A CONCEPTUAL SPATIAL INTERACTION MODEL FOR AGING IN, AND THROUGH, POLLUTED PLACES

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ABSTRACT

This paper extends traditional land-use and transport modeling by including the interactions between land use (demographics), transport and public health. The issues of event (environmental stressor), time (from cradle to the grave) and place (locations, especially those with their own time-dependent variable of environmental stress) are the basis of a new transport and epidemiological study proposed. Two inter-related areas of environmental sustainability and health require a comprehensive understanding of the effects of long-term global economic development and climate change on: ecosystem sustainability and on human health; emergent pollutants (from transport) and their effects within human communities; the interaction between environment, land use development, and human health; and the management of solutions at local, regional, and global scales. Research studies have not addressed the explicit recognition of *time* in these two inter-related areas of environmental sustainability and health. Little is known about *how environmental risks impact on individuals over time*, nor about *location* - the health differentials are due to individuals' accumulated exposures, differences in environmental stressors after internal migration (e.g., moves to and from the coast and rural areas), or selective mortality. A specific challenge is coping with the inter-related issues of sustainability and population aging because life-time exposure (in different places and locations) to transport environmental stressors and their cumulative affects health and well-being.

We show that spatial interaction models can be extended to include the long-term dynamics of change as to how peoples' travel patterns pass through "polluted" places as objects of investigation during their life histories as the body ages. A simple systems model with notation is presented. To show there are empirical differences in the health of individuals in "polluted" and "non-polluted places, the hypothesis is: there are long-term adverse health consequences (morbidities and mortalities) of the cumulative exposure to harmful pollutants. Statistical analyzes of all available waves (from 2001 to 2007) of the Australian HILDA survey were undertaken (1312 HILDA interviewees aged 45 years or more who had lived at their current address for 20 years or more) supports the hypothesis. HILDA is a comprehensive and nationally representative panel dataset that surveys both individuals and households. Given that transport contributes to this pollution that impacts on long-term health we give an example of a transport intervention policy based on road pricing and the environmental capacity of small areas based on carbon monoxide emissions. Further research is indentified in the conclusions.

Keywords: transport pollution, health, spatial models

INTRODUCTION

> "[D]ecreased efficiency in the blood-brain barrier and the cardiovascular, pulmonary, immune, musculoskeletal, hepatic, renal, and gastrointestinal systems can alter response to environmental agents, leading to heightened susceptibility to the toxic effects of air pollution, pesticides, and other exogenous threats to health" (Hood, 2003, p. A756).

"Sustainability" as a topic represents a core research theme of transport and the environment. Health can be viewed as a central criterion for judging human sustainability (McMichael, 2006). Therefore, it is logical when proposing research topics into transport and the environment that there are stronger connections between transport and health researchers. This new field of integrated, trans-disciplinary research (Issarayangyun, Black, Black, and Samuels, 2005; Black and Black, 2009) proposed is a logical extension of the land use, transport and environment domain - but with more attention paid to individual and population health. In this paper, we argue that the "aging population" in many advanced developed nations be explicitly incorporated into empirical analyses of transport and urban sustainability.

Two inter-related areas of environmental sustainability and health sustainability require a comprehensive understanding of the effects of long-term global economic development and climate change on: ecosystem sustainability and on human health; emergent pollutants (from transport) and their effects within human communities; the interaction between environment, land use development, and human health; and the management of solutions at local, regional, and global scales. A review of some 200 scientific papers (Black and Black, 2009) found that research studies have not addressed the explicit recognition of *time* in these two inter-related areas of environmental sustainability (pollution over time) and health (exposure of individuals over time).

Therefore, this conceptual, theoretical and empirical paper extends traditional spatial transport modeling through the inclusion of interactions between land use (with its demographic characteristics specified) and transport and public health (where health can be viewed as a central criterion for judging all human sustainability). The issues of pollution events (environmental stressors), time (from cradle to the grave) and place (locations, especially those with their own time-dependent variable of environmental stress) are the basis of a new transport and epidemiological study proposed. As people age their ability to defend against environmental stressors diminishes, and such exposures can accelerate the aging process and trigger, or exacerbate, disease and the erosion of independence and well-being. A major challenge is coping with the inter-related issues of environmental and health sustainability and population aging. The research challenge is to establish this life time exposure (in different places and locations) to the environmental stressors from transport systems and their cumulative effects on health and well-being. The significance of this line of research is that The World Health Organization's (WHO) global strategy for age-friendly cities has charted the way towards sustainable solutions: how 'active aging' can be enhanced through outdoor spaces, transport, housing, and social participation and inclusion, and civic participation and employment strategies. This activity should take place ideally in non-polluted locations.

Little is known about *how environmental risks impact on individuals over time*, nor about *location* - the health differentials are due to individuals' accumulated exposures, differences in environmental stressors after internal migration (e.g., moves to and from the coast and rural areas), or selective mortality. Conceptually, we need to establish the life-time exposure (in different places and locations) to environmental stressors from transport systems and their cumulative effects on health and well-being. We show that spatial interaction models can be extended to include the long-term dynamics of change as to how peoples' travel patterns pass through "polluted" places as objects of investigation during their life histories as the body ages.

The next section touches on some of the literature on urbanization and public health, noting that there is limited literature on the specific effect of living in cities on the aging compared with living in areas of high environmental quality. As this is a highly complex area, we resort to systems modeling to demonstrate the main ideas in outline, also in the next section. Polluted and non-polluted locations are defined, and spatial models outlined in their functional format following the mathematical notation in Black (1981). The following section defines from the literature the urban stressors on public health and then tests the hypothesis that there are long-term adverse health consequences (morbidities and mortalities) of the cumulative exposure to harmful pollutants. Analyzes of all available waves (from 2001 to 2007) of the Australian HILDA survey were undertaken. HILDA is a comprehensive and nationally representative panel dataset that surveys both individuals and households. We selected all participants who were interviewed in the HILDA database, aged 45 years or more at baseline (Wave 1, 2001). To ensure adequate exposure to their local environment, we selected participants who had lived at their current urban, regional, rural or remote location for 20 or more years. The presence of long-term health condition was based on the data provided by HILDA interviewees. Logistic regression was undertaken using SPSS version 16.0 with the presence of at least one long-term health condition as the outcome variable. The analysis at baseline demonstrated that urban and city dwellers ("polluted places") were more likely to have one or more long-term health conditions than those living in rural areas ("non-polluted places".

Having demonstrated that there are long-term health impacts associated with pollution from cities and transport, the obvious question to ask from the transport perspective is what can be done to contain pollution below national standards or targets. To do this, we draw on previously published research (Shiran, Hidas and Black, 1997; and Golzar and Black, 2002) to show the relevance of the concept of environmental capacity and how road pricing is one policy tool to achieve air quality objectives. The final section summarizes the paper and identifies areas for further research.

INDIVIDUAL HEALTH AND THE LAND USE/TRANSPORT SYSTEM

The local environments around people's residences and where they travel and participate in daily activities have both positive and negative impacts on the level of physical activity and therefore an impact on health status. Studies in Sydney have shown that *areas* with high levels of environmental noise, poor ambient air quality, and low socio-economic status have higher levels of cardiovascular disease. There are also differences in morbidity and mortality between urban and regional, rural and remote areas, for selected diseases and causes of death. The way human settlement patterns are organized, deployed and utilized by people going about their daily activities impact on the health of the population. The link between urbanization and public health is well known (Frumkin, 2002; Giles-Corti, 2006; Saarloos, Kim, & Timmermans, 2009), but there is limited literature on the specific effect of living in cities on the aging compared with living in areas of high environmental quality. As our bodies age, the ability to defend against environmental pressures diminishes, and exposures can accelerate the aging process and trigger, or exacerbate, disease. It is the complexity of these emerging public health problems that present a major new challenge for sustainable development, well-being and the quality of life in cities for the aging population. To gain some insights into such complexity we resort to systems modeling.

System Concepts

A system is a set of objects together with the relationship between those objects (Hall and Fagen, 1956, p. 18). Here, we extend the system conventionally used in transport analysis – with its main objects (and interactions) of land use, transport supply and traffic (Black, 1981, pp. 23 – 33) – to explicitly consider both the environmental consequences of these traffic flows and the direct health impacts of the pollution from that traffic on people. The aim is to identify a systems model of these interactions, where our mathematical model is a conceptual representation of something else (the real socio-economic world), designed for the specific purpose of understanding better a highly complex, spatial system. In this conceptual model, the purpose initial is one of understanding. (Only later, will we consider policies and interventions.)

Hypothesis

The working hypothesis is that contained within each uniquely defined spatial entity, which we call the land-use/transport system, is a sub-set of locations and transport routes that are “polluted places”. The dominant urban environmental stressors from transport (roads, railways, sea port and airports) are road traffic and aircraft noise that has well-understood physical properties from the source of the sound waves together with impacts on humans; and emissions from transport vehicles – where air quality is further complicated by the technology of the vehicle fleet, atmospheric conditions and the diffusion of pollutants. We are interested in the locational life histories of individuals and their health as they age, and how they move through these polluted places from cradle to grave through the mechanisms of migration and travel (two forms of spatial interaction). The hypothesis is that there are long-term adverse health consequences (morbidities and mortalities) of the cumulative exposure to harmful pollutants.

Locations of Polluted Places

What might constitute a “polluted” place in which environmental stressors are generated? Are these places continuously polluted? Or is there a time-dependent nature to this pollution? Whether or not a location is “polluted” is as much a political question as a scientific question. For example, The WHO (WHO, 2000) recommended that the air quality standards in any jurisdiction should be based on:

- Prevailing exposure levels;
- Environmental conditions;
- Social characteristics; and
- Economic and cultural conditions.

In Australia, for example, it is possible to draw on the promulgated noise (such as the NSW EPA noise standards) and national ambient air quality standards (Table 1) and to define “polluted places” as being where measured levels exceed the standards for specified periods of time.

Table 1 - Australian National Air Quality Standards

Pollutant	Concentration and averaging period
Carbon monoxide	9.0 ppm (parts per million) measured over an eight hour period
Nitrogen dioxide	0.12 ppm averaged over a one hour period
	0.03 ppm averaged over a one year period
Ozone	0.10 ppm of ozone measured over a one hour period
	0.08 ppm of ozone measured over a four hour period
Sulfur dioxide	0.20 ppm averaged over a one hour period
	0.08 ppm averaged over a 24 hour period
	0.02 ppm averaged over a one year period
Lead	0.5 µg/m³ (micrograms per cubic metre) averaged over a one year period
Particles as PM_{10}	50 µg/m³ averaged over a 24-hour period
Particles as $PM_{2.5}$	Advisory reporting standard: 25 µg/m³ over a one day period; 8 µg/m³ over a one year period

Source:http://www.environment.gov.au/atmosphere/airquality/publications/standards.html, accessed 25 January, 2010.

System Representation

A land use/transport system comprising of two zones and two routes has proved invaluable in explaining fundamental concepts and equations of state (Blunden, 1967; Black, 1981; and Blunden and Black, 1984). Here we add an additional residential zone (zone *r*) of high environmental quality to capture the migration dynamics. This zone is an “unpolluted place” where its residents’ enjoy healthy lifestyle choices of walking and cycling and a minimal amount of internal road traffic. This zone is in addition to the other residential zone (zone i) which generates a lot of car traffic and is connected to the employment centre (zone j) by a road system of two parallel routes (k=1; k=2). For simplicity of exposition we can use the numerical worked example in Black (1981, pp. 33-38) with equations and parameters that help explain fundamental concepts of traffic generation, the spatial pattern of traffic, transport mode and route choice, transport supply, and demonstrate the equilibrium flows of traffic of the road network. From vehicle emission models (or measured rates of tailpipe emissions), it is obvious that any properties along the main route (k=1) are located in a “polluted place”. Although the equations do not consider the internal traffic in zones *i* and *j* we can safely assume that these zones too are “polluted places”, whereas zone *r* is not polluted – by definition.

The specific parameters chosen for the worked example gave the equilibrium traffic assignment in the peak one-hour, and also showed how the equations of state could be applied to forecast peak-hour traffic under four different policy scenarios (Black, 1981, pp. 38-42). It is straightforward (if tedious) to specify different parameters by time of day for the base case situation then project traffic forward for each day of the week, for each week of the year, and so one. An equally straightforward calculation is that of the pollutants from the traffic which can be integrated over time to give total accumulated dosages (in zone *i*, zone *j* and along routes *k*=1 and *k*=2).

The problematic part of the analysis is to determine the population's exposure to these "polluted places." Let us take air pollution as an example. Air pollution epidemiology studies typically involve estimation of a statistical relationship between the frequency of a specific health outcome, observed in a study population in its normal place (location), and the air pollution concentration measured at that location (using a site-specific monitoring site as the proxy for individual locations). Typically, community-averaged outdoor pollution concentrations in the atmosphere are used in the statistical investigation of exposure-response relationships. The important point is that ambient monitoring at fixed locations does not reflect adequately, or accurately, total personal exposures to particulates and other pollutants (Wallace, 1996). The difficulty for our purposes is the highly time-dependent nature of the pollution phenomenon, primarily a function of the temporal traffic variation during 24 hours (including the imposition of legal curfews), and the time-dependent paths of individuals going about their activities – their time-space geographies.

The problem is to compute the integrated exposure as a sum of the individual products of the concentrations encountered by a person in a micro-environment and the time the person spends there. The integrated exposure permits computations of average exposure for any averaging period by dividing the integrated exposure by the duration of the averaging period. If the concentration within the microenvironment *j* is assumed to be constant during the period that the person I occupies microenvironment *j*, then the integrated exposure E_i for person I will be the sum of the product of the concentration c*j* in each microenvironment, and the time spent by the person *i* in that micro-environment will be as follows,

$$E_i = \sum_{j=1}^{J} c_j \, . \, t_{ij} \quad \text{where,}$$

E_i is the integrated exposure of person I over the time period of interest;
c_j is the concentration experienced in micro-environment *j*;
t_{ij} is the time spent by person I in microenvironment *j*; and
J is the total number of micro-environments

To compute the integrated exposure E*i* for person I, it obviously is necessary to estimate both c_j and t_{ij}. If T is the averaging time, the average exposure E_i of the person I is obtained by dividing T; that is $\bar{E}_i = E_i/T$.

To solve this problem it is necessary to determine the concentration outdoors, dispersion in ambient air, penetration across building envelopes, and exposure to the human respiratory tract. Human beings come in contact with pollutants of outdoor origin in many settings (micro-environments) including: ambient locations, indoors at home (in zone *i*), at work (zone *j*), or at school, in transit (along routes *k*=1 and *k*=2) while commuting or riding in a car or a bus. With particular reference to the worked example, we need specify a spatial model for aging in, and through, these "polluted spaces". The total population comprises:

1. Residents of zone *r* who remain in "unpolluted spaces" in the analysis period t_0 to t_n
2. Residents of zone *r* who migrate at time t*m* to re-locating in zone *i* or along routes *k*=1 or *k*=2 and live there from time t_m to t_n.
3. Residents of zone *i* who remain in "polluted spaces" in the analysis period t_0 to t_n
4. Residents of zone *i* or along routes *k*=1 or *k*=2 who migrate at time t*m* to re-locating in zone *r* or and live there in "unpolluted spaces" from time t_m to t_n.
5. Residents of zone *i* who commute to zone *j* along routes *k*=1 and *k*=2.
6. Employees working in zone *j* in the analysis period t_0 to t_n.
7. Employees of zone *j* who re-locate a job at time t_m by re-locating workplace to zone *r* from time t_m to t_n.

Health impacts in polluted and non-polluted spaces are analyzed in the next section.

However, the longer-term research goal is to formulate two spatial models: one for the migration component of residents and jobs; another for the commuting component. Both models must specify the age of the person and the time at which the spatial interactions takes place – hence there is an explicit time dimension. Therefore, lifetime exposure E from cradle t_0 to t_n is a function of the location at (zones=z) at different times and where the population is at time=t_m. This can be modeled using time-series analyzes where demographics, such as age, sex and socio-economic status, are included in the model below:

$$E=F_n(z_i, t_m|\text{demographics}).$$

The model assumes that location – that is, each zone - is independent of time. Research funded by the Australian Academy of Science in 2010 will aim to develop this model further.

EMPIRICAL EVIDENCE OF HEALTH IN ZONES *i* AND *r*

The hypothesis is that there are long-term adverse health consequences (morbidities and mortalities) of the cumulative exposure to harmful pollutants. In the case of the above example and system representation we need to establish that those residents who live and age in zone *r* are healthier than those residents who live and age in zone *i*.

Literature

The link between urbanization and public health is well known (Frumkin, 2002; Giles-Corti, 2006; Saarloos, Kim, & Timmermans, 2009), but there is limited literature on the specific effect of living in cities on the aging population. There is evidence of greater levels of social interaction in aging populations in urban environments of developed countries, and this can have a positive effect on both physical and mental health (AARP, 2009; Quinn, 2008). However, as our bodies age, our ability to defend against environmental pressures diminishes and exposures can accelerate the aging process and trigger, or exacerbate, disease. It is the complexity of these emerging public health problems that present a major new challenge for sustainable development, well-being and the quality of life in cities for the aging population.

There is a large literature on the impacts of urban stressors on public health (see Black & Black, 2009). These impacts are summarized in Table 2. Environmental stressors clearly have both location and time dimensions (duration by time of day, seasonality, trends over time). As a preliminary attempt at the difficult empirical analyses required to account for a person's life-time exposure to environmental stressors, we have used geographic location as a proxy for exposure level. There is growing evidence that environmental stressors have a significant impact on long-term health conditions. Litt and colleagues (2004) outline the lack of information on the role of environmental exposures in relation to the incidence of chronic diseases and other conditions including asthma, neurological disorders, diabetes and developmental disabilities. This is particularly relevant for aging populations because they have longer exposure to these pollutants in the environment.

Table 2 - Built Environment Impacts on Health and Geographical Scale of Problem

Interaction	Geographical Scale	Main Exposed Group
Road and rail noise – sleep disturbance, annoyance, stress	Localized - noise attenuates with increasing distance	All groups in population, but greater impact on low – medium socio-economic status
Cyclists and ultra fine particulate matter inhalation	Localized – on road	Cyclists especially in morning peak
Aircraft noise - sleep disturbance, annoyance, stress	Area surrounding airport within 15-20 NEF	All groups with greater impact on low socio-economic status
Leaded petrol and child development	Localized to houses playgrounds on main roads, but note residual lead from paint within houses and gardens	Young children
Low density suburbs and stress	Suburban	Lower socio-economic status and those without access to automobile and reliable public transport
Car dependency and obesity	Urban, especially suburban	Adults and children
Transport emissions and air quality	Metropolitan air-shed	All groups, with dispersal modified by local meteorological conditions
Freeways and vehicle emissions and respiratory problems	within 500m – 1000m	All groups, especially young and elderly, and sub-groups
Diesel trucks, particulate matter and health	Near sea-ports, along major roads and truck routes	All groups but with a distinct socio-economic dimension
Accessibility and quality of life	Local neighborhood with emphasis on street design & pedestrian environments	All groups
Footpath design and standards and pedestrian injuries	Localized around home to neighborhood activities	All groups but especially young and elderly
Poor dwelling design and layout and accidents in home	Household	Young children and elderly

(Source: Black & Black, 2009)

Analysis

Analyses of all available waves (from 2001 to 2007) of the Australian HILDA survey were undertaken. HILDA is a comprehensive and nationally representative panel dataset that surveys both individuals and households. We selected all participants who were interviewed in the HILDA database. The non-interviewed members of the household were excluded. Participants aged 45 years or more at baseline (Wave 1, 2001) were included. To ensure adequate exposure to their local environment, we selected participants who had lived at their current urban, regional, rural or remote location for 20 or more years. The presence of long-term health condition was based on the HILDA interviewee confirming they had one or more of the following conditions:

- Arthritis
- Asthma
- Any type of cancer
- Chronic bronchitis or emphysema
- Type 2 diabetes (adult onset)
- Depression/anxiety
- Heart/coronary disease
- High blood pressure/hypertension
- Other circulatory conditions.

Logistic regression was undertaken using SPSS version 16.0 with the presence of at least one long-term health condition as the outcome variable. Explanatory variables were included in the model if there was an association with the outcome at □=0. 25 (Hosmer & Lemeshow, 2000). Explanatory variables were considered significant in the logistic regression model at □=0.05 and 95% confidence intervals were used for odds ratios.

Survival was measured at each wave of the HILDA collection and defined as not reporting a long-term health condition occurring for the first time in that wave. Cox regression was used to determine predictors of survival. SPSS Version 16.0 was used for the survival analyses with □=0.05.

Results

At baseline, there were 1312 HILDA interviewees aged 45 years or more who had lived at their current address for 20 years or more. Around two-thirds (63%) lived in a major city, 21% lived in inner regional areas, 14% in outer regional areas and 2% in remote areas. In 2001, one third (33%) of the interviewees had an existing long-term health condition as defined above. The logistic regression results reported below in Table 3 show that increasing age, being male, living in major cities or inner urban areas, and living in an area with a lower socio-economic status (based on Socio-Economic Indicator for Area (SEIFA) (Australian Bureau of Statistics, 2001)) increase the odds of having a long-term health condition.

A one-year increase in age increases the odds of having a long-term health condition by 1.04 (95% CI 1.03-1.05, p<.001). Males have 1.61 greater odds of having a long-term health condition (95% CI 1.26-2.04, p<.001). For people aged 45 years or more, living in a major city compared to a remote area increased the odds of having a long term health condition by 6.51 (95% CI 1.48-28.59, p=.013). Similarly, living in an inner regional area compared to a remote area increased the odds of having a long term health condition (OR=7.19, 95% CI 1.63-31.67, p=.009). Living in the lowest decile of the index of relative socio-economic advantage/disadvantage compared to the highest decile increased the odds of having a long-term health condition by 3.92 (95% CI 2.25-6.82, p<.001). In fact, there were significantly greater odds, compared to the highest decile, of having a long-term condition if a person aged 45 years or more lived in the lowest decile through to the 8th decile.

Table 3 - Predictors of having a Long-term Health Condition at HILDA Baseline (2001)

Predictor	OR	95% CI	p-value
age	1.038	1.026-1.050	<.001
Male*	1.605	1.261-2.041	<.001
Living in major city**	6.511	1.483-28.585	.013
Living in inner regional area**	7.191	1.633-31.671	.009
Living in outer regional area**	4.271	.951-19.188	.058
SEIFA Lowest Decile***	3.916	2.249-6.820	<.001
SEIFA Decile 2***	2.290	1.342-3.908	<.002
SEIFA Decile 3***	1.935	1.096-3.418	.023
SEIFA Decile 4***	1.828	1.037-3.224	.037
SEIFA Decile 5***	2.677	1.537-4.663	.001
SEIFA Decile 6***	2.294	1.221-4.310	.010
SEIFA Decile 7***	2.239	1.281-3.914	.005
SEIFA Decile 8***	2.003	1.167-3.437	.012
SEIFA Decile 9***	.935	.514-1.702	.827

* compared to females
** compared to remote area
*** compared to highest SEIFA decile

The survival analyses of the 7 waves of HILDA (2001 to 2007) showed that survival without a long-term health condition was not statistically significantly worse for people aged 45 years or more at baseline living in major cities or inner regional areas compared to other geographic areas. The Cox regression demonstrates that only one factor explains greater survival and that is that older age at baseline increases one's long-term health condition free survival time.

Table 4 - Predictors of Long-term Health Condition Free Survival for HILDA Cohort Aged 45 Years or More at Baseline

Predictor	OR	95% CI	p-value
age	.988	.979-997	.008
Male*	.941	.783-1.131	.518
Living in remote/outer regional**	1.026	.767-1.373	.862
Living in inner regional area**	.988	.719-1.358	.941
SEIFA Lowest Decile***	1.033	.703-1.518	.868
SEIFA Decile 2***	1.026	.673-1.563	.906
SEIFA Decile 3***	.878	.575-1.340	.546
SEIFA Decile 4***	.969	.616-1.525	.892
SEIFA Decile 5***	1.072	.647-1.776	.789
SEIFA Decile 6***	.824	.508-1.337	.433
SEIFA Decile 7***	.907	.586-1.404	.661
SEIFA Decile 8***	.897	.587-1.371	.615
SEIFA Decile 9***	1.116	.736-1.694	.604

* compared to females
** compared to major city
*** compared to highest SEIFA decile

Interpretation

This study reinforces the association between long-term exposure to environmental stressors, such as air pollution and noise, in large cities and in individuals developing long-term health conditions. The analysis at baseline demonstrated that urban and city dwellers were more likely to have one or more long-term health conditions. However, the odds of developing a long-term health condition in a cohort of aging Australians was not significantly higher in more densely populated areas compared to rural locations with its implicit superior environmental quality.

Of course, there is a major limitation in using geographic location as a proxy for levels or dosage of exposure to environmental stressors. Nevertheless, the results give support to the theoretical model where residential zone *r* is designated as a “non-polluted” space, and that exposure to pollutants occurs in residential zone *i*. As noted in our conceptual model above, people living in the same location may have different exposure levels depending on their occupation and/or other lifestyle activities (Alfredsson, Hammar, & Hogstedt, 1993; Pilidis, Karakitsios, Kassomenos, Kazos, & Stalikas, 2009). There are also limitations in measurement of the response to exposure. Firstly, the long-term health conditions were self-reported and may be subject to error. Secondly, healthy lifestyle choices, such as undertaking exercise, impact on the occurrence of long-term conditions and are known to be affected by the built environment (de Nazelle, Rodriguez, & Crawford-Brown, 2009; Teo, *et al.*, 2009).

TRANSPORT POLICY IMPLICATIONS – CO AND ENVIRONMENTAL CAPACITY

The sustainable transport policy implications of these findings are clear: long-term health benefits will accrue from interventions in the transport sector if traffic flows (and hence vehicle emissions) are constrained below the threshold that exceeds any environmental limit. Air quality targets are selected by considering the relationship between adverse human health effects and level of air pollution. Air quality targets (standards), as in Table 1, for example, are set as the "environmental capacity" of the road. Indeed, this is an old concept (Buchanan, 1963) where the criteria may be road traffic noise, difficulties in pedestrians crossing the road and vehicle emissions (Song, Black and Dunne, 1993; Shiran, 1997).

The method is to calculate the traffic load in the defined area that will produce vehicle emissions that meet the air quality standards. To illustrate the approach we can draw on previously peer-reviewed research (Hidas, Shiran and Black; 1997; Golzar and Black, 2002). A statistical model links parameters representing vehicular traffic, meteorological conditions, land layout and land-use conditions, and the pollution concentration of carbon monoxide (CO). Variables incorporated into the model are:

- Ventilation Rate;
- Proportion of built-up environment;
- Percentage of travel in residential areas
- Building density and street aspect ratio; and
- The pattern of city land use and its orientation angle with respect to the predominant wind direction (Shiran, 1997, pp.293-295).

To simplify and represent the complexity of atmospheric conditions which impact on ambient air quality, the model has been developed for three meteorological scenarios represented by a composite explanatory variable named the Ventilation Rate (VR is measured in m^2/sec), that is a product of mixing height (meters) and wind speed (meters/second). There are three considerations for the calculation of AWEC. First, the ventilation rate is an appropriate measure for present meteorological conditions and their impact on pollution concentration. Secondly, the spatial units for AWEC calculation are a factor of land use settings with parameters such as Aspect Ratio (AR), developed to present percentage built and land-use density. The aspect ratio is calculated as the ratio of the average building height to the width of the adjacent street. The third is one-hour and 8-hour averaging time of pollution concentration are suitable for calculation of AWEC.

The model has been calibrated for Sydney conditions, with the development of AWEC parameters. Shiran formulated and tested both linear; and non-linear models (for example:

Formula - Example linear AWEC formula

$$AWEC = W_i + \alpha_i LOCALTRAVEL + \beta_i BULT + \gamma_i ANGLE$$

$$\alpha_i, \beta_i, \gamma_i = \text{Parameters for VR scenario } i$$

$$W_i = \text{AWEC constant for VR scenario } i$$

The basis for calculation of charges is the AWEC index, which itself is set based on a predetermined air pollution criteria (eg CO concentration). Various types of pollutants can be selected as criteria for developing AWEC. The three main pollutants considered in research for developing AWEC were CO, NO_x and lead (Shiran, 1997). However it can be postulated that by controlling NO_x's, lead and CO, a large part of the primary and secondary products can be reduced. After determining the type of pollutant for calculating AWEC, the level of pollutant concentration should be defined. Australian air quality standards have been previously used for the development of AWEC (Hidas, Shiran and Black, 1997).

To demonstrate the application of this model a case study to determine plausible environmental transport pricing for Central Sydney was undertaken (Golzar and Black, 2002). The study area covers about 14 square kilometers, including the Sydney CBD and part of North Sydney. A grid network of cells was overlayed on the study area, with each cell approximately 1 sq km in dimension. The vehicle kilometers travelled (VKT) as forecast by the travel demand model (with an embedded spatial interaction model) used by the New South Wales Department of Transport and Infrastructure Transport Data Centre were aggregated for each cell of the grid. The analysis is confined to the morning peak hour in 1999. TransCAD was used as the analysis platform to aggregate the vehicle kilometer travelled within the defined spatial areas.

The aggregated VKT is then compared with the AWEC parameter index derived from the AWEC model (Hidas, Shiran and Black, 1997) for each of these spatial areas (Figure 1 illustrates the results for one of the scenarios). The grid cells shown in the darkest color (Sydney CBD and North Sydney CBD) are where CO concentrations exceed the environmental capacity as determined by the ambient air quality standard. Scenario developments included different road pricing regimes and charges such that the estimated road traffic was reduced to meet the air quality standard. Whilst conventional economic analysis of such policies would calculate changes in consumer surplus following the introduction of road pricing or area pricing, we are argue that the long-term health benefits from such a policy be estimated and included in the decision making process.

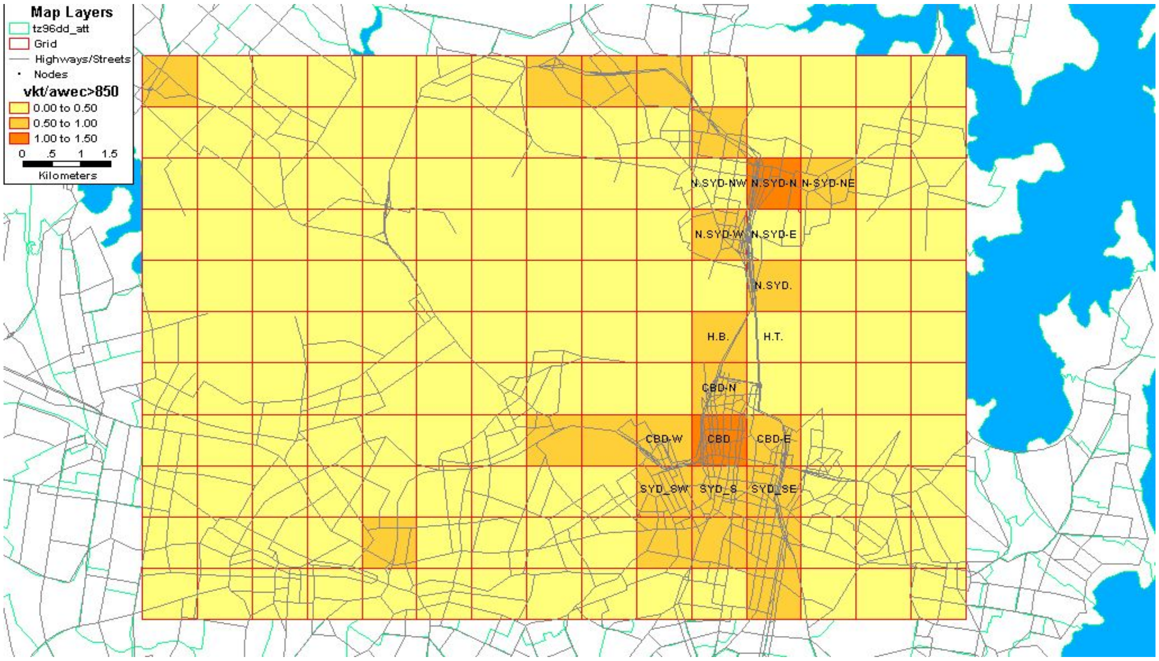

Figure 1 - Visualization of Vehicular Pollution: Example of the Grid Cell Over-layed on the Road Network of Central Sydney and Area-Wide Environmental Capacity Index (calculated as the ratio of Vehicle-Kilometers Travelled within each cell to Area-Wide Environmental Capacity of the cell)

CONCLUSIONS

This conceptual, theoretical and empirical paper has extended traditional spatial transport modeling through the inclusion of interactions between land use (with its demographic characteristics specified) and transport and public health (where health can be viewed as a central criterion for judging all human sustainability). The issues of pollution events (environmental stressors), time (from cradle to the grave) and place (locations, especially those with their own time-dependent variable of environmental stress) are the basis of what we propose as a new transport and epidemiological study. As people age their ability to defend against environmental stressors diminishes, and such exposures can accelerate the aging process and trigger, or exacerbate, disease and the erosion of independence and well-being. Therefore, we have set out a conceptual model, using a three zone, two route example, to tease of the spatial dynamics of travel and migration through polluted and non-polluted places.

The core hypothesis is that there are long-term adverse health consequences (morbidities and mortalities) of the cumulative exposure to harmful pollutants. Alalyzes of the HILDA study data reinforced the association between long-term exposure to environmental stressors, such as air pollution, in large cities and in individuals developing long-term health conditions. The analysis at baseline demonstrated that urban and city dwellers were more likely to have one or more long-term health conditions. However, the odds of developing a long-term health condition in a cohort of aging Australians was not significantly higher in more densely populated areas compared to rural locations with its implicit superior environmental quality.

Therefore, to address these limitations of the analyzes undertaken of the HILDA study data, a specifically-designed study should address the measurement of exposure to environmental stressors over the life-course of the aging populations, including accurate measurement of environmental stressors, such as ambient air quality and noise. Such a study should also include the diagnosis of non-infectious chronic disease by a health-care professional. Lifestyle choices that protect against or are a risk for non-infectious chronic diseases should be recorded in a systematic way. Notwithstanding the limitations of using a longitudinal database that was not specifically designed to measure environmental exposure (HILDA), this study has shown that aging Australians who live in urban areas are more likely to have a non-infectious chronic disease than those living more remotely (and implicitly in superior environmental conditions). Given that there is increasing urbanization, increasing aging, and increasing levels of pollutants in the environment, there is an urgent need to address the impact of environment exposures on society including aging populations.

Transport sector policies must be integrated with health sector policies to ensure greatest social benefit is obtained from various interventions. This point was reinforced in the paper with the use of one example of a transport policy. Given that transport contributes to airborne pollution we have reported on a method to calculate the road traffic load in a defined area that will produce vehicle emissions (given prevailing engine technologies) that meet the air quality standards. This is based on the environmental capacity of an area. Land use and transport interaction models have been calibrated for metropolitan Sydney, and road pricing modeled to drive demand downwards to achieve air quality standards (carbon monoxide) under prevailing meterological conditions.

The literature review as part of our research demonstrates richness across the themes of environmental stressors and their impacts on humans, on one hand, and of the processes of urbanization, transport and the environment, on the other. However, our review of this literature concludes with there still being relatively little integration of the material (Black and Black, 2009). Repeated search strategies of data bases on key words such as “public health, urbanization, transport and environmental stressors” failed to identify much material. It is clear from the mainstream transport literature, and through the special interest groups of the World Conference on Transport Research Society that, within their environment group, transport and health is currently not on the main topic agenda. Similarly, although with some exceptions, the public health researchers have not connected adequately enough with the urban researchers. Champions are needed in both fields to advance trans-disciplinary research.

Our long-term research aims are to build collaborative partnerships (such as within the World Conference on Transport Research Society, SIG 1) that can analyze how environmental stressors impact on individuals *over time* and by *location*; to identify data; and to propose methodologies of dose-response over individual life-spans. A major societal challenge is coping with environmental sustainability and population aging. As people age their ability to defend against environmental stressors, such as air pollution, diminishes. Such exposures can accelerate the aging process and trigger, or exacerbate, and the erosion of independence and well-being. Working within a trans-disciplinary framework, the research will collaboratively define the problem and generate hypotheses, and design methodologies for further research enquiries.

As a suggestion on research by way of bridging that gap, and recognizing that the core research team of a trans-disciplinary project must bring their our disciplinary skills and interests to the table, we suggest an ambitious challenge would be the explicit recognition of *time* and *spatial modeling* in all research methodological phases from problem definition, through to reviewing existing knowledge on the research problem, especially disciplinary and inter-disciplinary conceptualizations and explanations, designing the research enquiry from research gaps; implementing the research enquiry, refining conceptual understandings and synthesizing data sets; and specifying types of interventions (with stakeholders) and their costs and benefits. We need to establish the life-time exposure (in different places and locations) to the environmental stressors from transport systems and their cumulative effects on health and well-being. The methodology could be time-space geography but with the additional complexity of locations and magnitudes of environmental stressors mapped "through which people on their journeys" are exposed. The urban modelers – familiar with spatial interaction models using cross sectional data – need to turn their minds to the long-term dynamics of change and time series analyzes as to how peoples' travel patterns pass through "polluted" places as objects of investigation during their life histories as the body ages. The generalised urban and regional model presented by Sir Alan Wilson (Wilson, 2007) is the next point of departure. We suggest that the issues of event (environmental stressor), time (from cradle to the grave), and place (locations, especially those with their own time-dependent variable of environmental stress) are the basis of a new type of epidemiological study.

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