Urban Transport Energy Consumption Explored Through 3D Arc Maps

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ABSTRACT

We present a visualization tool for the analysis of the transport energy budget of a city, including the life-cycle energy embedded in the built infrastructure and the energy consumption by transportation. In our application, cumulative total energy is displayed as stacked, color-coded cylinders on a land use map. Transport energy consumption from traffic between inner-city travel zones is visualized as directed 3D Bézier curves. Our tool will support urban planners in assessing how urban form and infrastructure impact energy consumption and related greenhouse gas (GHG) emissions.

Index Terms: [Large Data Vis]: Multidimensional Data—; [Applications]: Geographic/Geospatial Visualization—; [Spatial Data and Techniques]: Geometry-based Techniques—;

1 INTRODUCTION

Over the past two decades, a large body of literature in urban planning and transportation research has investigated how urban form impacts transport energy use and greenhouse gas (GHG) emissions, both in terms of materials used and people's travel behavior [5, 3]. To estimate transport energy, most studies either use Life-cycle analysis (LCA) or travel demand models, which produce large datasets that are difficult to analyze because of complex activity-travel patterns. In this paper, we present a visualization tool to support the analysis of transport energy associated with urban form and travel behavior, combining outputs from LCA and travel demand modeling. We designed an interactive geovisualization with cylindrical glyphs on a 3D arc map. Stacked cylinders display the total transport energy consumption, and 3D Bézier curves represent travel patterns between inner-city zones. As a case study, we chose two sub-areas in metropolitan Phoenix, Arizona that differ in age and urban form. We compared infrastructure energy results for the years 2001 and 2009, incorporating ancillary information such as employment, population density, and land use in these areas.

2 RELATED WORK

The main challenge of graph-based geographic network visualization is to reduce visual clutter while preserving the spatial information of the network. Visualization techniques such as link maps, which display network connectivity over a map, are not suitable for large-scale networks, because they become cluttered as the number of links increases [2]. Phan et al. [7] proposed flow maps that aggregate links through edge-bundling. Flow maps work well for an egocentric perspective where a single source or sink is regarded for multiple links. However, they produce visual clutter with the addition of multiple sources. Andrienko et al. [1] added time-dependence to 2D flow maps in a 3D view, but this visualization requires additional views and diagrams to enhance the users understanding. Arc maps [4, 8] are another geographic network visualization technique using the third dimension. Here, links are rendered as 3D arcs with parameterization of the arc height, color, and shape to encode variables. Arc maps avoid heavy occlusion of the underlying map, eliminate link crossing as it occurs in 2D, and can integrate glyphs at the nodes to display ancillary variables.

3 TRANSPORT ENERGY MODELING

The total energy demand of the urban infrastructure system can be divided into two categories, embodied energy and operational energy. Embodied energy is the total energy consumed throughout the life-cycle of the infrastructure, from extraction of raw materials to construction, maintenance, and replacement or recycling. Operational energy is the amount of energy consumed during the in-use phase of the infrastructure and refers to travel and transport energy.

To calculate the life-cycle energy for infrastructure, we used the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) [6]. PaLATE yields energy consumption (MJ) of roads and pavement per construction unit. We aggregated the results to Travel Analysis Zones (TAZs), which are small geographic areas typically the size of a census tract, to get the cumulative energy demand for infrastructure life-cycle per zone (Figure 1). In order to estimate the energy consumed in the operational phase, we simulated travel patterns using the transportation demand model TransCAD. Based on the National Household Travel Survey (NHTS), TransCAD calculates a matrix of trips between input TAZs, connecting all TAZs in a spatially explicit bi-directed graph. Nodes of the graph are the TAZ centroids; edges represent transport flow on the road network between TAZs for different purposes, i.e., shopping and work. We derived operational energy from vehicle miles traveled and corresponding travel patterns, assuming a fixed distribution of vehicle ownership and average gasoline usage [9].

4 VISUALIZATION

Geovisualization tools such as ArcGIS or GoogleEarth display features in 3D, but dynamic rendering capabilities of large datasets and user interface customization for focus and context interaction are limited. Therefore, we implemented our visualization in OpenSceneGraph (OSG). OSG models all objects as nodes in a tree structure, which facilitates handling many small objects in

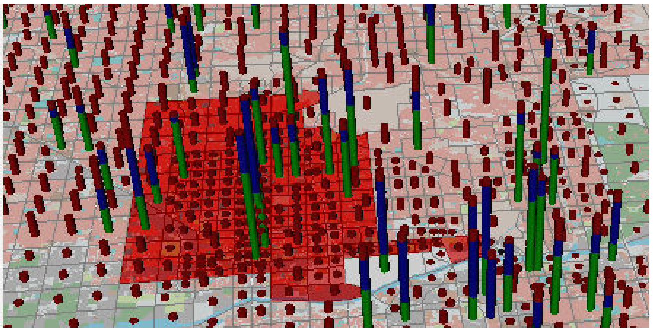

Figure 1: Transport energy consumption for each TAZ in downtown Phoenix (red zones): cylinders represent energy embedded in infrastructure (red) and energy use through shopping trips (blue) and work trips (green).

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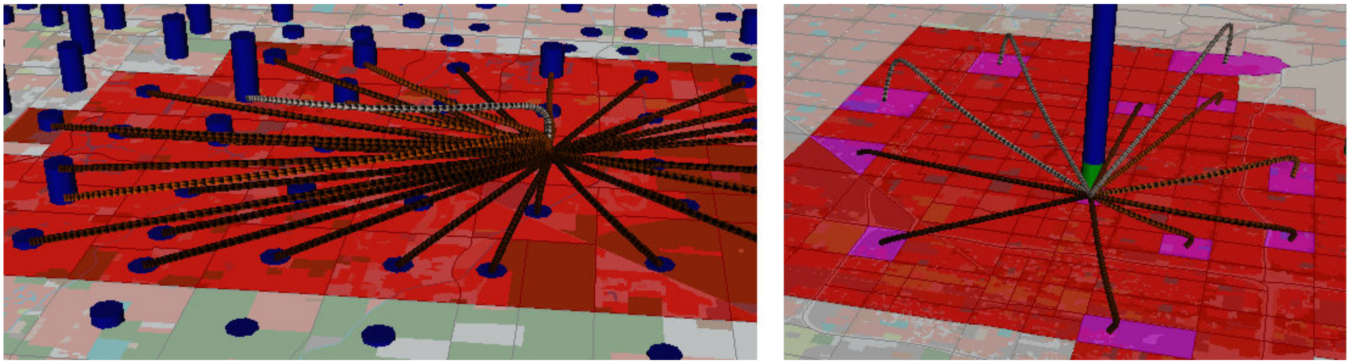

Figure 2: Cumulative travel energy for trips to a specific TAZ (left); user-selected travel energy for trips to a specific TAZ (right).

an organized way. To create complex geometries, we integrated the openGL framework in OSG. PostgreSQL serves as underlying database to store point and polygon geometries, each associated with a primary key and coordinates in space. All geometries are dynamically retrieved from PostgreSQL and rendered by OSG. The OSG view is embedded as a Qt widget into a QtGui application window.

To provide spatial context, we embedded a 12-category land use map as a base map for the transport energy visualization. Land use is a good indicator for the level of attraction an area has for incoming travel. On top of the base map, we layered a polygon map representing the TAZs in metropolitan Phoenix. For the operational transport energy visualization, we used tubes that trace Bézier curves, connecting all pairs of TAZs in the urban area (Figure 2). The curvature of each Bézier curve encodes the amount of energy consumed for travel from one TAZ to another with the highest control point of the curve representing the maximum travel energy. The total width of the curve is given by the distance between start and endpoint. The third and fourth control point are placed so that the tube fades out smoothly at the end. The third control point is scaled by a third of the distance vector multiplied with the normalized energy value for each TAZ pair. To avoid perception issues due to perspective distortion, the tubes are color-coded by their energy values. We used the HSV color space and linearly increased the V-value with increasing energy consumption. Cumulative energy consumption in each TAZ is displayed as a cylinder in the center of the TAZ (Figure 1). Different types of energy use are stacked and color-coded, i.e. energy embedded in infrastructure (red), incoming travel for shopping (blue), and incoming travel for work (green).

The GUI of our application enables the user to select a region and year of interest and to dynamically change the viewpoint. Through an energy panel, the user can activate or deactivate specific energy types for a focused analysis. Double sliders further help to filter the displayed energy results for cylinders and tubes through thresholding. The user can select certain energy intervals, travel trip lengths or numbers of trips to be visualized for a more detailed investigation. It is also possible to select a TAZ of interest and examine all ingoing or outgoing travel (Figure 2, left) or to manually select TAZ pairs that need further analysis (Figure 2, right). Supporting information on the selected TAZs is displayed in a data table below the OSG view.

5 DISCUSSION AND CONCLUSIONS

We presented a visualization to analyze urban transport energy consumption related to travel behavior and life-cycle energy of urban infrastructure. The benefit of our tool is twofold. First, our application provides quality control of the underlying energy models and facilitates the validation of the TransCAD model parameters. The representation of the total energy distribution by cylinders in combination with ancillary land use data helps to verify the energy use related to each TAZ. Errors in the traffic model can easily be detected in the global traffic flow. Second, the tool helps urban planners assess the implications of urban form on transport energy consumption. Future work will include an improvement of rendering efficiency. The application is currently not capable of displaying the complete trip matrix as 3D arcs at the same time. Rendering the complete dataset will provide a first overview of the data. We also plan on implementing the tool online for educational and research purposes. Understanding the impact of urban form on energy use will lead to better management of infrastructure systems to reduce GHG emissions in cities.

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