in the suburban third ring have a higher income than in the second ring. These results suggest that the socioeconomic status of households plays a more critical role than car dependence in determining oil vulnerability. Despite a lack of alternative transportation options, higher household incomes in the third ring reduce financial sensitivity to the increased costs of fuel.

It is important to note that the modified VIPER scores of some of the more affluent census tracts in the GTA may be slightly skewed to reflect higher oil vulnerability. The reason for this is due to one of the measures of car dependence: vehicles ownership. In certain census tracts, the number of vehicles owned may be more reflective of a household's affluence or socioeconomic status than their overall car dependence. While these households may still be car dependent, it is unlikely that the quantity of cars owned accurately reflects their transport needs and degree of dependence on a car. Therefore, for some affluent households in the third ring, the level of oil vulnerability may be lower than shown in this study. This further emphasizes the critical role of socioeconomics when contemplating oil vulnerability in the GTA's suburban areas.

This study reveals that the impact of rising oil prices will be unevenly distributed across the GTA. The three-ring pattern of oil vulnerability identified is reflective of socioeconomic and car dependence factors as well as observed differences in urban form and quality of public transportation services.

Similar to the study of Australian cities (Dodson and Sipe 2007), this study of the GTA evaluated oil vulnerability based on two main factors: socioeconomic status and car dependence. This study also works from the idea that the distribution of oil vulnerability across the GTA will reflect the impact that arises as a result of rising oil prices. While this study is a snapshot of the GTA that identifies who will be at risk, it does not explain how households will react to the increases in oil prices. Therefore, future research opportunities include examining reactions at the household level, especially in terms of the elasticity of demand for alternative modes of transportation, as well as changes to household spending or consumption patterns.

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