

A CARBON IMPACT SIMULATION-BASED FRAMEWORK FOR LAND USE PLANNING AND NON-MOTORIZED TRAVEL BEHAVIOUR INTERACTIONS

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ABSTRACT

This paper presents a sustainable mobility module for a new urban design simulation tool called umi. The module estimates transportation related carbon emissions for urban dwellers according to the proximity of their home to amenities such as schools, grocery stores, restaurants and the like. The traditional 4-step transportation model of trip estimations is utilized, but the underlying model assumes that residents of more walkable neighbourhoods will choose walking over driving if destination points are within walking range and outdoor environmental conditions are acceptable at the time of the trip. Transportation mode choices for each trip are determined based on a two-step stochastic process: Shortest distance paths are used to evaluate how 'walkable' the trip is. Ambient temperature and rainfall are then used as placeholders for outdoor comfort conditions to determine the likelihood that a resident will walk at a particular time. Carbon emissions are associated to each trip based on the trip's mode choice. Overall neighbourhood evaluations are conducted by summing up all trip-related carbon emissions throughout a year. A case study of a fictional mixed-use neighbourhood in Boston, built according to Passivhaus standard, is simulated in Energy Plus to compare the carbon impact of operational energy use versus transportation.

INTRODUCTION

Continuous urban growth, manifested through the development of new cities and neighbourhoods, is constantly changing urban landscapes in many parts of the world. Rapid global population increase in tandem with migration to cities and has amplified urbanization over time; the world's urban population is expected to reach 4 billion between 2015 and 2020 (BBC 2006). To accommodate this growth, numerous urban development projects happen *ad hoc* which contributes to carbon emissions due to the resulting uncoordinated concentration of people, vehicles and industrial activities (Svirejeva-Hopkins, Schellnhuber and Pomaz 2004). Emissions increase due to the limited input these projects have on what the environmental consequences of street grid layouts and land use planning decisions are. The frequent

absence of a larger planning framework is partly due to the absence of suitable simulation tools for urban designers and city planners. Efforts are now being made to develop environmental performance simulation software for the design of cities and neighbourhoods. The intention is to evaluate and analyse urban design principles and assumptions, and to bring reliable, accurate and rigorous tools to the practice of urban design and planning (Besserud and Hussey 2011). The authors are working on an overall urban modelling platform called umi to enable urban planners and architects to examine multiple performance aspects of their urban proposals including operational energy use, outdoor comfort and neighbourhood walkability (Reinhart, et al. 2013). This paper specifically focusses on the umi-mobility module, which concentrates on sustainable urban transport choices.

Transportation energy currently represents 25% of the world's carbon emissions and it is growing rapidly. In the developing world, two-thirds of such energy demands are directed towards personal mobility, and are expected to remain the same for the next 50 years (Zegras, Chen and Grutter 2009). These estimations along with accompanying health problems resulting from poor air quality (Wassener 2012) pertain to why numerous cities around the world have realized the consequences of accommodating driving at the expense of walking, biking and efficient utilization of public transit. Through the promotion of physical activity, sustainable planning of the built environment influences health, reduction of pollution, fuel savings and decrease of carbon emissions. Today, such urban environments promote active physical transportation through the manifestation of policy instruments and land use planning tactics. While these strategies have been discussed and implemented in many cities (MacNeil 2012), the sources of their positive influence on travel behaviour, demonstrated by savings in vehicle miles travelled (VMT), has been given minimal attention in the literature.

In theory, the utilization of high density and diversity in land-use is an effective strategy that decreases VMT and contributes to more sustainable modes of transportation (namely walking and biking), as a short proximity between amenities encourages non-motorized travel (NMT). There are formal

approaches to applying such a strategy through well-known schools of thought in urban planning practice. An example school of thought is New Urbanism, which is an urban design movement that encourages walkability through density (Rodriguez, Khattak and Evenson 2007). Another urban archetype is Smart Growth, which advocates compact, transit-oriented developments (Handy 2005). New Urbanism and Smart Growth share the goal of having more walkable/bikeable and healthier communities. The general hypothesis of these design movements is that – if given the choice and external weather condition allow for it – the majority of people choose walking over alternative modes of transportation. This means that the creation of many walkable destinations within a neighbourhood internalizes trips within the neighbourhood and thus reduces reliance on driving and reduces related carbon emissions and pollution.

To quantify the impact of applying such principles, the integration of simulation tools that evaluate cities' "walking friendless" in the design process is becoming significant. Previous relevant research presented a method which utilized hierarchical models that were validated against in-field traffic counts. The study first showed the impact of mixed-use developments in internalizing walking and transit mode share percentages in cities as high as Seattle (18.0%) and as low as Portland (15.9%). The model then varies "D" variables (density, diversity, design, destination accessibility, distance to transit and development scale) to predict trips generated (Ewing, et al. 2011). Another recent investigation demonstrated a model that uses annual non-motorized count data to estimate mode share changes and avoided VMT (Rasmussen, Rousseau and Lyons 2013). However, both models approach the research question on a macro scale and pay minimum attention to micro interactions between individual buildings and surrounding amenities. This paper is concerned with the study of walkability among groups of buildings based on situations and opportunities at the individual building and city scale that can be accumulated to the complete city.

Assessment of neighbourhood walkability has long been considered a function of quarter mile to one and a half mile walking distances from housing units to vital amenities. This idea has been adapted by many walkability evaluation schemes in different forms, and has been proven to be a good indicator of "walking environments." Popular indices such as the "Walkscore" (Walkscore 2010) have been validated in terms of estimating neighbourhood walkability and health (Duncan, et al. 2011) as well as real estate

prices (Stephanie , Thrall and Hangen 2010). However, to date it has not been demonstrated that walkscore type evaluations are capable of predicting the probability that a population of a certain urban area are more likely to walk than a comparable neighbourhood with a lower mean Walkscore rating. The reason for this may be that the evaluation of walkability is subjective and depends on many interfacing parameters that are currently not included in these models. Other factors include pedestrian thermal comfort, climatic conditions and pleasantness of routes, to name a few. In order to be able to predict if future urban developments are going to be friendly to active modes of transportation, and if occupants will actually walk, modelling the aforementioned factors is key for a predictive urban modelling tool. Another potential difficulty for an urban designer is that even if the walkability of a given neighbourhood design can be realised, how can such an evaluation be put in context with other environmental performance measures such as building's access to daylight and solar gains to optimize operational energy use?

In this paper we are describing a simulation module to model and examine the performance of NMT behaviour and land-use planning interventions on a microscopic scale. This is to assess urban form parameters for "walkability." The tool aims to help answer questions such as: How likely is it that people will walk or bike in different neighbourhoods? What urban design parameters contribute to more walkable/bikeable cities? The tool forms part of a new urban modelling platform called umi that also simulates operational energy use in buildings and daylighting potential. The tool specifically investigates choices regarding the mode of transportation chosen by residents over the course of the year. The underlying model combines trip choices to multiple destinations (such as grocery, shopping, entertainment, etc.) based on Walkscore calculations. The choice to walk, bike, take public transport or drive is then simulated based on distances to destinations and climatic conditions. Next, it is tabulated and converted into a carbon emissions balance. As a proof of concept for this simulation workflow, the paper focuses on VMT averted as a result of occupants walking to destinations in various simulated weather conditions. This is illustrated through a comparison of carbon emissions due to operational energy use and transportation energy in a fictional mixed use neighbourhood in Boston, MA, USA. The simulation framework is described in detail next.

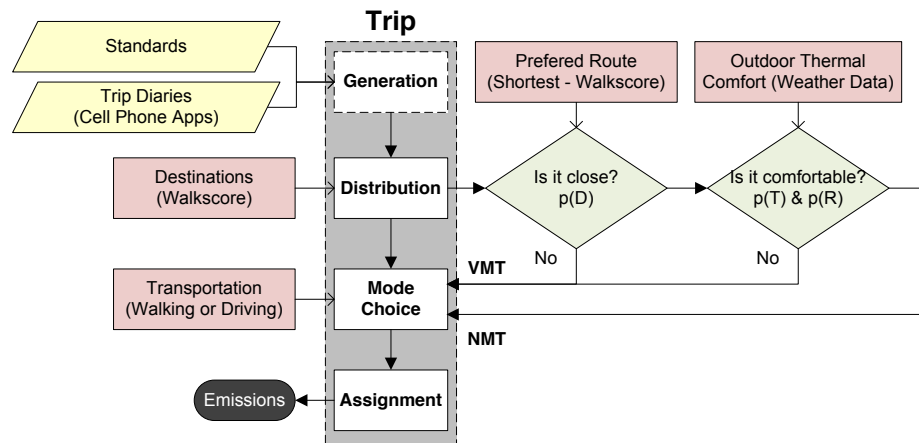


Figure 1: Simulation-based Framework to estimate annual trips for individual households

SIMULATION METHOD

The presented simulation framework (Figure 1) is conceived in the three dimensional modelling environment Rhino3D as a walkability assessment tool. It is scripted in the Grasshopper plug-in as a parametric custom definition coded in the C# programming language. The following section presents how the utilized “Street Smart Walkscore” algorithm works, and how it was altered and combined with the traditional 4-step model of transportation engineering (Singleton and Clifton 2013) to quantify the carbon impact of NMT.

Street Smart Walkscore

Walkscore measures the ease of residing in a certain area without depending on your car. We adapted this web-based tool to be used within the design environment of Rhino as a comprehensive modelling approach. The algorithm tests points of interest for proximity to nine North-American oriented amenities (Schools, Restaurants, Coffee, Shopping, Entertainment, Parks, Banks, Grocery and Books).

Each amenity receives a different weight based on importance. Egress points for addresses are then rewarded based on distances to amenities, and a polynomial distance decay function is used to calculate scores. Within a distance of quarter mile, a full score is received, and at one mile, amenities receive about 12% of the score as a penalty. After one mile, scores slowly decrease with greater distance, until it reaches zero at 1.5 miles. There are other reward scores received by examined points based on street intersection densities and average block length. Walkscores are ranked between 0 and 100, and the detailed methodology is publicly available (Walkscore, Walk Score Methodology 2010). This method was coded in as a custom C# component in Grasshopper and a command in Rhino. To measure proximity of egress points to amenities, the Shortest Walk add-on was implemented within the code. It calculates the shortest route from a start

point to an end point in a given network of curves (streets and walk pathways) based on a topology calculator and the A* search algorithm (Figure 2). The source code for Shortest Walk is also available publicly (McNeelEurope 2011)

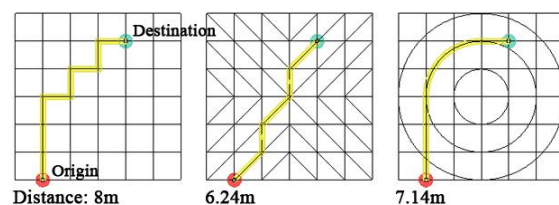


Figure 2 Illustration of Shortest Walk algorithm in different street grids

Proposed Framework

The scale of the studied area is left to the modeller, and it can go from the design of a few blocks within a neighbourhood to a complete city. The model is created in Rhino as building masses with housing egress points, amenity locations as points that have to be placed even if not in an immediate proximity to the studied area, and streets and walk pathways network. The buildings can be further explored for operational energy use and daylighting potential within umi, but it is out of scope for this paper.

Traditionally, the four step method of transportation engineering to estimate the number of trips within an urban area of a certain scale involved trip generation, distribution, mode choice and finally assignment of trips. We propose modifications to this workflow that are adapted to what would be of interest to urban designers and planners.

- Trip Generation

In order to accurately estimate travel trips within a certain urban area, travel surveys or comprehensive trip diaries of residents within proximity should be utilized. The use of smart-phones is ubiquitous around the world and is utilized for a variety of activities. Consequently, the employment of mobile

phone apps that track travel behaviour using built-in GPS devices has recently become popular for research concerned with different areas within disciplines of transportation (Calabrese, et al. 2013). These trips could be synthesized to estimate what are the time ranges when certain trips occur, and what is the probability of such trips to occur within the city. At the time of this research, we are using approximations for trip probabilities. For 8760 hours of the year, each hour a trip probability is given for amenities considered by the Walkscore algorithm.

- Trip Distribution

After all trips have been generated, they are distributed to destinations within the modelled urban area. From each identified housing egress point, the Walkscore algorithm is used to identify where the closest amenity is. From this distribution origins and destinations are identified with the streets network, and it then becomes a question what mode of transportation residents will choose (assuming that they have access to a car).

- Mode Choice

The first aspect examined in order to determine mode-choice is distance. If the amenity tested is within walking distance from the household (< 0.25 miles) all trips are considered walkable and no VMT values are computed. However, if the amenity is not within a walkable distance (> 1.5 miles), all trips to that destination are considered to be done using a personal motor vehicle and VMT is added as a trip to and from this amenity. For different cases these distances are modifiable according to what occupants would consider “walkable.” At this point climate is disregarded, and is only considered when the distance of interest is between these two values. If the destination is anywhere between 0.25 and 1.5 miles, a probability function P is used:

$$P = p(D) * p(T) * p(R) \quad (1)$$

Where $p(D)$ is the distance decay function used to predict the probability of occurrence of a given trip. $p(T)$ is a probability function used for dry bulb temperature (dbt), and $P(R)$ is used for rainfall. Weather becomes a factor to be considered. As a proxy for outdoor thermal comfort TMY3 weather data is used to extract dbt and rainfall values at the hour in which the trip is going to occur. Therefore, how outdoor temperature and rainfall affects travel behaviour are required input, and have to be estimated, within reason, by the simulator. The case study presented later gives an example of how to approach this.

After P is calculated, a random number is generated between 0 and 1, and if it falls within the probability P then the trip will be considered as non-motorized. If it does not, the trip is added as VMT.

- Trip Assignment

Now that the trips have been generated and distributed to amenity points within proximity and the mode choice logic is applied, trips are assigned and VMT is computed for each housing unit. Cumulative VMT is calculated for each point and is tabulated for the whole development under assessment. This allows the prediction of how many driving trips are estimated to occur, and how that totals in terms of carbon emissions. A case study is presented next to demonstrate how this workflow is utilized.

CASE STUDY SIMULATION RESULTS

An example neighbourhood was modelled in Rhino to represent a dense urban area of 1200 dwellings (Figure 3). The housing units varied in size between single-family houses, multi family structures and residential blocks and towers in a relatively small

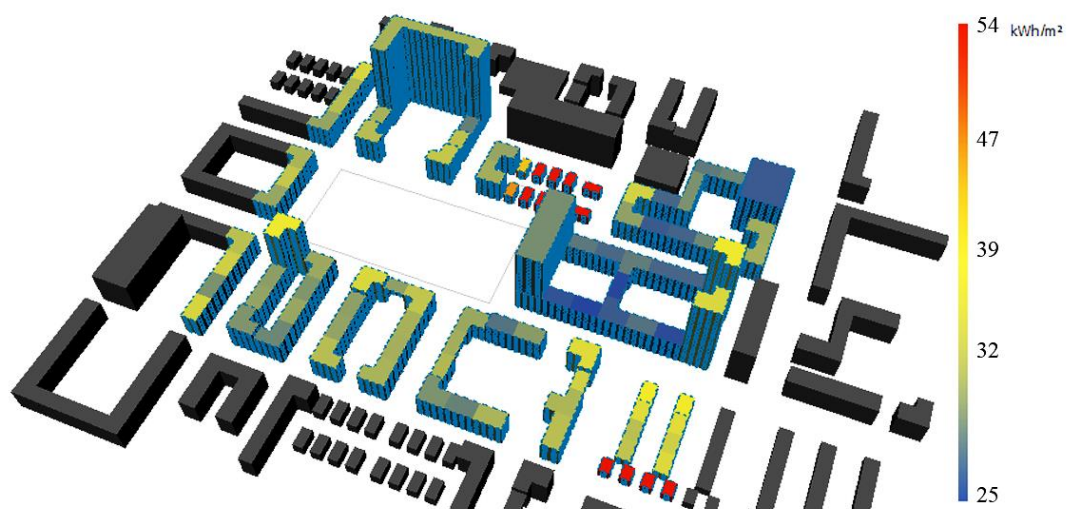


Figure 3: Example urban development modelled in Rhino. Annual energy consumption was simulated in Energy Plus using umi. The PassiveHaus construction standard was used for all buildings, and they are false colored to illustrate operational energy use.

area (70,000 m²). All buildings had a 35% Window to Wall Ratio (WWR) and overhangs on South facing windows of 0.5m depth. The model was simulated in umi through both the Energy and the Mobility components.

Operational Energy Use

The model was simulated in the umi-energy module for operational energy use using Energy Plus, as shown in Figure 3, and the location chosen was Boston, MA. umi generates EnergyPlus files and runs annual simulations individually. Multi-zone Energy Plus models are generated through the modelled building massing. It is then broken into different levels, where core and envelope zones are generated automatically. In this case, all zones are assigned the construction types, schedules and infiltration rates specified in the PassivHaus standard. The aim was to represent an energy efficient neighbourhood in terms of operational energy, and simulate the impact of land-use decisions on travel behaviour and consequent transportation energy use. Energy Use Intensity (EUI) varied between different buildings due to the influence of urban form. Smaller, single-family units that were more exposed had an EUI of 52 kWh/m² due to cooling loads, while bigger structures that shared different systems had EUIs of 25 kWh/m². To compute carbon equivalents we used ASHRAE standard 189.1 section 7.5.3 for 2010 for fuel factors (0.232 kg/kWh for gas and 0.758 kg/kWh for electricity). This results in 2265 metric Tons of Carbon annually.

VMT and Carbon Emissions

The mobility module in umi was used to generate both walkscores and estimations of VMT and resulting carbon emissions. Each housing structure had an egress point for analysis, and table 1 shows assumptions for the trip generation portion of the simulation workflow. As a proof of concept, they act as placeholders for times when typical non-work trips in a North American context take place.

Table 1
Assumption for daily household travel behaviour probabilities to modelled amenities

	Time Period (Time)	Probability (Percentage)
Schools	7:00 – 9:00	95%
Restaurants	12:00 – 13:00 &	30%
	20:00 – 22:00	10%
Coffee	8:00 – 10:00 &	50%
	17:00 – 18:00	50%
Shopping	16:00 – 18:00	5%
Entertainment	22:00 – 24:00	5%
Parks	10:00 – 11:00	30%
Banks	11:00 – 12:00	10%
Grocery	18:00 – 20:00	5%
Book	14:00-15:00	5%

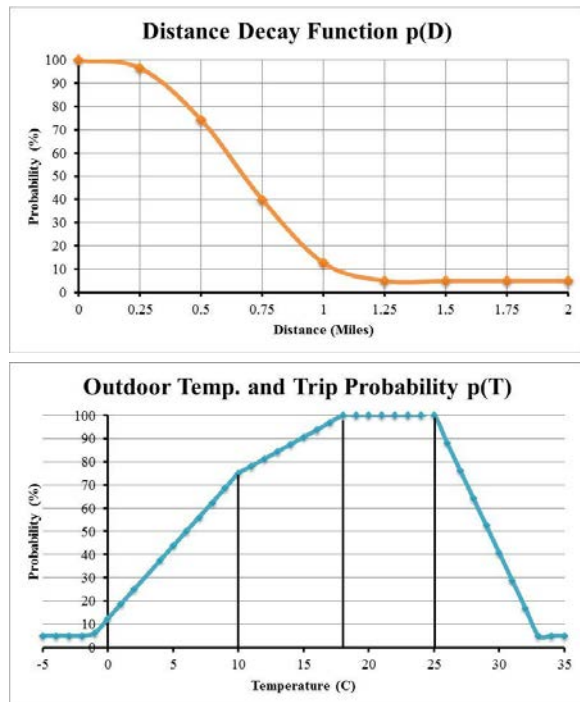


Figure 4 Probability functions used in the annual simulation for distance decay and dbt respectively

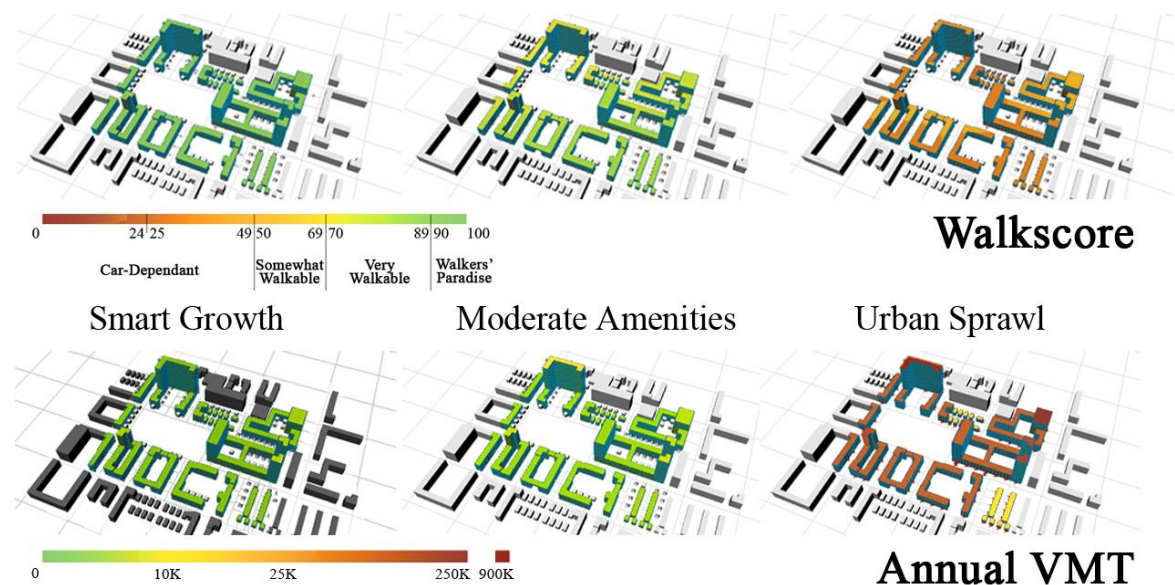


Figure 5 Simulation results for the example neighbourhood in umi-mobility with three variations.

An annual simulation ran for three variations of the model, where the massing and housing egress remained the same but amenity points are varied. One adopted the Smart-growth approach of creating dense and mixed land-use, the second assumed amenities are placed in a near-by neighbourhood at approximately 0.3 miles from its North end. The third had amenities placed at a 3 mile distance away from the development to represent urban sprawl in a motor-vehicle dependant development. To estimate the probability of trip occurrence for various outdoor dbt, a function designed to estimate how residents of the Boston area would react to weather, and it is shown in figure 4. Rainfall was excluded from simulations due to the unavailability of the required data in the Boston TMY3 weather file. Therefore, trips were only estimated using $p(D)$ and $p(T)$.

Figure 5 shows simulations results for both Walkscore and annual VMT. The trends were similar, but the interpretation of the outcomes is significantly different. The Walkscore rating “Walker’s Paradise” translates to almost zero VMT, which is expected. However, when Walkscores deteriorate as the distances to amenities increase, VMT increase dramatically. Walkscore ratings of “Somewhat Walkable” translate to 6000 VMT in single-family houses, and 40,000 VMT for multifamily structures. This means that on an annual basis VMT increases exponentially as amenities move away from households and becomes in a non-walkable distance. This could be attributed in part to the variations in probabilities due to uncomfortable weather conditions, as well as difficulty to reach destinations due to proximity. Additionally, multi-family buildings that housed a considerable number of residential units are the most affected by the unavailability of amenities, as shown in table 2 which presents a breakdown of the simulation outcomes.

Table 2
Breakdown of simulation result

	Walkscore			VMT		
	Hi	Lo	Av	Hi	Lo	Av
Smart-growth	90	89	89	3612	0	67
Moderate	85	64	76	102240	348	6259
Sprawl	34	27	31	912320	5608	66437

In order to estimate aggregate carbon emissions from personal transportation for each household we used US EPA’s emissions factors, where VMT is divided by average gas mileage to determine gallons of gasoline consumed per vehicle per year (21.6 miles per gallon). Gallons of gasoline consumed are then multiplied by carbon dioxide per gallon of gasoline to determine carbon dioxide emitted per vehicle per year (8.92×10^{-3} metric tons CO₂/gallon gasoline). Carbon dioxide emissions are then divided by the ratio of carbon dioxide emissions to total vehicle

greenhouse gas emissions to account for vehicle methane and nitrous oxide emissions (1 CO₂, CH₄, and N₂O/0.985 CO₂). Carbon emissions from the three simulations are presented in figure 6. It becomes obvious that even the most energy efficient of neighbourhoods in terms of construction standards is estimated to consume as much as (if not more than) its annual operational energy use in personal transportation trips if it is not planned correctly.

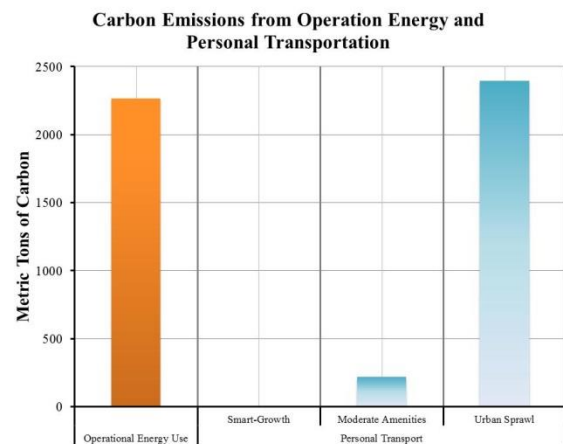


Figure 6 Carbon equivalents for simulated operational energy use and transportation in the three variants of land-use

DISCUSSION

The presented workflow, as demonstrated by the case study, explores a new field in building performance simulation (BPS). This area is positioned between energy modelling for buildings and transportation. This research effort takes the typical approach of transportation modelling to a micro scale, where the effect of land use allocation is represented as energy use in terms of VMT and associated carbon emissions. Although the aim is for designers to have the ability to simulate the consequences of their design decisions and interventions, the outcomes go beyond that. The awareness of what the tool does and how it works should shift the focus of designers. Simulation outcomes show what it means to have no destinations suitable for walking and what impact that has on energy and walkability of neighbourhoods. Since the designer is conscious of that, the mobility module in umi becomes a powerful tool for advocates of mixed land-use developments, liveable communities and designers interested in sustainable urban planning.

Residents’ travel behaviour in the case study was assumed, and this is a limitation that should be considered. For application in realistic situations data has to be drawn from reliable sources such as detailed travel diaries. The uncertainty of occupancy behaviour has long been an issue in BPS (Hoes, et al. 2009), but has evolved over time, so this constraint of suitable behaviour templates is expected to be addressed in future studies. Another aspect to be

tackled is the logic behind trip generation. People don't plan their trips discretely, they are usually in chains. The model presented deals with trips between origins and destinations separately, however modelling of trip chains should also be considered.

This modelling approach is meant to be used on different scales. Therefore, a small neighbourhood can be simulated to understand the impact of form and land-use on both operational energy and expected transportation behaviour. This can be scaled up to a complete city to understand all interactions between different groups of buildings within varying street networks. A simple Walkscore calculation is often used exclusively to determine how walkable the built environment is. However, a follow up is recommended with a detailed simulation that factors outdoor thermal comfort and expected walking behaviour. In an ideal scenario, this will be modelled side-by-side with operational energy in umi to have a full overview of how an urban area performs holistically. This simulation tool is not expected to replace any transportation engineering workflows or simulation engines, it is meant to be used by architects, urban designers and planners on a finer grain than typical transportation forecast studies.

The use of umi-mobility can be extended to include not just environmental impact but also economic aspects of land-use. Realistic expected visits from households to amenities in their vicinity can be simulated, and that can give a base minimum of how amenities will perform in terms of annual visits. This also means that cultural adaptations to the amenities template used are necessary to address what different communities value. Replacement and addition of amenities is likely when using the tool in different contexts and cultural backgrounds.

CONCLUSION

This paper presented an innovative tool for the simulation of sustainable urban transportation. The workflow is built on traditional means of transportation forecasting, but is tailored to the interests of urban designers and planners. The integration of weather analysis as a placeholder for outdoor thermal comfort is an issue to be addressed, so is the issue of customizing amenity templates to be able to suite different cultural aspects. The expansion of the analysis to include other forms of non-motorized transport such as bikeability assessment should be integrated in future research, as well as estimations for different kinds of trip chains.

The goal of this work is to give designers the ability to estimate the impact of their design interventions on non-motorized travel behaviour, and consequential effects on the environment in terms of carbon emissions. The case study presented showed how a popular index such as Walkscore can be expanded in terms of quantifying environmental effects. It also demonstrated how energy efficient constructions can make their users waste energy

through transportation and how this can contribute significantly to carbon emissions if urban areas are not planned carefully for sustainable urban transport.

As BPS plays an increasingly critical and reliable role in determining the effect individual buildings have on human comfort and environmental performance, the exciting field of urban modelling is on the rise. Incorporating a deep understanding of how residents interact with their built environment and what that means on different scales is achievable using simulation tools, and that is what the authors aim to give to designers; simple tools that inform design decisions and contribute to a more sustainable built environment.

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