Geographical Research

Investigating Private Motorised Travel and Vehicle Fleet Efficiency: Using New Data and Methods to Reveal Socio-Spatial Patterns in Brisbane, Australia

TIEBEI LI*, NEIL SIPE and JAGO DODSON
Griffith University, 170 Kessels Road, Nathan, Qld 4111, Australia.
**Corresponding author. Email: t.li@griffith.edu.au*

Received 16 April 2012; Revised 3 December 2012; Accepted 9 December 2012

Abstract
Australian cities have seen continued long-term growth in private motor vehicle travel that has imposed increasing vehicle energy consumption and greenhouse gas emissions. This paper investigates the spatial patterns of vehicle energy consumption on urban areas through an analysis of vehicle travel and of vehicle fleet efficiency in Brisbane, Australia. This is achieved by combining motor vehicle registration records and Australian government's 'Green Vehicle Guide' of vehicle fuel efficiency database. The results of a spatial analysis of the private vehicle trip distances derived from journey to work data and fuel energy consumption associated with the private-owned vehicles decomposed to local areas show that private vehicle energy use tends to increase with increasing distance from the city centre (e.g. central business district). This analysis demonstrates that differences in vehicle trip distances and lower proportions of high-efficiency vehicles in the outer suburbs aggravate vehicle energy consumption in those locations. The paper further compares vehicle energy use results for Brisbane against spatial patterns of suburban socio-economic disadvantage. The paper demonstrates that access to vehicle fleet technology may compound other forms of socio-economic disadvantage and vulnerability.

KEY WORDS *motorised travel; fuel efficiency; oil vulnerability*

Introduction

Australian cities have seen continuous long-run growth in car travel (BTRE, 2007). In most capital cities, over 80% of households use private vehicles for trips, including those for work (Australian Government, 2010). With suburbanisation continuing, long-distance travel and traffic congestion are ongoing problems that have increased energy consumption and greenhouse gas emissions and complicated mobility in urban areas (Weisbrod *et al*., 2003). In addition, the increase in automobile dependence in Australian cities has placed them at greater risk from potential adverse social and economic outcomes arising from increasing petrol prices (Dodson and Sipe, 2008). Because automobile dependence has placed increased pressures on the environment, particularly via greenhouse gas emissions, and has added to household energy costs, there is a growing need to reduce transport energy consumption. Developing an improved understanding of the spatial distribution of household transport energy, its variation across urban regions and how it differs by socio-economic

doi: 10.1111/1745-5871.12001

distribution is recognised as necessary to help government craft policies to achieve affordable and efficient transport outcomes. This paper aims to address this issue.

Transport energy consumption is a complex urban phenomenon. Numerous social and spatial factors are considered to influence household transport energy demand including the local economic structure, the form and structure development, the socio-economic composition, and the levels of transport infrastructure and services (Banister, 1980; Newman and Kenworthy, 1999; Mees, 2000; O'Neill and Chen, 2002). Most studies attempting to understand urban transport energy patterns have typically focused on the relationship between urban travel demand and transport energy outcomes, arguing that the urban development types may have direct influences on household transport energy consumption (Breheny, 1995; Whiteman and Alford, 2009). For example, households located in dispersed outer suburban areas with low accessibility to public transport typically become car dependent, which results in correspondingly longer vehicle distance travelled and greater fuel energy consumption. In contrast, households in high-density areas tend to be closer to employment and public transport services and thus require less vehicle travel and energy use (Maher, 1994; Burnley *et al.*, 1997; Whiteman and Alford, 2009).

The level of energy consumption is not only related to household travel patterns but also on motor vehicle type. This is because a household's preference for vehicle type is strongly influenced by residential location and travel patterns (Kitamura *et al.*, 2001; Bhat *et al.*, 2009; Eluru *et al.*, 2010). This spatial variation is observable in high-density areas that tend to have less and smaller parking spaces, narrower street, and more congested traffic. These conditions all work in favour of choosing smaller, more manoeuvrable, and often more fuel-efficient vehicles (Choo and Mokhtarian, 2004). In contrast, households in low-density areas with fewer constraints on car transport operations (e.g. greater space for parking, less road traffic) may have lower frequencies of fuel-efficient vehicles (Kockelman and Zhao, 2000; Cao *et al.*, 2006). These spatial variations in household motor vehicle preference can translate into important differences in household fuel consumption patterns. This relationship between household transport energy outcomes and motor vehicle type and use has not been fully examined in previous transport energy research in Australia.

This research provides an advanced method for examining the spatial distribution of household vehicle fuel consumption for the Brisbane urban area, a fast growing city in South East Queensland, Australia. This is achieved by integrating household vehicle travel distance and motor vehicle fleet composition. One key element of this work involves an examination of the impact of vehicle energy efficiency on household vehicle fuel consumption. This analysis allows vehicle fuel efficiency to be included as a key factor in determining the household transport energy use. The outputs are then used to evaluate socio-economic disadvantage arising from unevenly distributed fuel energy expenditure across Brisbane. These results provide a much improved evidence base for those with responsibilities for managing transport energy growth and mitigating household transport energy vulnerability. One management option might examine how land use policies could be used to alter household vehicle choice and vehicle use characteristics, thereby reducing energy use and emissions.

The remainder of the paper is structured as follows. The next section provides an overview of the literature on household transport energy use. The third section describes the study area and datasets used in the analysis. The fourth section describes the methods of analysis and the fifth section provides the results. The paper concludes with a discussion of the limitations of our approach and outlines avenues for future research.

Geographical study of urban transport energy

The distribution of household energy consumption and its variation in the urban and regional context has received growing attention over the last couple of decades (Newman and Kenworthy, 1999). There has also been a great deal of attention focused on urban form and transport energy consumption. For example, Rickwood *et al.* (2008) investigated spatial patterns of energy consumption, suggesting a relationship between land use characteristics and household transport energy consumption. The implications of urban spatial structure for transport energy patterns were also widely debated in Holden and Norland (2005), Permana *et al.* (2008), and Brownstone and Golob (2009).

While much research has shown that the spatial variation in household transport energy consumption is related to urban spatial structure and human travel behaviour, very little research has investigated the spatial nature of the technological dimension (i.e. vehicle type and efficiency) of transport energy cost and its impact on the household energy consumption and vulnerability. VandeWeghe and Kennedy (2007) applied a spatial-based approach to analyse the transport energy consumption by different motorised modes in Toronto. Although the analysis provided a measure of energy consumption based on the vehicle travel data, the use of uniform vehicle fuel efficiency coefficients across all vehicle types is a limitation. In a more recent study, Lindsey *et al.* (2011) used recent vehicle travel survey data to analyse vehicle energy use in Chicago. Through an explicit analysis of travel patterns and vehicle energy efficiency, they found that the variation in household transport energy consumption can be partly explained by differences in the vehicle fleet. These studies demonstrate that it is possible to track spatial travel behaviour by motor vehicle type in an effort to understand the spatial nature of household transport energy use.

In the urban transport literature, social-spatial analysis of household vehicle energy use has received little attention. Dodson and Sipe (2007) developed a vulnerability index for petroleum energy rises (VIPER) based on the analysis of the number of motor vehicles owned, journey to work (JTW) motor vehicle use, and household income to assess socio-economic oil vulnerability in Australian cities. The results showed that household oil vulnerability is a socially regressive phenomenon. The relative weaker socio-economic households in Australia's outer suburbs are most vulnerable to higher energy prices. The issue of household energy pressure from the composition of vehicle fleet was recently further investigated by Dodson *et al.* (2010) who used the Queensland motor vehicle registration database to compare the socio-economic status with age and engine size of vehicles for Brisbane. Although the analysis used a relatively crude measure of vehicle fuel efficiency, the result confirmed that outer-urban disadvantaged groups tend to be more vulnerable to fuel prices due to their more frequent ownership of old and large engine vehicles.

Thus, transport energy consumption is a complex problem especially when considering household travel dynamics and vehicle efficiency in a large urban area. Current approaches for assessing urban transport energy consumption and oil vulnerability do not address the links between household travel demand and vehicle energy efficiency, and the resulting levels of transport energy consumption. The analysis presented in this paper addresses this gap by combining household vehicle travel demand and vehicle fuel efficiency. The methodological contributions of this paper are the following: (1) it links vehicles in the current vehicle registration database to standard vehicle fuel efficiency ratings at an individual vehicle model level and (2) it applies advanced geographical techniques to analyse private vehicle kilometres travelled per trip using JTW data. The results provide a richer depiction of household transport energy cost, not only of car ownership but also of fuel consumption under current household travel demand. These results are then linked to socio-economic data to develop a better understanding of the relationship between socio-spatial structure and suburban transport energy consumption. This will then help us to determine whether the composition of the vehicle fleet compounds socio-economic disadvantage and vulnerability.

Study area and data

Study area

Brisbane is one of the fastest growing cities in Australia. During the last two decades, the city has experienced extensive low-density residential development with a highly centralised employment core in the central business district (CBD). In addition to its mono-centric and dispersed urban structure, Brisbane has high levels of transport heavily car-dominated travel demand. In 2006, 78.1% of all trips in Brisbane were by car (DTMR, 2010). This has placed pressure on transport infrastructure and household vehicle energy costs. As a part of the Queensland government's strategy for sustainable growth, Brisbane is to reduce the rate of private car trips from its current 78.1% to 56% by 2031 (OUM, 2006). Brisbane, with high vehicle travel demand, its large number of cars, and the availability of critical datasets, makes it an ideal location for evaluating the nature and distribution of vehicle fuel consumption and improving understanding of oil vulnerability in a large metropolitan area.

Data

Three databases were used in the study: (1) the Queensland motor vehicle registration data; (2) Australian Green Vehicle Guide data; and (3) JTW data.

Queensland motor vehicle registration data Motor vehicle registration data are held by the Queensland government. The data were obtained for the fourth quarter of 2008 and comprise 441 930 motor vehicle records containing the make, model, year, body shape, number of cylinders, suburb, and postcode location.

Australian Government Green Vehicle Guide data The Australian Government Green Vehicle Guide provides information on the environmental performance for 14 996 vehicle types, by make and model, which were sold in Australia between 1986 and 2003 and manufactured between 2005 and 2009. The Green Vehicle data provide air pollution rate, CO_2 emissions, noise, and fuel consumption by vehicle make/model. For this study, the fuel consumption rate (litres 100 km^{-1}) was used for the vehicle energy efficiency analysis as it provides accurate information on fuel consumption in urban driving conditions.

JTW data The JTW datasets from the 2006 Census (Australian Bureau of Statistics [ABS]) were used to calculate the average vehicle trip distance. The reason of using JTW is that commuting travel typically constitutes a daily activity for most of the population, placing significant demands on the transportation system, and is linked to significant household transport costs (Horner, 2004). The JTW dataset contains information on trip origins (usual residence of employed persons), trip destinations (workplaces), and the origin-destination matrix with the number of commuting trips between each origin and destination. The JTW data used in this study comprise all vehicle trips between 300 origin and 300 destination zones for South East Queensland, which include Brisbane, Gold Coast, and Sunshine Coast. The standard units used to represent origin and destination zones of origins and destinations are statistical local areas (SLAs).

Methodology

Measuring vehicle trip distance

The average vehicle trip distance was measured using 2006 JTW data. The advantage of using JTW data is that it is a complete enumeration of the population, which provides more accurate information on travel demand than that provided by sampled household travel surveys.

The average vehicle trip distance was computed for each SLA using the road network to determine the travel distance between each origin and destination. Because SLAs are relatively large geographical units, especially in peri-urban areas, the measure of JTW distance using geographic centroids was deemed not to represent an accurate estimate of available route possibilities for commuters. As a methodological remedy, ten points were randomly located within each SLA and each point used as the single departing location and arrival location of travel. The use of randomly distributed points can be affected by the size of a peri-urban SLA. However, as the peri-urban SLAs are often large geographical areas with more dispersed populations and employment activities, this approach is considered reasonable. The average point-to-point network travel distances were computed for each SLA that was then multiplied by the number of vehicle trips between each origin-destination pair, and the total travel distance for all vehicle trips in a SLA was calculated by summing all vehicle trips that depart from a SLA. The average vehicle trip distance for each SLA was finally derived from the total number of vehicle trips in the SLA. Because this study focuses on private vehicle travel and vehicle fuel consumption for the Brisbane urban area, we only report the average trip distance results for 210 SLAs in Brisbane, which excludes the 90 SLAs outside of the Brisbane urban area.

Spatial analysis of vehicle fleet and fuel efficiency

The question raised earlier suggests that in addition to the vehicle travel demand, the distribution of vehicle fuel efficiency may be an important determinant in fuel energy consumption. This study examines the issues of motor vehicle efficiency and spatial distribution by combining Queensland motor vehicle registration records with the 'Green Vehicle Guide' fuel efficiency data. The Guide provides fuel efficiency and carbon emissions for a broad range of vehicle types, while the vehicle registration data provide important information on vehicle types. The fuel consumption rate by make and model was made by matching vehicles in the two datasets.

The main issue with matching records was the large number of vehicle types in the vehicle registration database that were not found in the Green Vehicle Guide. Therefore, if a vehicle type was not found in the Green Vehicle Guide, the information for the closest vehicle match was allocated. For example, if the fuel consumption rate for a *Alfa Romeo 156* was not available, the fuel consumption rate for *Alfa Romeo 159* (the closest match in terms of vehicle make and model) in the Green Vehicle Guide was used.

Matches were not found for approximately 20% of vehicle types in the registered vehicle database and thus they were omitted from the analysis. Fortunately, these vehicle types represent a small number of the total registered vehicles (0.7%); thus, the impact of their omission is not statistically significant. Once the fuel efficiency information was allocated to registered vehicles, the data were then aggregated at the postcode level and the average vehicle fuel efficiencies were calculated.

Mapping vehicle fuel consumption

To calculate fuel consumption for household vehicle travel, we combined the results of average vehicle efficiency with the average vehicle trip distance derived from the JTW data. While there is a mismatch between the use of the 2008 vehicle registration data and the 2006 JTW data, we assumed that there was no major vehicle ownership change between 2006 and 2008 for Brisbane.

As the geographical identifier for the vehicle efficiency (postcode) was not spatially conterminous with the desired mapping unit (SLA), a method of allocating postcodes to SLAs was required. This was achieved by finding the spatial intersection between SLAs and postcodes. The vehicle fuel efficiency value for a SLA was estimated based on the proportioning the postcode value by area, based on the geographic intersection between the two mapping units. Although this process can potentially introduce errors into the analysis, it was deemed acceptable given that more than 80% of SLAs were solely contained by postcodes (i.e. no overlapping boundaries). Once the average vehicle efficiency was allocated to SLAs, they were multiplied by the average vehicle trip distance for each SLA to calculate the average fuel consumption for vehicle travel for that SLA.

Results and discussion

The results are presented in four parts: (1) distribution of average vehicle trip distance; (2) vehicle efficiency distribution; (3) distribution of fuel consumption; and (4) socio-spatial vulnerability.

Private vehicle trip distance

The spatial distribution of average vehicle trip distance by SLA for Brisbane is shown in Figure 1. It shows that the average trip distance tends to be shorter for households living closer to the CBD, while those living further from the CBD have longer trip distances. Travel distance tends to increase as one moves away from the city centre. One reason for this is that people living in outer suburban areas have more dispersed commuting patterns with many commuting across suburbs. (Based on the analysis of the JTW data, there were only 1.6% of commuters in the outer suburbs travelling to Brisbane City, which is very low compared with 21.3% in the inner suburbs.) The data also suggest that the outer suburban trips are not well supported by public transport. Only 7% of travel in outer suburbs is by public transport compared with 10% in middle suburbs and 16% in inner suburbs. The average vehicle trip distances in some suburbs around a regional centre (e.g. Ipswich) are considerably higher than the regional average distance (14 km). This may be due to the decentralised form of suburban development found in Brisbane that has not been concentrated around major activity centres. Instead, development has been more dispersed, reflecting

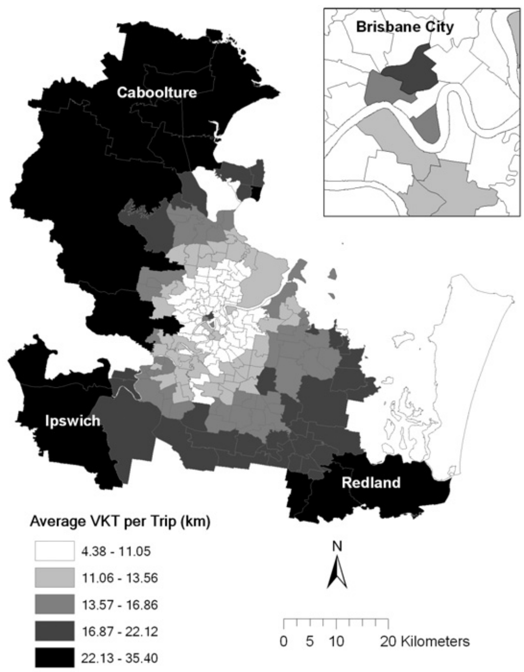

Figure 1 Average private vehicle trip distance by SLA. SLA, statistical local area; VKT, vehicle kilometres travelled.

weaknesses in planning compact and self-contained sub-regional centres. The inset map shows that the average vehicle trip distance for car commuters from inner city areas (e.g. Brisbane CBD) appears to be longer than those in the surrounding inner suburbs. The longer average vehicle trip distance for reverse commuting is most likely due to a number of long-distance trips from inner city Brisbane (e.g. toward the Gold or Sunshine Coasts) and the relatively small number of car-based trips in inner Brisbane City. The reason behind this may be related to the occupational profile of local residents as a large number of inner city commuters are professionals and government employees who live in the Brisbane City but may drive long distance to their workplaces. Because the share of car-based travel in the Brisbane City is relatively small (only 26% of total travel), this occupational factor was not fully investigated in this paper.

Vehicle fuel efficiency

Figure 2 displays the distribution of average vehicle fuel efficiency (litres 100 km^{-1}) at the SLA level. Although private vehicle composition within a SLA can be quite diverse having a wide mix of fuel efficiencies, some important differences in vehicle fuel efficiencies are revealed. As is shown in Figure 2, vehicle fuel efficiency tends to be higher in the inner urban areas surrounding the Brisbane CBD. These areas are surrounded by SLAs with moderate average vehicle fuel efficiency. In contrast, SLAs to far north, far west, and southeast exhibit the lowest vehicle efficiencies. While vehicle fuel consumption tends to increase with increasing distances from the CBD, some local variations exist. For example, the average vehicle efficiency in Kenmore Hills appears to be slightly lower than nearby suburbs. This can be explained by the higher proportion of large- (e.g. sport utility vehicles) and/or high-performance vehicles found in some high-income suburbs that reduced overall vehicle fuel efficiency. The lower efficiencies observed in some blue-collar suburbs (e.g. Rocklea and Kingston) suggest that the occupation and employment sector may affect vehicle choice (e.g. a higher proportion of light trucks, utes, and minivans).

Vehicle trip fuel consumption

The distribution of average vehicle trip fuel consumption is shown in Figure 3. This only includes households who use vehicles for com-

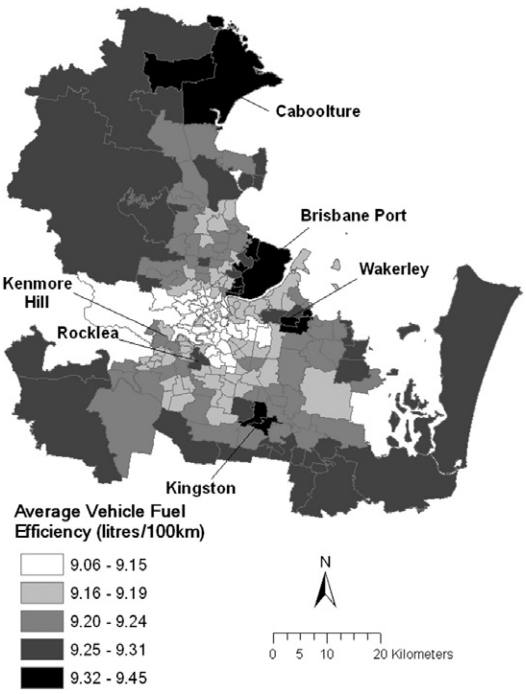

Figure 2 Average vehicle fuel efficiency (litres 100 km^{-1}) by SLA. SLA, statistical local area.

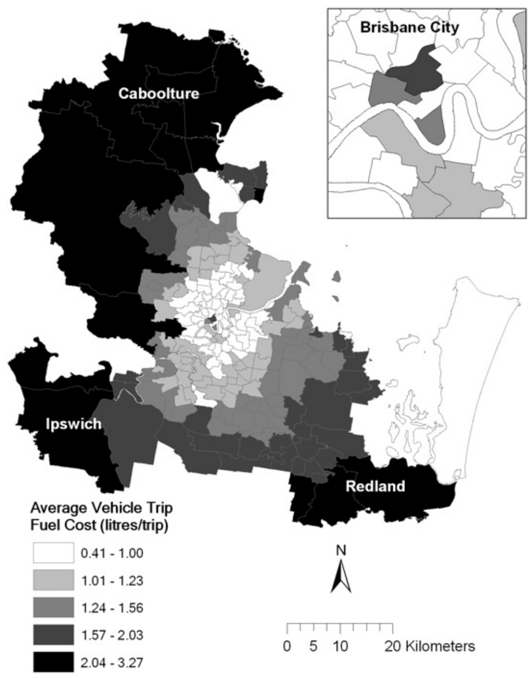

Figure 3 Average private vehicle trip fuel consumption (litres trip^{-1}) by SLA. SLA, statistical local area.

muting. The overall pattern is similar to that of average vehicle trip distance in Figure 1; however, again there are local variations that can be explained by the differences in vehicle fuel efficiencies. In general, the average vehicle fuel consumption per trip for households in the inner city areas is high because of their commuting distance. Households in the inner urban areas exhibit relatively low fuel expenditures, reflecting their closer proximity to employment and higher proportion of fuel-efficient vehicles. In contrast, the average vehicle fuel consumption in the middle to outer-urban areas is greater, given the fact that these areas have longer trip distances and are typically those with a low proportion of fuel-efficient vehicles. Those living in outer-urban area households tend to travel longer distances for work and use less fuel-efficient vehicles, which increase vehicle fuel consumption in these areas. Despite using different datasets, this finding is similar to that of Lindsey *et al.* (2011) who found that in the U.S. cities, transport energy value increases with distance from the CBD with some deviation at local levels influenced by vehicle type used.

Socio-spatial vulnerability distribution

In this section, we compare vehicle energy intensity results with household socio-economic status in an effort to assess Brisbane's energy vulnerability. Household socio-economic status is an important factor when assessing resilience to increasing fuel prices (Dodson and Sipe, 2007). For this research, the ABS Socio Economic Index for Areas (SEIFA) for 2006 was used to measure socio-economic disadvantage. The SEIFA index is constructed from a number of socio-economic factors including (but not limited to) income, home ownership, and education levels to measure household disadvantage. The SEIFA however does not include an explicit transport dimension (e.g. household travel activity or cost). The distribution of the SEIFA for Brisbane is shown in Figure 4. The SEIFA classes presented were based on the quintile classification (1–5). For example, the lowest SEIFA refers to the lowest quintile of SEIFA (752.6–910.8), the next lowest SEIFA refers to second lowest quintile (958.3–965.8), and so forth. Those disadvantaged households, as indicated by low SEIFA values, have less ability to afford higher fuel prices than households with higher SEIFA values.

To assess vulnerability, we first examined the relationship between vehicle fuel consumption and suburban social-economic disadvantage. Because this study mainly focuses on oil vulnerability for households who use vehicles for travel, the vehicle fuel consumption was not weighted by the travel mode share (i.e. the proportion of car-based travel) within each SLA. Also, all households within a SLA are assumed to have an equal SEIFA score. As shown in Figure 5, there is a tendency for SLAs with low SEIFA scores to have higher levels of fuel consumption than SLAs with higher SEIFA scores. The results suggest that the impacts of spatial differentiation of social advantage and disadvantage in Brisbane are likely to be compounded by the effect of energy consumption for motor vehicles. The highest average fuel consumption was represented by the next lowest SEIFA households due to their dispersed travel patterns and lower uptake of energy efficient vehicles than the households in the lowest SEIFA category. In addition, nearly 36% of the highest SEIFA SLAs (31 out of 85) were found to have higher levels of fuel consumption than SLAs in the next highest SEIFA level due to higher household travel demand and higher ability to afford inefficient vehicles.

The next step in assessing vulnerability was to overlay the highest levels of transport energy

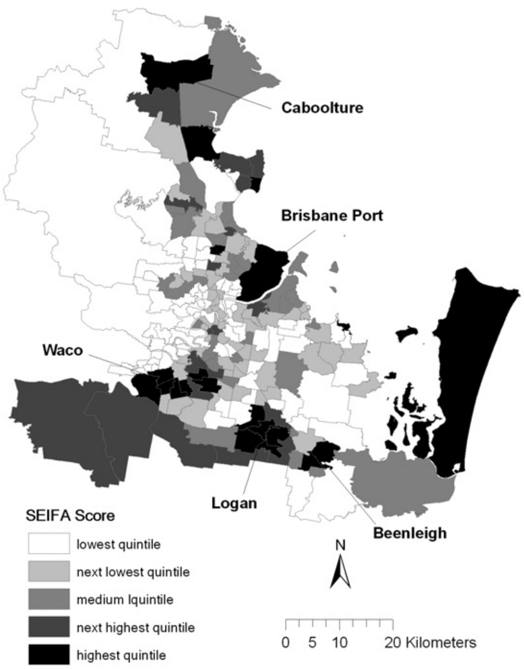

Figure 4 Socio Economic Index for Areas (SEIFA) by SLA. SLA, statistical local area.

consumption with the most disadvantaged suburbs. This analysis identified 'hotspots' of transport energy consumption and social vulnerability. The most energy intensive suburbs were classified as those suburbs with average vehicle energy values greater than one standard deviation from the mean (1.72 L $trip^{-1}$). The most disadvantaged suburbs were those with SEIFA scores in the lowest decile.

The analysis shows that one-third of the most disadvantaged suburbs (11 out of 33) in the Brisbane are situated within the most energy intensive class. Households in these areas are deemed highly vulnerable to costs associated with vehicle fuel consumption. As shown in Figure 6, the most energy vulnerable areas are concentrated along Brisbane's outer suburbs – Ipswich in the west, Logan City and Beenleigh in the south, and Caboolture in the north. Some of the most disadvantaged suburbs in Brisbane were not situated within the high energy areas (e.g. Wacol), and households in those suburbs were not deemed as highly vulnerable due to their moderate transport expenditure. These results yield some slightly different results than those found in previous analyses of oil vulnerability for Brisbane (Dodson and Sipe, 2007). For example, by including vehicle fuel efficiency and travel distance into the analysis (which were not used in the previous studies), previously identified highly vulnerable areas along Brisbane-Ipswich corridor, Hemmant-Lytton in the east, and Griffin in the north have become moderately vulnerable suburbs. This analysis demonstrates the value in using a variety of methodologies when examining oil vulnerability to provide greater detail on different facets of the issue. This research shows that fuel efficiency-weighted vehicle trip distance can provide an alternative measure of car dependence to that used by Dodson and Sipe (2007; 2008) who used vehicles per household and proportion of JTW trips by motor vehicle.

Conclusions and future work

The analysis of household vehicle energy consumption has gained increasing importance in recent years in the face of rising concerns about transport energy sustainability, greenhouse gas emissions, and oil vulnerability. This paper has provided an exploratory analysis of the spatial patterns of vehicle energy consumption based on an analysis of household vehicle travel and the efficiency of the vehicle fleet in Brisbane. Through a spatial analysis of vehicle trip distance derived from JTW data and fuel consumption associated with the vehicles, the results show that vehicle energy use tends to increase as one moves away from the CBD. This demonstrates that not only longer vehicle trip distances but also the lower proportions of efficient vehicles in the outer suburbs increase energy consumption in these locations. Further spatial analysis was done

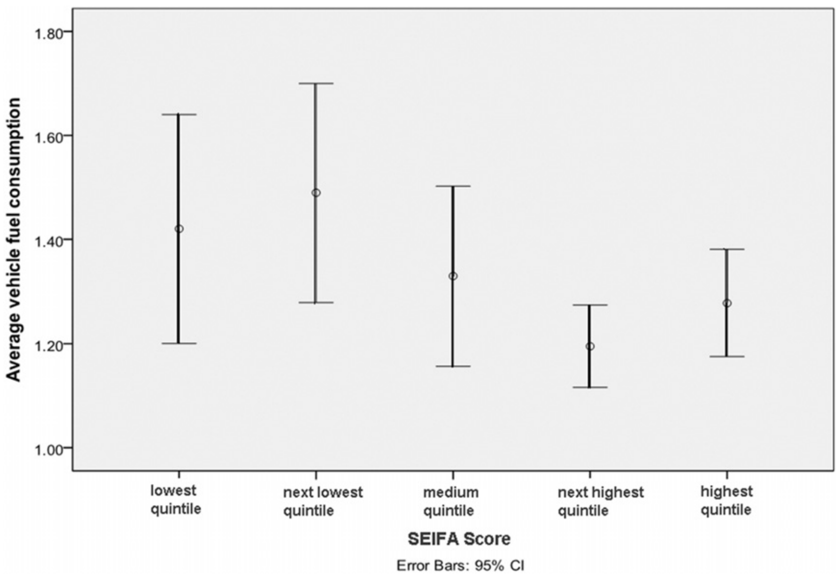

Figure 5 Relationship between average vehicle trip fuel consumption and SEIFA. CI, confidence interval; SEIFA, Socio Economic Index for Areas.

to test the relationship between the fuel intensity and socio-economic characteristics. By comparing the vehicle energy intensity results with patterns of socio-economic disadvantage, we demonstrate that the composition of the vehicle fleet exacerbates household exposure to higher transport costs and compounds other forms of disadvantage.

This paper has focused on the household vehicle energy patterns and vulnerability. While the methods and data presented are applicable to model the spatial patterns of household vehicle fuel consumption, there remain a number of areas that require more research. Firstly, temporally consistent datasets (i.e. motor vehicle data and JTW data) should be used to investigate the spatial relationship between vehicle travel patterns and vehicle ownership and fuel efficiency across the region. Secondly, a spatially disaggregated analysis should be used to better identify the spatial variation in vehicle fleet efficiency and explore how household vehicle fuel consumption patterns differ according to socio-economic status. Both data collection and analysis should be improved in the future research. In addition, in extending this research, it will be important to do more analysis to explore the patterns of household energy consumption from vehicle travel activities for all trip purposes – not only the JTW. Finally, while this paper examined spatial patterns of vehicle energy consumption for a single city, Brisbane, further work should be done to see how the findings for Brisbane compare with other cities to gain broader perspective on the relationship between household vehicle energy patterns and oil vulnerability.

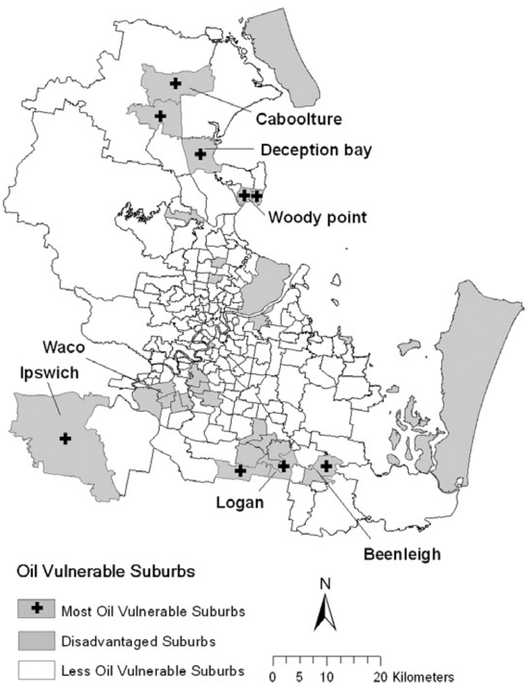

Figure 6 Distribution of oil vulnerable SLAs. SLA, statistical local area.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the helpful comments of two anonymous reviewers. This research was supported under Australian Research Council's Discovery Projects funding scheme (Project Number DP1095562).

REFERENCES

Australian Government, 2010: Our cities – the challenge of change. Background and Research Paper. Canberra.

Banister, D., 1980: *Transport Mobility and Deprivation in Inner Urban Areas*. Saxon House, Farnborough.

Bhat, C., Sen, S. and Eluru, N., 2009: The impact of demographics, built environment attributes, vehicle characteristics, and gasoline prices on household vehicle holdings and use. *Transportation Research Part B* 43, 1–18.

Breheny, M., 1995: The compact city and transport energy consumption. *Transaction of the Institute of British Geographers, New series* 20, 8–101.

Brownstone, D. and Golob, T.F., 2009: The impact of residential density on vehicle usage and energy consumption. *Journal of Urban Economics* 65, 91–98.

BTRE, 2007: *Estimating Urban Traffic and Congestion Cost Trends for Australian Cities*. BTRE, Canberra.

Burnley, I., Murphy, P. and Jenner, A., 1997: Selecting suburbia: residential relocation to outer Sydney. *Urban Studies* 34, 1109–1127.

Cao, X., Mokhtarian, P.L. and Handy, S.L., 2006: Neighborhood design and vehicle type choice: evidence from Northern California. *Transportation Research Part D* 11, 133–145.

Choo, S. and Mokhtarian, P.L., 2004: What type of vehicle do people drive? The role of attitude and lifestyle in influencing vehicle type choice. *Transportation Research A* 38, 201–222.

Dodson, J. and Sipe, N., 2007: Oil vulnerability in the Australian city: assessing socioeconomic risks from higher urban fuel prices. *Urban Studies* 44, 37–62.

Dodson, J. and Sipe, N., 2008: Shocking the suburbs: urban location, homeownership and oil vulnerability in the Australian city. *Housing Studies* 23, 377–401.

Dodson, J., Li, T. and Sipe, N., 2010: Urban structure and socio-economic barriers to consumer adoption of energy efficient automobile technology in a dispersed city: a case study of Brisbane, Australia. *Journal of Transportation Research Board* 2151, 111–118.

DTMR, 2010: *Connecting SEQ 2031: An Integrated Regional Transport Plan for South East Queensland*. Queensland Government, Brisbane.

Eluru, N., Bhat, R., Pendyala, R.M. and Konduri, K.C., 2010: A joint flexible econometric model system of household residential location and vehicle fleet composition/usage choices. *Transportation* 37, 603–626.

Holden, E. and Norland, I., 2005: Three challenges for the compact city as a sustainable urban form: household

consumption of energy and transport in eight residential areas in the greater Oslo region. *Urban Studies* 42, 2145–2166.
Horner, M.W., 2004: Spatial dimensions of urban commuting: a review of major issues and their implications for future geographical research. *The Professional Geographer* 56, 160–173.
Kitamura, R., Akiyama, T., Yamamoto, T. and Golob, T.F., 2001: Accessibility in a metropolis: towards a better understanding of land use and travel. *Transportation Research Record* 1780, 64–75.
Kockelman, K.M. and Zhao, Y., 2000: Behavioral distinctions: the use of light-duty trucks and passenger cars. *Journal of Transportation and Statistics* 3, 47–60.
Lindsey, M., Schofer, J.L., Durango-Cohen, P. and Gray, K.A., 2011: The effect of residential location on vehicle miles of travel, energy consumption and greenhouse gas emissions: Chicago case study. *Transportation Research Part D: Transport and Environment* 16, 1–9.
Maher, C., 1994: Residential mobility, location disadvantage and spatial inequity in Australian cities. *Urban Policy and Research* 12, 185–191.
Mees, P., 2000: *A Very Public Solution: Transport in the Dispersed City*. Melbourne University Publishing, Melbourne.
Newman, P. and Kenworthy, J., 1999: *Sustainability and Cities: Overcoming Automobile Dependence*. Island Press, Washington, DC.
O'Neill, B.C. and Chen, B.S., 2002: Demographic determinants of household energy use in the United States. *Population and Development Review* 28, 53–88.
OUM, 2006: *South East Queensland Infrastructure Plan and Program 2006–2026*. Queensland Government, Brisbane.
Permana, A.S., Perera, R. and Kumar, S., 2008: Understanding energy consumption pattern of households in different urban development forms: a comparative study in Bandung Cit, Indonesia. *Energy Policy* 36, 4287–4297.
Rickwood, P., Glazebrook, G. and Searle, G., 2008: Urban structure and energy – a review. *Urban Policy and Research* 26, 57–81.
VandeWeghe, J.R. and Kennedy, C., 2007: A spatial analysis of residential greenhouse gas emissions in the Toronto census metropolitan area. *Journal of Industrial Ecology* 11, 133–144.
Weisbrod, G., Vary, D. and Treyz, G., 2003: Measuring economic costs of urban traffic congestion to business. *Journal of the Transportation Research Board* 1839, 98–106.
Whiteman, J. and Alford, J., 2009: Macro-urban form, transport energy use and greenhouse gas emissions: an investigation for Melbourne. Department of Transport, Victoria Government.