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An Ambit-Based Activity Model for Evaluating Green House Gas Emission Reduction Policies

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An Ambit-Based Activity Model for Evaluating Green House Gas Emission Reduction Policies

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ABSTRACT

This study presents an Ambit-Based Activity Model (A-BAM) for evaluating Green House Gas (GHG) emission reduction policies that are being considered for implementation in transportation sector in the wake of more stringent emission reduction targets envisaged in a post-Kyoto international climate treaty. This study demonstrates how A-BAM can be used to estimate the *effectiveness* of reducing GHG emissions from multiple policy interventions from year to year in a given geographical area. The A-BAM model builds upon the fact that any change in the current state of transportation systems through policy interventions will inevitably cause a change in the transportation activities of agents. So, for quantifying GHG emission reduction policy effectiveness, A-BAM requires that the transportation activities of randomly sampled agents for the evaluation area be systematically tracked and analyzed.

At the core of the A-BAM is the concept of agents' ambit that represents movement through space around an agent's home place in all directions over a period of time. Analytical notions of trip-weighted and time-weighted centroids are formally derived to calculate the ambit of agents. Although GPS devices are empirically better to track agent's ambit, this study, due to cost limitations, uses memory-based, travel-diary kind of a survey instrument to operationalize the spatial parameters of A-BAM. Survey data from 74 volunteers in California is deployed to track their ambit and carbon footprints. It is found that trip-weighted centroids are generally smaller than time-weighted centroids; and as the magnitude of the trip- and time-weighted centroids increases, the carbon footprint grows non-linearly.

INTRODUCTION

Growing dependence on fossilized sources of energy, under business as usual scenarios, are very likely to cause adverse impacts on global environmental and climatic systems. Combustion of fossil fuels in transportation, residential, commercial and industrial applications releases Green House Gas (GHG) emissions that have the potential to cause global warming due to the green house effect in the earth's troposphere (1). Shifting temperature and precipitation patterns, sea level rise, extreme weather events (i.e. intense hurricanes, tornados, floods and droughts), and biodiversity loss are but few of the expected impacts of anthropogenic addiction to fossil fuels. Mitigation strategies are being designed and implemented in many countries of the world to decrease GHG emissions by reducing societal dependence on fossil sources of energy.

In the absence of action by the federal US government to mitigate climate change by reducing its GHG emissions, many state and local governments have begun taking mitigation actions on their own. About 28 States are setting targets for reducing their greenhouse gas emissions by developing statewide climate action plans in transportation, power generation, residential, commercial and industrial sectors. This study presents an Ambit-Based Activity Model (A-BAM) for evaluating GHG emission reduction policies that are being considered for implementation in transportation sector in the wake of more stringent emission reduction targets envisaged in a post-Kyoto international climate treaty. In particular, this study demonstrates how A-BAM can be used to estimate the *effectiveness* of reducing GHG emissions through various policy interventions from year to year in a given geographical area.

GHG EMISSION REDUCTION POLICY OPTIONS

At least, 44 policy options have been identified that can be implemented, independently or jointly, to reduce GHG emissions from surface transportation activities. More background information about these 44 policy options can be found in CCAP Transportation Emissions Guidebook (2) and ETAAC (3). For analytical convenience, in Figure 1, these 44 policy options are organized under two major categories: (a) Reducing CO_2 per Vehicle Mile Traveled (VMT), and (b) Reducing VMT/year.

Reducing CO_2 per VMT, in general, refers to the broad category of policy options that improve efficiency while reducing VMT/year refers to the set of policy options that improve energy conservation by providing viable alternatives to reduce VMT from gasoline driven vehicles. CO_2 per VMT reduction policy options are sub-categorized for passenger vehicles (14 options) and freight operations (7 options).

The policy option of low GHG tailpipe standards is contested by US Automakers, but if implemented, it will potentially result in more fuel efficient and lower GHG/mile fleet averages, which will change the system-wide GHG impact of transportation activities (4). Feebates will similarly incentivize consumers to buy more fuel efficient vehicles (5). Negative feebates against inefficient vehicles can also be instituted. Carbon tax will potentially also result in lower GHG/mile from transportation activities (6). Procurement of low/alternative fuel vehicles will reduce GHG/mile, as will biofuel standards (4). Vehicle scrappage can lead to cleaner and more fuel efficient vehicular fleets active on the roads. Driver training can improve their acceleration/deceleration practices and lead to lower GHG/mile. Laws against idling can reduce GHGs emitted for no obvious transportation activity. Introduction of speed reduction laws and ITS in all major and minor traffic arteries can reduce GHG/mile. Proper maintenance of vehicles, such as proper tire inflation, can also reduce GHG/mile (3). Introduction of more hybrid, electric, or fuel cell driven vehicles can also cause total life-cycle reductions in GHG/mile (3, 4). In a nutshell, all of the 14 policies listed under A11 in Figure 1 have the potential to lower GHG/mile for all passenger vehicle transportation activities. Freight options under A12 similarly apply to lower GHG/mile from freight-related transportation activities.

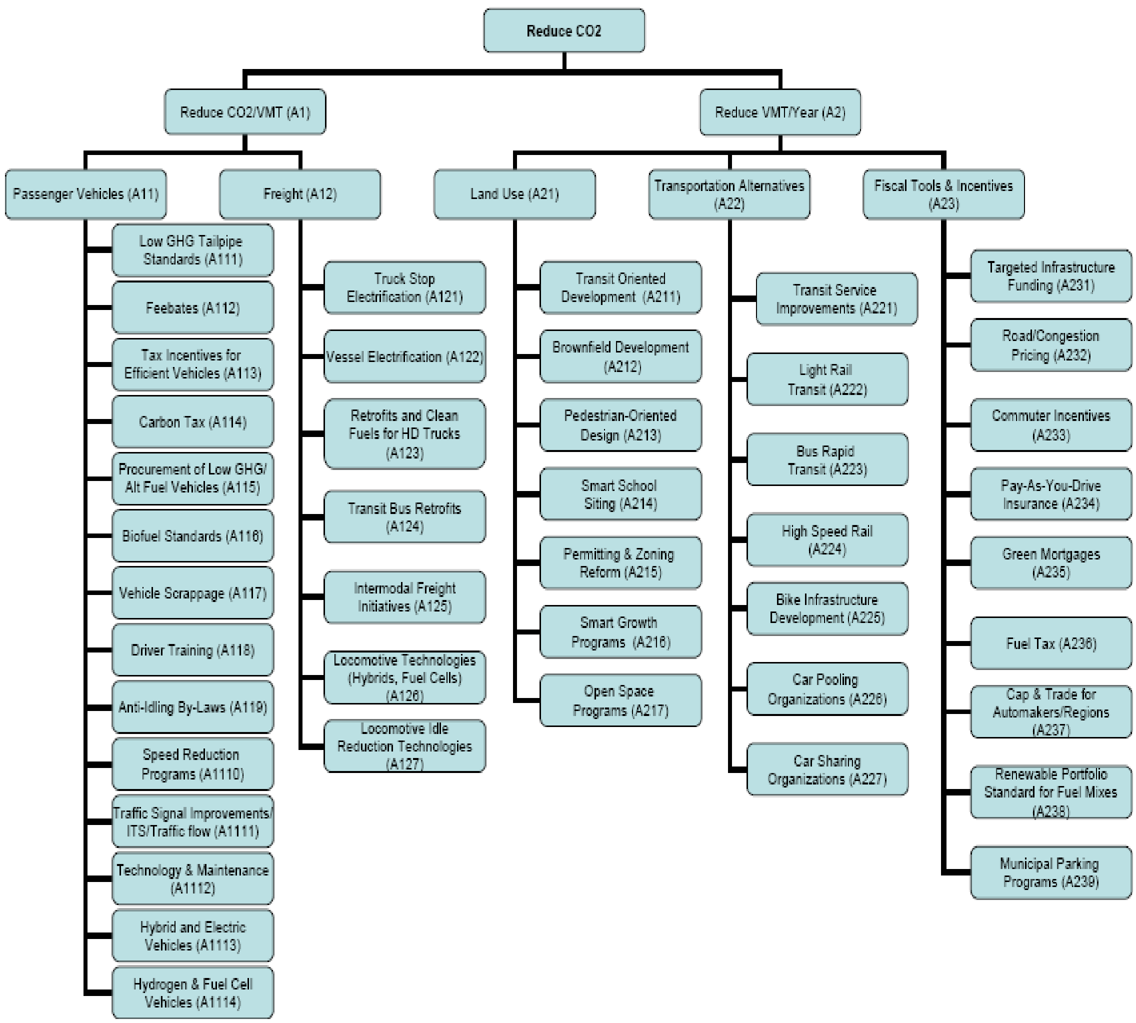


Figure 1 A Snapshot of 44 Policy Options to Reduce GHG Emissions from Transportation Sector.

Similarly, VMT per year reduction policies are sub-categorized as land use (7 options), transportation alternatives (7 options) and fiscal tools and incentives (9 options). Transit oriented developments can potentially shift more and more agents to take public transportation as their preferred modal choice, thus potentially reduce VMT per year (7). Brownfield development can reverse suburbanization trends and potentially lead to more urbanization and reduce transportation activity caused by suburban developments. Pedestrian oriented designs can be used to encourage walking as preferred transportation activity and, implicitly, to reduce VMT per year. Smart growth programs aim at minimizing the need for transportation activities and provide easier access to public transport systems, thus overall reducing VMT per year(4). In a nutshell, all the policy options listed under A2 can reduce VMT per year.

The ultimate goal of all the policy options shown in Figure 1 is to stimulate a change in the current state of transportation systems, either towards reducing GHG/VMT or VMT per year. Any change in the current state of transportation systems through policy interventions will inevitably cause a change in the transportation activities (for both VMT per year and GHG/VMT) of individuals, firms and other entities. ***A policy evaluation model thus must measure the changes in the real world transportation activities, i.e. both VMT per year and GHG/VMT before and after the implementation of GHG emission reduction policies.*** The A-BAM model presented below provides a quantifiable method to evaluate the GHG emission reduction policies on the criteria of "emission reduction effectiveness". The A-BAM model, in its current state, however, is limited in only enabling measurement of effectiveness for a "cumulative set" of policies in a given place for specific time periods. This model can however be extended in future to estimate the effectiveness of individual policy options.

"TOP-DOWN" AND "BOTTOM-UP" POLICY EVALUATION MODELS

While simulation models present interesting information about developing and designing policy options, the evaluation of implemented (and ignored) policy options requires real world analysis (8). In response to such policy evaluation research needs, a proto-typical ambit-based activity model (A-BAM) is developed and demonstrated to be empirically operational in this paper. The key objective of A-BAM is to measure the real world differences in the GHG emissions from transportation activities from year to year, given that any or a combination of the available 44 (or any additional) policy options are implemented in pursuance of mandated policy interventions, such as California's AB32. The aggregate, top-down model, such as used by CCAP Transportation Emissions Guidebook (2), can be used to assess GHG reductions. Typically, CCAP model evaluates the GHG emission reduction effectiveness of a policy intervention as shown in equation 1:

$$\text{Policy effectiveness (\%)} = 100^* (E_{baseline} - E_{policy})/ (E_{baseline}) \quad [1]$$

Where $E_{baseline}$ are GHG emissions prior to the policy intervention. So, for example, for measuring the GHG emission reduction effectiveness of policy alternative A_{111} (lower GHG emission reduction standards), CCAP proposes to measure $E_{baseline}$ as shown in equation 2

$$E_{baseline} = (V)_{baseline} \times (VMT/V)_{baseline} \times (\text{GHG emissions/mile})_{baseline} \quad [2]$$

Where $V_{baseline}$ represents the total number of vehicles; $(VMT/V)_{baseline}$ represents the Vehicle Miles Traveled per Vehicle and $(\text{GHG emissions/mile})_{baseline}$ shows the GHG emissions per mile in the area for a given year prior to policy intervention. Post policy intervention GHG emissions can be calculated by a similar equation 3

$$E_{policy} = (V)_{policy} \text{ x } (VMT/V)_{policy} \text{ x } (\text{GHG emissions/mile})_{policy} \quad [3]$$

While such aggregate top-down models provide a quick and synoptic methodology to estimate GHG emission reductions gained from pursuing policy interventions, bottom-up models such as A-BAM proposed in this paper provide an analytically tractable methodology to calculate GHG emission credits due to agent-based changes in transportation activities (e.g. increase in walking or biking) that may follow from the implementation of mandated policy options. A-BAM can also be used to quantify individual and community level GHG emission reduction credits that are expected to require documentation in a post-Kyoto (post 2012) global governance regime. Most importantly, A-BAM can be deployed to counter-verify the GHG estimates for baseline and alternate policy scenarios generated from conventional top-down models.

AMBIT-BASED ACTIVITY MODEL (A-BAM)

An ambit-based activity model tracks all the transportation activities of an agent (individual) in a landscape and the transportation modal choices made by the agents to pursue those activities. Ideally, ambit-based activity models could be measured by installing Global Positioning System (GPS) devices on sampled agents, with a follow-up travel diary type of surveys, assigning trip destination for each transportation activity undertaken by the agents. The collection of GPS-based data at a time scale of one year is very costly and has not been pursued for this project. However, significant efforts are being put in place to operationalize the proposed A-BAM model with GPS data. Instead, a second-best memory-based survey instrument has been developed to track the activities of sampled agents. The survey instrument is attached as appendix A in the associated MTI white paper. The memory-based survey instrument is second-best because human memory is imperfect. Time measurements are included in the survey protocol to analyze the completeness of reporting, but self-reporting (as opposed to GPS) introduces another set of biases.

Ambit and Centroids of Agent’s Space Time Activities

A simple way to represent movement through space around one's home place is to identify one’s ambit as the limits of movement from the home of the individual/organism/group outward in all directions over a period of time. Integrating across *longer durations* can provide a periphery outlining the "regular ambit" of the individual as it is expressed in trips to destinations in various directions. Differential choice of temporal scale (e.g. 1, 10, 25, 50 or 75 years) for aggregation across *longer durations* will result in different ambulatory patterns. Temporal choice will also affect how demographic mobility, arising from individual/household level choices, is understood at larger spatio-temporal scales. Technological changes that occur during the *longer durations* will further complicate the analysis

The ambit, for a given spatio-temporal scale, provides, a behavioral measure of the extent of movements which can be understood as a proxy variable for many individualized choices taken for many particular decisions of individuals as they move through the space around their home place. Figure 2, for example, shows different nodes of an ambit of a Californian survey respondent around her home place in 2007. The nodes of an ambit show agent’s trip destinations away from home: work, school, family, friends, shopping, recreation, entertainment, hospital and so forth.

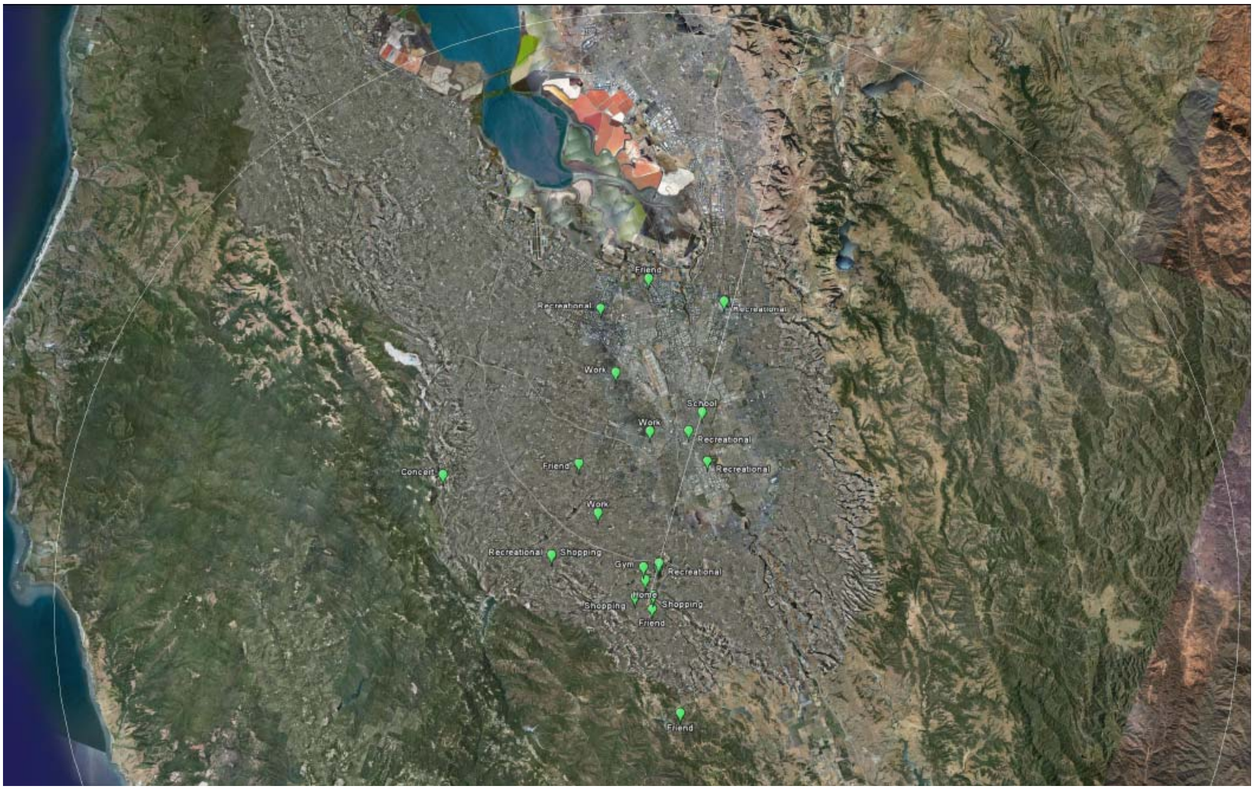


Figure 2 Ambit and Trip-Weighted Centroid of a Respondent in California.

Typically, GPS data driven maps present "data-glut" issues where it is an analytical challenge to ascertain meaningful information out of the individual's space-time activity network maps (9,10). For analytical tractability of such vast amounts of information, the A-BAM model uses a measurable variable called "centroid" of an individual. The circle in figure 2, for example, represents the centroid of our sampled Californian respondent.

Centroid

The centroid measure represents a great deal of detailed behavioral information about spatial movements—both with respect to the direction or the duration of trips away from home in very condensed form.

The centroid of activities could be derived from weighted time spent in different locations (centroid of duration), or from weighted number of trips taken to different locations (centroid of trips). The centroid may be formalized as follows:

Centroid of Duration

The centroid of an individual's movements through space represents the weighted average of the time spent in various locations over a period of time, with long durations in a place being represented in the placement of the centroid. Formally, if we attach time-spent proportional weights ($w_1, w_2, \ldots w_T$) to each location (P_k) of an agent's ambit for k locations (nodes), where the k^{th} location is agent A_i's home, then the Centroid (Ψ) in a two-dimensional space for a given time period T can be located at:

$$\Psi_{(x,y)} = w_t P_k + w_{t-1} P_{k-1} + , \ldots + w_1 P_1 \text{ ; for } \sum w_t = T \qquad \text{(Equation 4)}$$

Let us then consider X_i for the i^{th} agent as the Euclidean distance between agent A_i's home (P_k) and centroid location to be the **time-weighted centroid radius**:

$$X_i = | P_k - \Psi_{(x,y)} | \qquad \text{(Equation 5)}$$

Centroid of Trips

The centroid of an individual's movements through space can be represented as reflecting the spatial footprint of an individual, measured as the cumulative number of trips to that location. Formalism will remain the same as in equations 4 and 5, except that the weights in equation 4 will represent the distribution of trips τ, and not time spent, across all the locations P_k. So, $\sum w_t = \tau$.

Measurement of GHGs

While trip-weighted and time-weighted centroids provide ambit-based analytical measures to track the spatial footprint of agents' transportation activities, the carbon footprint of transportation activities can also be directly measured by spatially analyzing the distance for each transportation activity (including VMT per year as discussed in connection with evaluation of policy options listed under A1 in Figure 1), number of trips taken to that specific trip destination, transportation modal choice and the GHG (or CO2) emission factor (i.e. GHG/Mile, as discussed under policy options under A2 in Figure 1) for that particular modal choice, as shown in equation 6:

$$\text{E (CO2/year)} = \sum_{i=1}^{n} \sum_{j=1}^{m} S_i \text{ x } 2\tau_i \text{ x } M_{ij} \text{ x } EF_j \qquad \text{(Equation 6)}$$

Where S_i = Distance for Activity i (Miles), for i=[1,2,….n] activities. This variable includes VMT/year as well as additional non-vehicular distances traveled by the agent for any i^{th} activity.
τ_i = Number of trips per year for Activity i
M_{ij} = Transportation Mode j for Activity i, for j=[1,2,…m] transportation modes
EF_j = Emission Factor (in GHG/mile) for transportation mode j

The relationship between centroids and GHGs

Intuitively, the larger the spatial footprint of an agent's transportation activities, the bigger will be her/his carbon footprint, assuming energy inputs remain constant for vehicular based modal choices. The relationship between spatial footprint and carbon footprint of agent's transportation activities requires special analytical treatment in A-BAM for evaluating the changes in transportation activities due to the introduction of GHG emission reduction policies. More specifically, the null hypothesis can be stated as: there is no relationship between an agent's ambit (or trip-weighted or time-weighted centroid) and carbon footprint. The alternative hypothesis tested in this study states that: as the time-weighted or trip-weighted centroid of an agent (or a community) shrinks, their carbon footprint also reduces in size. Further, quantifying the precise relationship between trip- and time-weighted centroids of agents and their respective carbon footprints can provide a testable and empirically measurable methodology to track/predict the changes in the carbon footprints before and after the introduction of GHG emission reduction policies.

EMPIRICAL DATA

A pre-test sample of 74 volunteers in California has completed a travel-diary type of memory-based survey. The data from each survey protocol is coded in a spreadsheet software and then imported in spatial analysis software to calculate Euclidian and/or "Network" distances for annualized trips of an agent. Euclidean distances provide the minimum amount of carbon emitted by transportation activities. Network distances are typically higher than Euclidean distances for almost all transportation activities. Google Earth Pro, for example, is used to calculate the Euclidean distances from a respondent's home to all the trip destinations for the respondent shown in Figure 2. Figure 3 below shows the homes of almost all the 74 survey respondents, with blue dots showing respondents with annual carbon footprint from transportation activities of 5 tons or less and red dots show respondents with annual carbon footprints from transportation activities of more than 5 tons. The numbers besides the red or blue dots in Figure 3 show the trip-weighted centroid radii for each survey respondent.

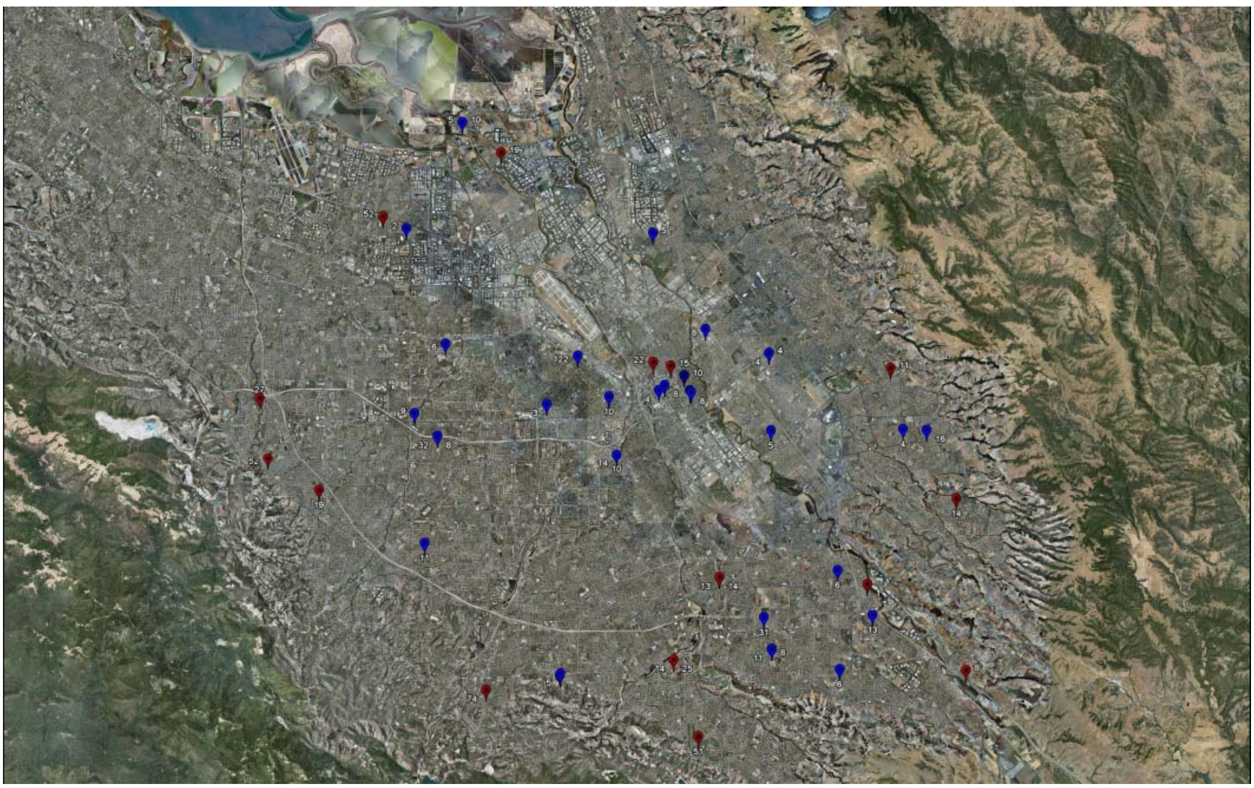


Figure 3 Carbon Footprints and Trip-Weighted Centroids of the Survey Sample.

The carbon footprint for different trip purposes (i.e. commute to work, school, recreation, shopping, family, friends, etc.) can be generated by A-BAM. Figure 4, for example, shows carbon footprint by activity type for the same respondent whose ambit is shown in Figure 2. This particular respondent has accumulated the largest carbon footprint from recreational type of transportation activities, followed by trips to visit friends, work, gym, school and so forth.

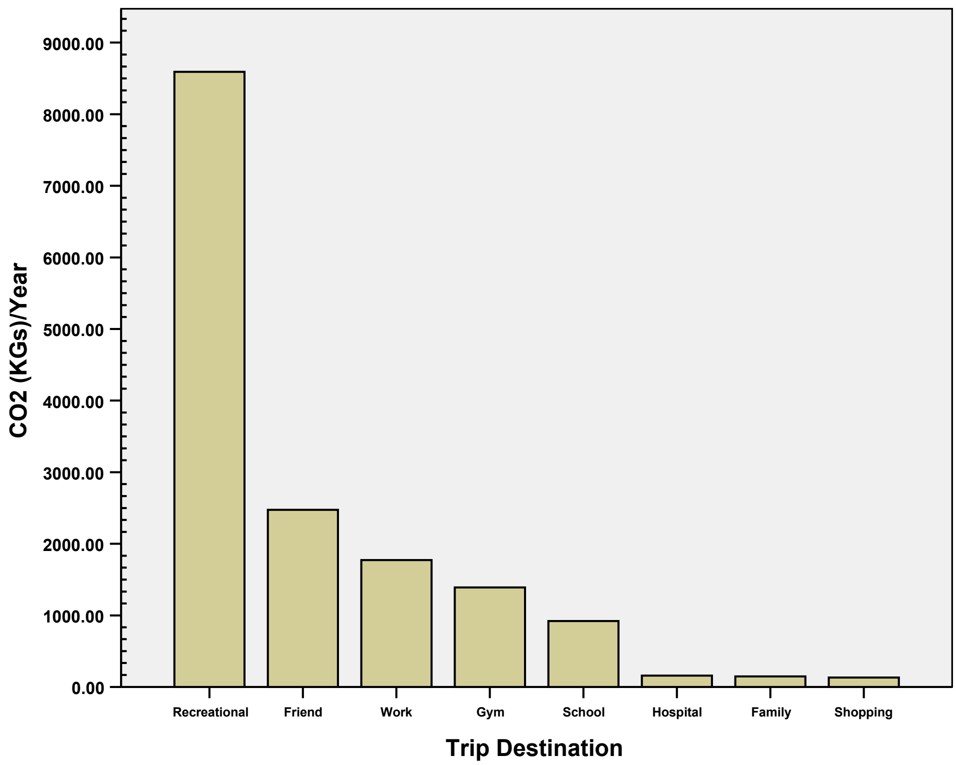


Figure 4 Distribution of Carbon Footprint by Transportation Activity Types for a Respondent.

RESULTS

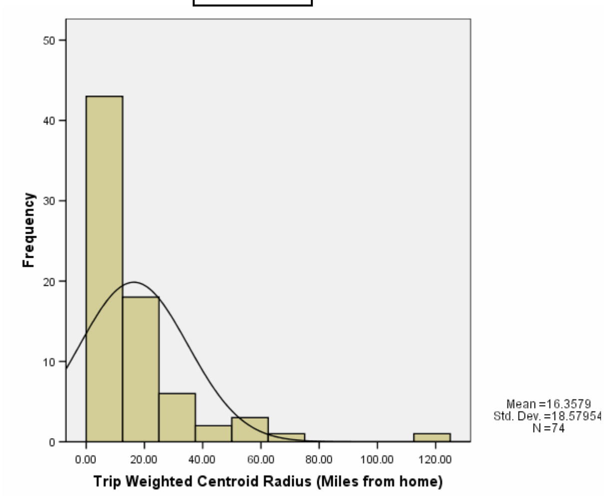
Table 1 presents descriptive statistics for the three key variables that are at the core of A-BAM policy evaluation model: Time-Weighted Centroid of 74 respondents averages around 96 miles with a standard deviation of about 244 miles, which is relatively much larger in magnitude than the Trip-Weighted Centroid, averaging at only 16 miles around the respondent homes with a standard deviation of 18.5 miles. The average carbon footprint from transportation activity for the 74 respondents stands at 5.78 tons of CO_2/Year with a standard deviation of 5.74 tons of

CO2/Year. Statistical distributions for all the three variables are skewed towards right, as shown in Figure 5, panels a, b and c, which has repercussions on the results from the regression analysis.

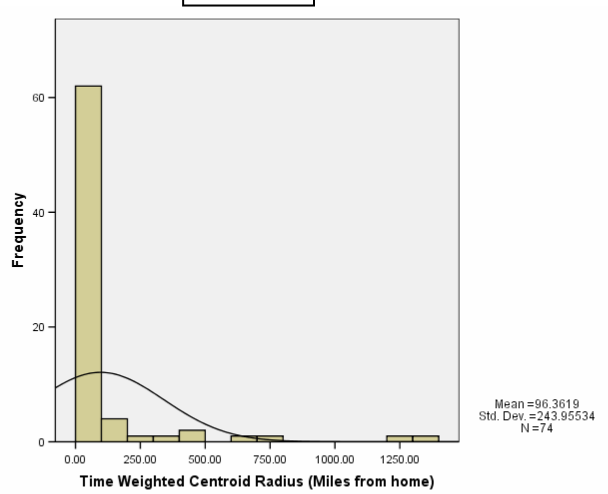
Table 1 Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation	Skewness	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error
Time Weighted Centroid Radius (Miles from home)	74	.36	1330.88	96.3619	243.95534	3.848	.279
Trip Weighted Centroid Radius (Miles from home)	74	1.60	122.68	16.3579	18.57954	3.390	.279
Carbon Footprint from Transportation Activity (Tons of CO2/year)	74	.11	29.78	5.7884	5.74643	2.082	.279

Panel a



Panel b



Panel c

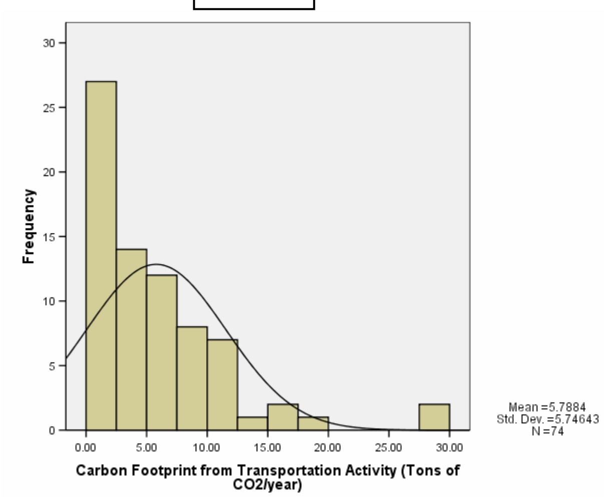


Figure 5 Skewed Distribution Curves for Trip-Weighted (panel A), Time-Weighted (panel B) and Carbon Footprints (panel C) of the Survey Respondents.

Table 2 presents model 1 results that tests the null hypothesis about the relationship between trip-weighted centroids and carbon footprints. Figure 6 shows the relationship between the two variables under linear, lograthmic, quadratic and cubic underlying functional assumptions. The R^2 is the highest for the cubic function in table 2 at 44.2%, which suggests that there is a slight initial decrease in the carbon footprint from transportation activities as the trip weighted centroid increases, but it increases very significantly for the middle range centroids and then decreases for much larger centroids, greater than 80 miles from their homes.

Table 2 Model 1 Summary and Parameter Estimates

Dependent Variable: Carbon Footprint from Transportation Activity (Tons of CO2/year)

Equation	Model Summary					Parameter Estimates			
	R^2	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.219	20.147	1	72	.000	3.423	.145		
Logarithmic	.195	17.401	1	72	.000	-1.606	3.062		
Quadratic	.345	18.660	2	71	.000	.948	.395	-.003	
Cubic	.442	18.456	3	70	.000	4.357	-.129	.012	-8.76E-005

The independent variable is Trip Weighted Centroid Radius (Miles from home).

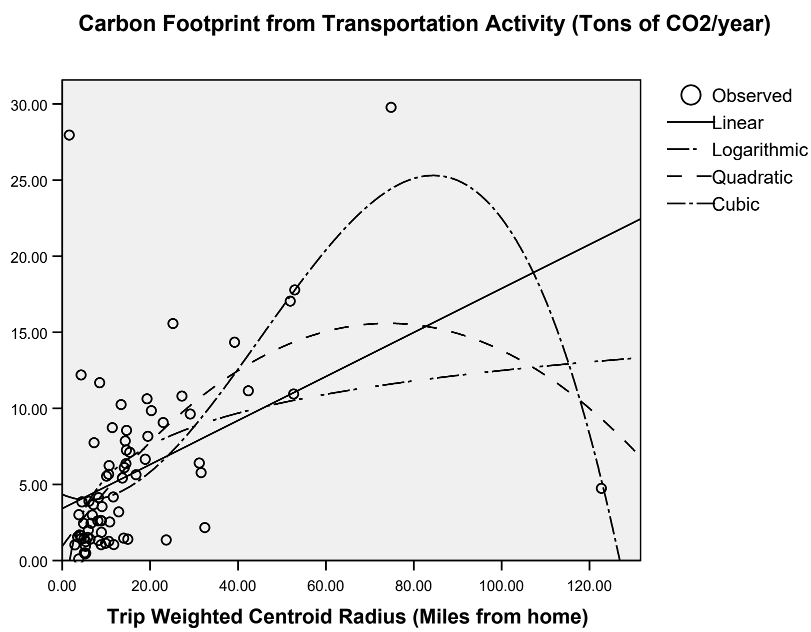


Figure 6 The Relationship Between Trip-Weighted Centroids and Carbon Footprints.

Similarly, Table 3 presents model 2 results that test the null hypothesis about the relationship between time-weighted centroids and carbon footprints. Figure 7 shows the relationship between the two variables under linear, lograthmic, quadratic and cubic underlying functional assumptions. The R^2 is again the highest for the cubic function in table 3 at 29.1%, which suggests that the carbon footprint from transportation activities increases as the time weighted centroid increases, and it increases very significantly for the middle range centroids and then decreases for much larger centroids, greater than 750 miles from their homes.

Table 3 Model 2 Summary and Parameter Estimates
Dependent Variable: Carbon Footprint from Transportation Activity (Tons of CO2/year)

Equation	Model Summary					Parameter Estimates			
	R^2	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.119	9.706	1	72	.003	5.006	.008		
Logarithmic	.255	24.707	1	72	.000	1.495	1.558		
Quadratic	.287	14.291	2	71	.000	3.999	.037	-2.61E-005	
Cubic	.291	9.558	3	70	.000	4.165	.028	-1.33E-006	-1.41E-008

The independent variable is Time Weighted Centroid Radius (Miles from home).

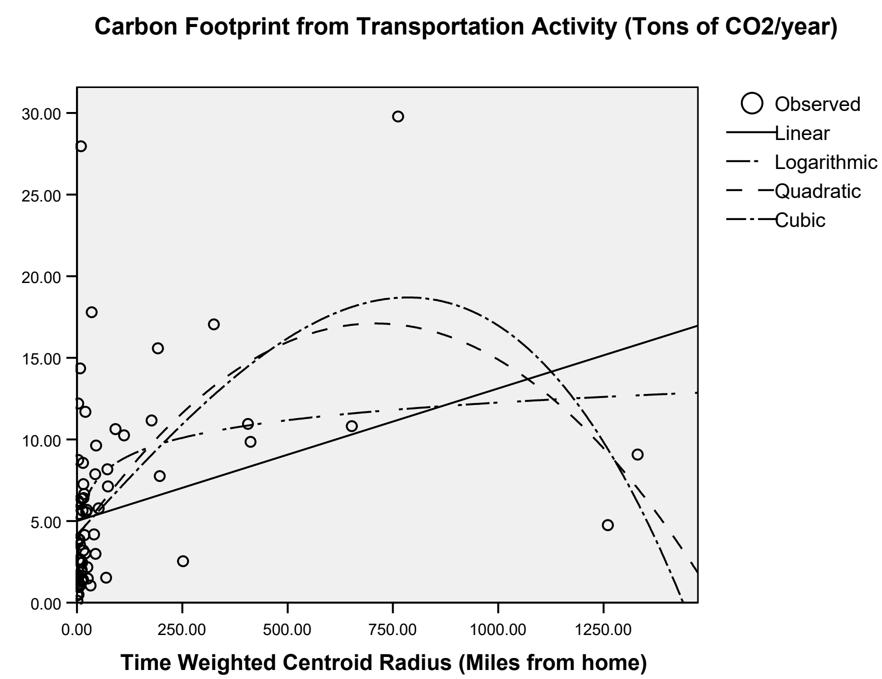


Figure 7 The Relationship Between Time-Weighted Centroids and Carbon Footprints.

LIMITATIONS, IMPLICATIONS OF THE RESULTS AND FUTURE RESEARCH

The results of the empirical sample has demonstrated that A-BAM can be made operational with travel diary type of survey instruments to measure the carbon (GHG) footprint of agents in a given policy context. Spatial analytical variables, such as trip- and time-weighted centroids have been shown to significantly affect the carbon footprint.

The empirical methodology deployed in this study has four major limitations: (1) Survey methodology is imperfect as respondents do not remember all of their trips undertaken in the last one year, which typically results in the underestimation of their carbon footprints. GPS method, coupled with surveys, is expected to be better in future studies. (2) Euclidean distances were measured to estimate carbon footprints, and trip- and time-weighted centroids, which provide a minimum threshold of transportation activities, but typically underestimate all three variables as compared to network distances. Future studies must compare both Euclidean and Network distances. (3) Geocoding of various trip destination addresses is not perfect at 85% successful geocoding rate for the study, as some respondents either provided incomplete addresses or wrong addresses that were not matched by Google Earth Pro. GPS based studies will not have geocoding address matching issues. Finally (4) the sample of this study is based on eliciting responses from 74 volunteers for minimizing the cost of survey collection and demonstrating a prototypical application of A-BAM. Future studies will need to be designed to elicit appropriately chosen random sample for the study area.

For a study evaluating U.S. GHG emission reduction policies that are expected to be implemented in 2012 in pursuance of post-Kyoto international treaty, approximately 2500 randomly-selected individuals will required to be contacted to complete the memory-based survey, assuming 95% margin of error and 40% response rate. At least, one thousand individuals who are expected to fill the survey will need to be provided with GPS devices for one or more years duration to track the changes in their traval activities and estimate their carbon and spatial footprints.

The analysis of nation-wide sampled survey/GPS data will provide a baseline estimate of average carbon footprints generated by the transportation activities of agents residing in the US. The survey/GPS can be replicated from year to year to track the changes in the transportation activities and their associated carbon footprints at any geographical scale of interest (city, state, nation or international).

The proposed A-BAM can provide independent means to test the changes in the GHG emissions from transportation activities. In follow-up research, the extensions of the A-BAM can be developed to provide an independently collected, data-driven methodology to test for systematic variations in travel cost ($/mile) and emission reduction cost ($/ton of CO_2) across a wide spectrum of socio-demographic and economic profiles of agents for a given geographical scope. Social equity impacts can also be derived from analyzing the variations in the redistribution of travel costs ($/mile) and emission reduction costs ($/ton of CO_2) across various sub-populations. Changes in CO_2 emissions for various trip purposes can also be tracked. The A-BAM methodology proposed in this study thus has the potential to provide systematic and process-based means to explore the inter-relationships among transportation, land use, the environment and the economy with particular focus on evaluating the GHG emission reduction effectiveness of climate change mitigation policies in the transportation sector.

CONCLUSIONS

GHG emission reduction effectiveness of climate change mitigation policies can be measured through an Ambit-Based Activity Model (A-BAM) by tracking the ambits of agents/citizens in a given geographical area on a periodical basis. Spatial analysis measures such as trip-weighted and time-weighted centroids can be used to predict the cumulative patterns of GHG emissions. The regression models can be extended in the future studies to control for the effects of socio-demographic and economic variables in evaluating the relationships between ambits of agents and their carbon footprints. GPS, coupled with travel-diary survey methods, can provide a more accurate and precise estimate about the transportation activities and their concomitant effects on GHGs from transportation sources. Memory-based survey methods have some biases that typically result in under-estimation of GHGs, so survey methods can, at best, be used to estimate the lower threshold of GHGs/Year for a given policy evaluation area.

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