Explore the Improvement of Humanity-Oriented Transportation through Adaptive Topology Optimization of Traffic Networks Using Density Fields

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Abstract

The concept of "humanity-oriented transportation" primarily stems from the negative impacts of "car-oriented transportation," prompting a shift in thinking towards emphasizing a more humane approach to traffic planning to ensure public safety. This involves prioritizing pedestrian and bicycle traffic on roads, increasing pedestrian activity space, and reducing the impact of motor vehicles on road users. This prompted the present study to explore the utilization of Shepard density interpolation method to establish traffic density fields and to introduce topological optimization models to investigate how to reasonably reduce vehicular space within the acceptable range of overall service levels on urban roads, thereby releasing more space for pedestrian activities. By combining adaptive refinement strategy, this allows for more accurate estimation of traffic density, facilitating effective allocation of both vehicular and pedestrian spaces.

Keywords: Humanity-Oriented Transportation, Topology Optimization, Shepard interpolation, Adaptive Refinement Strategy

1. Introduction

The Athens Charter mentions that "transportation" plays a crucial role in connecting residence, work, and leisure. Since World War II, the rapid development of motorized vehicles, mainly cars, has occurred worldwide, starting with European cities, followed by the United States, and later by Asian cities. However, virtually all cities worldwide have been affected. With increased mobility and accessibility, users have multiplied, but so have traffic congestion, conflicts, and accidents between vehicles and users.

The efficiency and convenience brought by car-based transportation come with negative consequences such as increased traffic conflicts, decreased quality of life, and ecological imbalances. European cities, first captivated by cars, began reflecting in the 1960s on how to break free from the grip of vehicle traffic and return to a humanity-oriented urban environment from a "car- oriented" urban model.

European cities recognize earnestly that "cities cannot continue to be dominated by vehicles. It is impossible and inappropriate for cities to accommodate unlimited traffic and activities by vehicles. People should find ways to reclaim cities, making them humanity-oriented again." Thus, initiatives like the "Vision Zero" were launched, aiming for zero fatalities in traffic accidents. So, some practical actions come out which includes:

(1) Car-Free Movements and Car-Free City Centers: The "International Car-Free Day" originated in France. On September 22, 1998, a group of French youths first chanted the slogan "In Town, Without My Car!" hoping to reclaim their cities from vehicles for a cleaner environment. This movement quickly gained attention and response from neighboring countries. By February 2000, the French-originated car-free day was integrated into the European Union's environmental policies. The first European Car-Free Day took place on September 22 of the same year with 760 European cities jointly organizing car-free day activities, marking a significant milestone. Furthermore, in addition to hosting car-free days in 1999, all participating cities actively identified car-free zones within their city centers as part of action plans to promote old city areas as pedestrian zones.

(2) Bicycle Culture: While pedestrian zones ensure that only a portion of the city remains unaffected by vehicles, the entire city still experiences significant daily transportation needs. Therefore, "bicycles" have once again become a mode of transportation for urban residents in advanced countries like Europe. In the Netherlands, known as the world's cycling country, 70% of urban streets have a speed limit of 30 kilometers per hour, making streets safer for cyclists and pedestrians alike[1].

The US media CNN once described Taiwan's traffic chaos as a "living hell" in its reports. For example, narrow roads filled with motorcycles and cars, obstructed by lampposts and transformer boxes, and storefronts crowded with plants or signs, forcing pedestrians to often walk on the roadway or shuttle between congested lanes and sometimes blocked sidewalks. Additionally, pedestrians must beware of numerous small motorcycles weaving through traffic. When crossing the street, caution is advised as many drivers do not respect pedestrians' right of way or traffic regulations [2].

Furthermore, in Taiwan, in the past five years, there have been over three million traffic accidents annually, resulting in nearly three thousand deaths each year, with over four hundred of them being pedestrian fatalities, accounting for 13% of the mortality rate. In the past decade, nearly fifteen thousand pedestrians have been injured in traffic accidents while walking, leading to long-term impacts on their lives and significant costs to families and society. According to statistics from 2022, those aged 65 and above account for 69% of pedestrian fatalities[3].

In light of this, the Taiwanese government is striving towards the ultimate goal of zero traffic accidents, gradually shifting from the concept of "vehicles" dominating road spaces to a mode of thinking where "humanity" take center stage in urban spaces and transportation systems, emphasizing the humanization of urban spaces and transportation systems and considering both the safety of the public and the environmental burden.

Defining "humanity-oriented transportation" as a system that is oriented towards people, pursuing a transportation system necessary for sustainable and better human life. In a narrow sense, it can be defined as a transportation system primarily based on "human-powered" modes such as walking or cycling, which are low-pollution and environmentally friendly. However, in a broader sense, regardless of the development of motor vehicles or other mass transit vehicles, or the construction of roads, all should be oriented towards people, meaning they should align with the "values of sustainable and better human life," avoiding harm to people and hindering the ways people achieve a better life.

Its four main contents are:

(1) Maximizing the use of green transportation: Transitioning from past reliance on motor vehicles to prioritizing human-powered modes such as walking and cycling as the main "green transportation."

(2) Natural energy as the primary source of mobility: Transportation development in the new century should aim to achieve comprehensive goals such as health, safety, efficiency, environmental protection, and sustainability, considering the use of natural energy for energy consumption and mobility maintenance.

(3) Target system emphasizes humanization: Adjusting the functional structure of road systems, changing the configuration of road space, coordinating overall greening efforts, reducing the impact of through traffic, lowering the speed of traffic in the area, ensuring traffic safety, and increasing pedestrian activity space.

(4) Construction methods focus on localization and community: Designing an urban living space where residents can achieve various travel purposes by walking, which could potentially change the history of transportation development. Under this design concept, various transportation projects will no longer prioritize car travel but instead focus on walking, cycling, and public transportation. Mixed land use and pedestrian-oriented road systems will be developed based on the scale of community space [4,5].

Current efforts in Taiwan towards humanity-oriented transportation include the establishment of pedestrian lanes, the delineation of marked pedestrian paths, the installation of pedestrian-specific traffic lights and pedestrian refuge islands, the removal of motorcycles from sidewalks, and the reconfiguration of lanes [6,7]. Research directions mostly explore how to adjust vehicular spaces[6-12], seeming to lack rational studies on reducing vehicular spaces. Therefore, this study initiates a preliminary investigation into the rationality of reducing vehicular spaces.

2.Concept of Methodology

The inspiration for this study stems from combining topological optimization with Shepard interpolation method and adaptive refinement strategy, applied to the rigidity assessment of material structures [13,14]. The aim is to minimize material usage while maintaining a certain level of rigidity strength to support loads. Extending this argument to the allocation of traffic lanes, the goal is to reduce the maximum amount of road space while still maintaining an acceptable overall service level.

2.1. Definition and Classification of Traffic Service Levels

In Taiwan, the primary purpose of analyzing urban arterial roads is to estimate average travel speeds to assess the overall traffic function service level of an arterial road. Another purpose is to assess the traffic operation at intersections that affect the continuity of traffic flow on arterial roads, to help determine which sections need improvement or how to improve them. The division standards for transportation service levels (Table 1) are analyzed.

Table 1. The division standards for urban and suburban arterial road service levels[15].

Level of Service	Average Speed /Speed-limit ($\bar{V}/V_L$)
A	$\bar{V}/V_L \geq 0.8$
B	$0.6 \leq \bar{V}/V_L < 0.8$
C	$0.5 \leq \bar{V}/V_L < 0.6$
D	$0.4 \leq \bar{V}/V_L < 0.5$
E	$0.2 \leq \bar{V}/V_L < 0.4$
F	$\bar{V}/V_L < 0.2$

Here, we define the overall service level and its acceptable range.

(1) Overall service level: Consideration of the individual service levels of each road (main roads, secondary roads, local highways) within the study area (urban areas).

(2) Acceptable range of overall service level: Within the study area, allocation of proportions between service levels based on different road hierarchies (main roads, secondary roads, local highways).

2.2. Construction of Traffic Density Field

2.2.1. Defining the Design Variable Points:

In Fig 1, assume we have n design variable points $x_i = (X_i,\ Y_i)$, where $X_i,\ Y_i$ define the ith point location in a Cartesian coordinate system, with the volume values $q_i (i = 1,2, \dots, n)$.

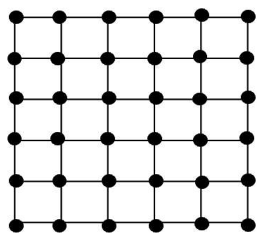

Fig 1. Design variable points are defined in the study area.

2.2.2. Adaptive Refinement Strategy

There are two conditions for adding nodes. One is that the node is located on the boundary of the study area, and the other is that within each unit area set, different speed limits exist on road segments. The estimated volume values of the added nodes (empty circles) are the average volume values between the surrounding nodes (solid circles) (Fig 2).

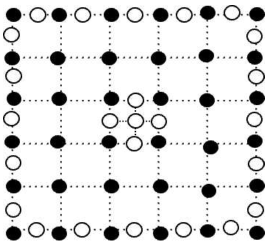

Fig 2. Newly-added nodes by adaptive refinement strategy.

2.2.3. Shepard Interpolation Method

Before using the Shepard interpolation method, it is necessary to define the influence region that affects the calculation of volume value at point x, for example, a circular area with a radius of R_C. The volume value at the interpolation point is then related to the design variables within its influence region (Fig 3).

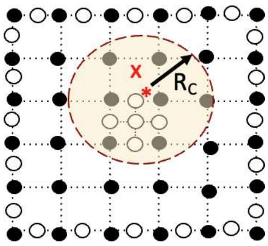

Fig 3. Only design variable points within the influence region R_C. contribute to the volume value of point x

Within the study area, at regular intervals, using the Shepard interpolation method to calculate the volume value:

$$q(x) = \sum_{i \in S_x} \Theta_i(x) q_i \tag{1}$$

where $\Theta_i(x)$ is a Shepard-family interpolation function expressed by

$$\Theta_i(x) = \frac{d(x - x_i)}{\sum_{j \in S_x} d(x - x_j)} \quad (i \in S_x) \tag{2}$$

with $d(x - x_i) = \|x - x_i\|^{-2} \quad (i = 1,2, \ldots, n)$ being the Euclidean distance between the points x and x_i and the set S_x denoting the design variable points located within the influence domain of point.

2.3. Topology Optimization

The size of road space will affect the volume value (or flow rate) and average speed of lanes, thereby leading to either a decrease or increase in the level of road service. The premise of implementing humanity-oriented transportation is to first reduce the road space, minimizing road capacity while still meeting the overall level of road service. This involves adjusting the proportion of service levels according to different road hierarchies (main roads, secondary roads, local roads), and the allocation of service level proportions can be adjusted appropriately according to different regions. Therefore, the topology optimization can be expressed as

$$\text{Minimize } C_{Mi} + C_{Sj} + C_{Lk}$$
$$Subject\ to \begin{cases} SL_{\alpha M} * r_1 + SL_{\beta M} * (1 - r_1) \\ SL_{\alpha S} * r_2 + SL_{\beta S} * (1 - r_2) \\ SL_{\alpha L} * r_3 + SL_{\beta L} * (1 - r_3) \end{cases} \tag{4}$$

where C_{Mi} $(i = 1,2,\dots,n)$, C_{Sj} $(j = 1,2,\dots,m)$ and C_{Lk} $(k = 1,2,\dots,o)$ are the capacity of main roads, secondary roads and local roads, respectively. The capacity is calculating by [16]

$$C = F * N * 1000 + (W - P) * 200 \tag{5}$$

where F is the road type correction coefficient, N is the number of express lanes, W is the width of slow lanes, and P is the width of parking spaces. SL_α, SL_β are different levels of service, with subscripts M, S, L representing main roads, secondary roads, and local roads respectively. r_1, r_2, r_3 are the proportions allocated between different levels of service.

3. Discussion and Conclusion

This study utilizes the Shepard interpolation method, supplemented by adaptive adjustment strategy, to establish a traffic density field. Through topological optimization analysis, it evaluates whether the overall traffic service level remains within an acceptable range to determine the rationality of reducing vehicular space. Since this study focuses on the overall service level rather than the traditional individual segment service level, it assesses traffic flow smoothly. Therefore, even if congestion occurs on certain road segments, other segments may remain unimpeded, resulting in smoother overall traffic.

Thus, through the methodology proposed in this study, it aims to re-examine spatial configurations and adjustments before implementing humanity-oriented transportation. This approach seeks to simultaneously meet the needs of pedestrian and vehicular spaces, contributing modestly to emissions reduction and sustainable development, thus addressing climate change.

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