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Physarum-Inspired Bicycle Lane Network Design in a Congested Megacity

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Abstract: Improvement of mobility, especially environment-friendly green mobility, is challenging in existing megacities due to road network complexity and space constraints. Endorsing the bicycle lane network (BLN) in congested megacities is a promising option to foster green mobility. This research presents a novel bioinspired network design method that considers various constraints and preferences related to the megacity for designing an optimal BLN. The proposed method is inspired by natural Physarum polycephalum, a brainless, multi-headed single-celled organism, which is capable of developing a reticulated network of complex foraging behaviors in pursuit of food. The mathematical model of Physarum foraging behavior is adapted to maneuver various BLN constraints in megacity contexts in designing the optimal BLN. The Physarum-inspired BLN method is applied to two case studies on the megacity Dhaka for designing BLNs: the first one covers congested central city area, and the second one covers a broader area that includes major locations of the city. The obtained BLNs were evaluated comparing their available routes between different locations with the existing vehicle routes of the city in terms of distance and required travel times in different time periods, and the BLN routes were found to be suitable alternatives for avoiding congested main roads. The expected travel time using BLNs is shorter than other transport (e.g., car and public bus); additionally, at glance, the average travel speed on BLNs is almost double that of public buses in peak hours. Finally, the designed BLNs are promising for environment-friendly and healthy mobility.

Keywords: megacity; green mobility; bicycle lane network; bioinspired network design; physarum polycephalum

1. Introduction

Various modes of transport and their integrated networks are essential for modern urban life [1]. In most megacities, both motorized and non-motorized transport with inseparable networks grew over centuries without well-planned urbanization, resulting in congested, costly, unhealthy, and inefficient mobility. Today, environment-friendly green mobility is highly desired to reduce the environmental impact of mobility in terms of greenhouse gas emissions, air pollution, and noise. Green mobility is becoming popular in many planned urban areas and cities, and in some, it has become a trend in recent years [2]. The major elements of green mobility are walking and cycling in cities rather than using motorized vehicles. Among the non-motorized transport, the bicycle is considered the most popular and easy alternative for green mobility, particularly in Europe and Japan, where planned urbanization facilitates sufficient space for bicycles alongside the main road networks [3].

In the ever-growing megacities, deployment of additional vehicles are not an effective solution to cope with congestion since expanding the existing transport networks is almost impossible. In any megacity, mobility enhancement with new transport networks or expanding existing ones with new roads is common, but it is always a very costly, as well as time consuming, solution. Scarcity of space and other challenges are also incurred in the case of congested and unplanned megacities; thus, such expansion might not ensure green mobility, which is a necessity, today, for sustainable development [4]. As an alternative, facilitating the comfortable employment of bicycle use is explored in the present research as a promising way to enhance mobility in a congested megacity.

The bicycle is an environmentally friendly means of transport, with no carbon emission, air and sound pollution, that has health and convenience benefits over motorized vehicles. Notably, motorized vehicles contribute about 20% of CO_2 emissions worldwide [5]. In order to reduce carbon emissions, the bicycle is encouraged as a part of green mobility in the European Union. Riding bicycles is also good physical exercise that is beneficial to urban life worldwide. It is notable that low physical activity (or physical inactivity) in urban areas is recognized as one of the leading health risk factors causing disease, including cardiovascular, chronic lung, and heart disease, stroke, diabetes, and cancers [6]. Bicycling is popular in well-organized cities worldwide and it offers more freedom of movement, without further constraints, in crowded and unpleasant conditions. Recently, bicycling has gained more attention as a means to avoid public transportation and thus to travel in a manner safe from communicative diseases, such as COVID-19 [7–9]. Bicycles can enhance green mobility in urban areas and also safeguard accessibility in congested cities if suitable facilities are provided for a bicycle infrastructure [5]. Therefore, an effective BLN design within existing space constraints is explored in this study to enhance green mobility in congested megacities or congested areas, especially city centers or old town areas. Obviously, designing an optimal BLN, considering the complexity of congested megacities, is challenging, and such a challenging task is dealt with in this study.

Designing a BLN falls within a class of network design problems that have significant differences from typical transportation network design (TND). A road network usually has to fulfill two requirements: (i) maximize direct connections between nodes to avoid large detours; and (ii) minimize costs for road construction and maintenance [10]. In general, TND concerns the optimal selection of a project from various alternatives, satisfying associated constraints to maximize cost-benefit. Various approaches have been applied to solve TND problems in the last decade, including different heuristic and bioinspired methods [11–13]. The major issue with the existing methods is optimizing network length to minimize construction costs. In contrast, the major issue of BLN design is the selection of appropriate links for optimal routes while ensuring the feasibility of the links for riding bicycles. Generally, there are two types of roads in any megacity area: the wider main roads that connect zones and serve as the backbone for inter-city communication; and the narrower link roads that interconnect different residential blocks within a zone. Managing space for a bicycle lane on the main roads is almost impossible due to massive traffic; footpaths alongside these roads are not suitable for bicycles, in most cases, as those are either narrow or mostly occupied by pedestrians and street hawkers [14]. On the other hand, link roads have issues as well, e.g., some link roads are very narrow and are left without any connections to other routes, which must be considered in BLN design. Therefore, a suitable network optimization problem needs to be formulated to design a BLN that considers the constraints mentioned above and with the preference of not disrupting traffic on the main roads. Most importantly, the desired BLN might not always be the shortest path connecting individual zones, but nonetheless be considered suitable for bicycle use. Finally, constraints of BLN design are different from a typical network design, and hence appropriate mechanisms are sought for BLN design.

A novel network optimization technique has recently been identified from natural Physarum polycephalum, a brainless multi-headed single-celled slime mold organism [15]. Despite lacking brain and neurons, it shows complex decision-making ability in food foraging behavior and develops a reticulated network shape [16,17]. Its ability to optimize its shape attracted the research community to solve complex optimization tasks, such as optimal network design [16]. The computational model of Physarum's network design technique is expected to solve complex design problems more effectively than the existing bioinspired and traditional methods [11–13].

The aim of this research is to develop a Physarum-inspired novel BLN design method to improve the mobility of a congested megacity. The basic mathematical model of Physarum is modified to handle various BLN constraints of megacity contexts in designing an optimal BLN. Notably, we introduced hinder issues (e.g., footpath conditions, traffic conditions, aside marketplace conditions, etc.) in conductivity assignments to expose individual links' feasibility, and modified flux measurements adapted to a BLN to make the optimization technique effective, as well as efficient. The proposed Physarum-inspired BLN design method is applied to the megacity Dhaka to design two BLNs. The first BLN covers the congested central city zone, and the second one covers a broader area that includes the central zone and other major locations of the city. The designed BLNs are analyzed to evaluate the expected improvements in green mobility (in terms of travel time) in congested megacities and other benefits, in terms of transportation cost, health, and environmental impacts.

Section-wise overviews of the rest of the paper are as follows. Section 2 describes natural Physarum and mentions important tasks inspired by it. Section 3 presents the proposed Physarum-inspired BLN design method. Section 4 demonstrates BLN design in the megacity Dhaka, employing the proposed method. Section 5 gives an overall discussion on model significance, outcomes and related issues. Finally, Section 6 is given to the conclusions of this study, together with an outline of future directions for research opened up by this work.

2. Physarum Polycephalum and Tasks Inspired by It

Physarum polycephalum is a multi-headed, brainless, giant multi-nucleated, single-celled slime mold organism [15,18]. As a pictorial view shown in Figure 1, Physarum polycephalum grows by building a network that links several food points. Recently, Physarum has arisen as a fascinating illustration of biological computation through morphogenesis [19,20]. For convenience in developing a Physarum-inspired BLN design, firstly, we review relevant works and the mathematical model of Physarum in this section.

Figure 1. Network connecting food sources (FSs) by Physarum polycephalum. "Slime mold" image by Björn S. is licensed under CC BY-SA 2.0.

2.1. Review of Natural Physarum Polycephalum and Relevant Works

Physarum naturally grows toward food sources in its neighborhood and develops a typical reticulated shape that seems to be an optimized network structure. The pioneering experiments on Physarum conducted by Nakagaki et al. revealed its intelligent behavior, specifically, the ability to develop the shortest path between two selected points in a maze [21,22]. Tero et al. investigated Physarum for path-finding in a maze [23] and connecting routes in a few source points [24]. Physarum creates a form of spatial memory, by avoiding areas previously explored, to navigate a complex environment [25]. Although Physarum is a single-celled organism, studies have shown that it can overcome different minimum-cost flow problems through its growth process [19]. Aono et al. [26] experimented with Physarum to solve a traveling salesman problem (TSP) consisting of only eight cities, and later, Jones and Adamatzky [27] solved larger TSPs with various sizes. Physarum was also cultured for logic gates and combinational circuit operations [28–30]. Tero et al. [31] cultured Physarum to develop the Tokyo railway network system and showed a similar structure to the existing system. Since then, Physarum has been used to rebuild other large-scale road networks, such as Iberian motorways in Spain and Portugal [32] and Mexican federal highways [33]. Adamatzky [34] modeled a world population migration network scenario that considered 24 majors cities around the globe.

Based on Physarum's network-growing capability, a number of models are investigated to design various transportation networks. Becker et al. [35] developed fault-tolerant connection networks for the Tokyo rail system using an agent-based simulation of Physarum. Adamatzky et al. [36] developed a model to construct networks in China's major urban areas. Gao et al. [37] applied the Physarum-inspired method to identify influential nodes in complex real-life networks, including the US Airline network. Zhang et al. [38] developed a Physarum-inspired shortest-path-finding method between two points in a network, and the method was later evaluated on a road network in China. Zhang et al. [39] developed a model for large road networks and compared it to major transport networks in Mexico and China. Most recently, Gao et al. [40] investigated a Physarum-inspired model for randomly generated networks of different sizes and two man-made transportation networks, the Berlin Mitte Prenzlauerberg Friedrichshain (BMPF) center network and the Chicago-area transportation network.

2.2. Network Development Model of Physarum Polycephalum

The mathematical model of Physarum's adaptive network construction mechanism was developed based on intelligent behavioral observations in laboratory experiments [23]. In the network model, edges represent plasmodial tubes in which protoplasm flows, and nodes are junctions between tubes. The model considers feedback loops between the thickness of each tube and the internal protoplasmic flow. High rates of streaming stimulate an increase in tube diameter, whereas tubes tend to decline at low flow rates. Suppose the pressure at nodes i and j are P_i and P_j, respectively, and the two nodes are connected by a cylinder of length L_{ij} of radius r_{ij}. Then, considering the flow is laminar, the flux through the tube following the Hagen-Poiseuille equation is given by

$$Q_{ij} = \frac{\pi r_{ij}^4 (P_i - P_j)}{8\varepsilon L_{ij}} = \frac{D_{ij}(P_i - P_j)}{L_{ij}} \quad , \tag{1}$$

where ε is the viscosity of the fluid and $D_{ij} = \frac{\pi r_{ij}^4}{8\varepsilon}$ is a measure of the conductivity of the tube. As the length L_{ij} is a constant, the behavior of the network is described by the conductivities of the tubes. If the flux amount I_0 flows from the source node N_1 and the sink node is N_2 then,

$$\sum_i Q_{i1} + I_0 = 0 \quad \text{for Source Node 1} \tag{2}$$

$$\sum_i Q_{i2} - I_0 = 0 \quad \text{for Sink Node 2}$$

$$\sum_i Q_{ij} = 0, \text{ inflow and outflow must be balanced for } (i \neq 1, 2).$$

To accommodate the adaptive behavior of the plasmodium, the conductivity of each tube evolves according to

$$\frac{dD_{ij}}{dt} = f(|Q_{ij}|) - \mu D_{ij}, \tag{3}$$

where $f(|Q_{ij}|)$ describes the expansion of tubes in response to the flux, and μ is the decay rate of the link [24]. The equation implies that the conductivity of a particular tube becomes nil if there is no flux; thus, the tube will gradually disappear. The function $f(|Q|) = \frac{|Q|^{\gamma}}{(1+|Q|^{\gamma})}$ describes a sigmoidal response, where γ is a parameter that controls the nonlinearity of feedback ($\gamma > 0$). Considering the above features, the basic steps of the computational model of Physarum are as follows:

Step 1: Initialize the environment.
Step 2: Measure flux through individual links, based on edges' pressures.
Step 3: Update the conductivity of individual links, based on flux through it.
Step 4: Return the network with links having appropriate conductivity.

3. Physarum-Inspired Bicycle Lane Network Design

The following subsections describe the BLN design task by considering a specific congested area and then proposes a Physarum-inspired method to solve the BLN design problem.

3.1. Problem Statement: BLN Design Considering Feasible Routes

Roads in the congested areas of any megacity are categorized as either wider main roads or narrower link roads. Main roads connect zones and serve as the backbone for inter-city communication, with high importance placed on maintaining their flows. Link roads mainly interconnect different residential blocks within a zone and allow mainly small vehicles to pass. Both main and link roads have different issues to consider in BLN design. Main roads usually carry massive traffic, with oversaturated flows in the peak hours, and therefore allocating space for a bicycle lane on such roads is impossible. The footpaths alongside these roads are also unsuitable for bicycles, for several reasons, e.g., it is either narrow or mostly occupied by pedestrians and/or street hawkers. On the other hand, some link roads are very narrow and often end up disconnected from other routes, i.e., exhibit lack of connectivity; such roads are not suitable for inclusion in a BLN. However, some link roads provide easy connectivity between the residential blocks and the main roads.

A suitable network optimization problem needs to be formulated to design a BLN with the constraints mentioned above. Most importantly, the desired BLN might not always be the shortest path connecting individual zones, but be considered suitable for bicycle use. Furthermore, the BLN should bypass main roads as much as possible to avoid disrupting major traffic in congested megacities.

3.2. Physarum-Inspired BLN Design Method

Suppose a graph $G = (N, E)$ denotes a road network, where N denotes a set of n nodes representing zones, e.g., $N = \{1, 2, \ldots n\}$, and E represents a set of e connections or links among those nodes. Thus e_{ij} represents a link between nodes i and j. According to Physarum-inspired techniques, individual links are characterized by conductivity, which relates to three parameters: initial conductivity, the pressure difference between the pair of nodes connected by the link, and flux. In the context of BLN design, node pressure is considered to be bicycle traffic demand (i.e., the number of bicycles that travel from one zone to another). In the following subsections, the major steps of the process are described briefly, and then the complete algorithm is presented.

3.2.1. Initialization

The tasks involved in the initialization are the preparation of inputs and then the setting of required variables and matrixes. Pressure assignment of individual nodes is an essential task in this step. A *1D* pressure matrix is denoted by p, where p_i is the pressure of the node n_i and is defined based on the demand of a node. Links are represented with three distinct parameters, which are length L, radius R, and conductivity D. Therefore, three $n \times n$ matrices are used to maintain the link parameters. An element L_{ij} in the length matrix

(L) denotes the length of the link e_{ij}. An element r_{ij} in the radius matrix (R) is the radius (i.e., tubular thickness) of the link e_{ij}. An element D_{ij} in the conductivity matrix (D) denotes the conductivity of the link e_{ij}. The flux matrix denoted by Q is also maintained, where an element Q_{ij} denotes the flux of the link e_{ij}. The values of matrices L and R depend on the link conditions and remain unchanged throughout the iterative process. The matrixes D and Q are populated with initial values, and they are updated in an iterative process to build the network.

In this study, an innovative idea is considered to define the initial conductivity of individual links (D_{ij}), including a hinder parameter (h_{ij}) along with the width (r_{ij}) and viscosity (ε) of the link:

$$D_{ij} = \frac{\pi r_{ij}^4}{h_{ij}\varepsilon}. \tag{4}$$

The fixed value 8 in the existing conductivity equation (Equation (1)) is replaced with the hinder value of an individual link. The value of a hinder parameter represents the value of the collective obstacle of the link. The conductivity is inversely proportional to the hinder value (i.e., $D \; \alpha \; h^{-1}$); a lower h_{ij} value represents the suitability of the link condition and vice versa. A collective measure of different hinder parameter values is used to set h_{ij} value of link e_{ij}:

$$h_{ij} = w\left(f_{ij} + \tau_{ij} + \alpha + \beta + t\right). \tag{5}$$

In the above equation, f_{ij} is the footpath condition, τ_{ij} defines the traffic condition, α defines the marketplace condition aside the link, β denotes the divider condition of the road (i.e., one-way or two-way), and t represents the terminal condition of the link (with or without a dead-end). Moreover, the weighted parameter (w) is used to provide different preference conditions for the main and link roads.

Pressures for individual nodes, i.e., $p = \{p_1, \ldots, p_n\}$ are defined based on the demand of individual commercial/residential areas where the pressure of a particular node (P_i) is considered as the accumulated pressure of the node for different source-target pairs of the network. If F_{st} is flow from starting node s to target node t, then flux conservation considering Equations (1) and (2) is

$$\sum_{i \neq j} \frac{D_{ij}}{L_{ij}}\left(p_i^{st} - p_j^{st}\right) = \begin{cases} -F_{st}, & j = s \\ +F_{st}, & j = t \\ 0, & j \neq s,\ t \end{cases}. \tag{6}$$

Setting $p_t = 0$ (pressure at target or sink node to 0) as the base pressure level, the unique pressure level at every node p_i is achieved by solving a system of linear equations of Equation (6). Then, the accumulated pressure of a particular node (P_i) is the sum of pressures in the node for different source-target pairs solving Equation (6):

$$P_i = \sum_{st} p_i^{st}. \tag{7}$$

3.2.2. Conductivity Update of Individual Links

While the pressure of individual nodes and the initial conductivity of links are set, the main task of Physarum-inspired method is to update the conductivity of individual links (D_{ij}) considering the flux flow through each individual link (Q_{ij}) iteratively. Flux resembles protoplasmic flows, and there is a protoplasmic flow (Q_{ij}) in each link e_{ij} in this model. In general, plasmodium flows through a link from one node to another (and vice versa) based on the pressure differences between the two nodes connected to the link. In this study, pressures of individual nodes are maintained fixed, and the amount of flux Q_{ij} in link e_{ij} is considered proportional to the amalgamation of pressures between the two terminals of this link, i.e., $Q_{ij} \propto \left(P_i + P_j\right)$. It is logical for BLN design because the flow might be bidirectional; $Q_{ij} \propto P_i(P_j = 0)$ and $Q_{ji} \propto P_j(P_i = 0)$. Thus, flux Q_{ij} in link e_{ij} is considered following Equation (8) instead of Hagen–Poiseuille (Equation (1)) used in existing studies.

$$Q_{ij} = \frac{D_{ij}}{L_{ij}}(P_i + P_j). \tag{8}$$

Then, the conductivity of the individual links is updated based on the flux. The rate of conductivity update formula is considered, based on the change in tubular thickness of Physarum due to flux, as follows

$$\frac{d}{dt}D_{ij} = f(|Q_{ij}|) - \mu D_{ij}\,, \tag{9}$$

where $f(|Q_{ij}|)$ is an increasing function, and μ is a positive constant. In our case, we considered $f(|Q_{ij}|) = |Q_{ij}|$ for simplicity. Thus, the conductivity change (ΔD_{ij}) is

$$\Delta D_{ij} = |Q_{ij}| - \mu D_{ij} \tag{10}$$

The equation of the conductivity update suggests that conductivity tends to increase with large flux edges. Consequently, the conductivity of individual links is updated, reflecting the above physiological mechanism as

$$D_{ij} = D_{ij} + \Delta D_{ij}\,. \tag{11}$$

After updating the conductivity using Equation (11), the system calculates flux with a new conductivity and continues the process. The iterative processes of flux calculation and conductivity are performed until termination criteria are reached, which might be the maximum number of iteration or steady-state of the conductivity matrix. Finally, the conductivity of the network is normalized with respect to its maximum value, thus $0 \leq D_{ij} \leq 1$.

$$D_{ij} = \frac{D_{ij}}{\max(D)}. \tag{12}$$

3.2.3. Final Network Construction

A threshold value of conductivity (δ) is considered to select individual links in the final network; a link e_{ij} is considered for BLN if $D_{ij} \geq \delta$. A link is also considered even for $D_{ij} < \delta$ when the entire network is not traversable without it. The network construction may be summarized in the following steps:

Case 1: For $\forall e_{ij}$ i.e., $e_{ij} \in E$, link e_{ij} is considered in the network if $D_{ij} \geq \delta$.
Case 2: For $\forall e_{ij}$ i.e., $e_{ij} \in E$, link e_{ij} is considered in the network even $D_{ij} < \delta$ when the entire network is not traversable without it.

3.2.4. Complete Algorithm of BLN Design

Algorithm 1 shows the complete steps of the proposed BLN design. The method takes pressure (p), link length (L) and link hinder (h) as input for a particular road environment; it returns *BLN* as a selected number of links for the bicycle lane network, based on the provided data. In initialization, links' conductivity (D_{ij}) and the accumulated pressures of individual nodes (P_i) are prepared accordingly. The viscosity (ε), total number of nodes (N), and the conductivity decay (μ) are used at different steps.

Algorithm 1 Physarum-inspired Bicycle Lane Network Design (p,L,h)

```
// p is a 1D pressure matrix, where p_i denotes pressure of individual node i
// L is a n × n matrix, L_ij denotes the length of link e_ij between node i and node j
// h is a n × n matrix, h_ij denotes the hinder value of link e_ij between node i and node j
// ε is the viscosity value, N is total number of nodes, and μ is the conductivity decay
//δ is a threshold value of conductibility
// MaxItrn is the Maximum Number of Iteration as the termination criteria
// D is a n × n matrix, D_ij denotes the conductivity between node i and node j
// Q is a n × n matrix, Q_ij denotes the flux between node i and node j
   Set links' initial conductivity D_ij according to Equations (4) and (5)
   Normalize links' conductivity according to Equation (12)
   Calculate accumulated pressure of each individual nodes P_i according to Equations (6) and (7)
   For itr = 1: MaxItrn do
        //Flux Update
        For i = 1: N do
   For j = i + 1: N do
   Q_ij ← D_ij × (P_i + P_j) / Lij // Using Equation (8)
   end for
   end for
        //Conductivity Update
        For i = 1: N do
   For j = i + 1: N do
```

$$\Delta D_{ij} \leftarrow \left|Q_{ij}\right| - \mu D_{ij} \quad //\text{UsingEquation}(10)$$
$$D_{ij} \leftarrow D_{ij} + \Delta D_{ij} \quad //\text{UsingEquation}(11)$$

```
   end for
   end for
   Normalize links' conductivity according to Equation (12)
   itr ← itr + 1
   end for

   // Bicycle Lane Network Construction
   BLN = [ ] // Empty
   For i = 1: N do
   For j = i + 1: N do
        If (D_ij ≥ δ) | | (Traversal discontinued without e_ij)
        BLN = BLN ∪ e_ij // Include the link in the network
   end if
   end for
   end for
return BLN
```

The main task of the conductivity update is performed in an iterative process up to a maximum number of iterations (i.e., *MaxItrn*), the termination criteria of the algorithm. At every iteration, the individual links' flux are measured first, and then conductivity is updated. In this study, bidirectional flows are considered and flux and conductivity matrixes are assumed to be symmetrical; thus, the nodal loop is optimized as i = 1: N and j = i + 1: N. Finally, the *BLN* is populated with selected links based on its conductivity value comparing with a threshold value (δ) and its importance to make the network traversable.

4. Computational Experiments

This section presents BLN design on a real-life congested megacity with the proposed Physarum-inspired method. The megacity Dhaka, the capital of Bangladesh, is considered in this study. In the following subsections, an overview of Dhaka is provided to establish the necessity of a BLN, and then the effectiveness of a BLN developed with the proposed method is presented.

4.1. Mobility Problems and BLN Prospects in a Congested Mega City: Dhaka as a Case Study

Dhaka is the ninth-largest and the sixth-most densely populated city in the world, with a population of over 21 million. Moreover, the population of Dhaka is increasing daily and putting pressure on public transportation systems that are not well planned for expansion. The city has neither efficient public transport nor mass transit [41]. The city's road transport systems are not capable of handling huge traffic; thus, the city is very congested at present, especially in the city centre. On the other hand, every year about twenty thousand private cars are introduced [42]. According to a World Bank report, the average traffic speed in Dhaka has dropped from 21 km/h to 7 km/h in the last several years, only slightly above the average walking speed [43]. By 2035 the speed could drop to 4 km/h, which is slower than the standard walking speed [42]. Traffic congestion in Dhaka consumes about 5 million working hours a day and costs the country $11.4 billion a year [42]. Additionally, traffic jams and huge vehicles worsen other problems like air pollution, noise pollution, extra fuel consumption, etc.

To improve mobility and environmental impacts, construction of new roads or expansion of the existing road network(s) in the city is not feasible due to space scarcity and cost. Although vertical expansion with an elevated expressway and a metro service is under construction, such huge, costly facilities will cover only limited areas and might not solve mobility problems entirely. Therefore, how green mobility may be promoted within existing road networks is a challenging issue. Although bicycling is an alternative means of travel, in the present scenario, riding a bicycle is difficult (i.e., neither safe nor comfortable) in congested city areas due to space scarcity; footways are not suitable because street vendors and hawkers occupy these spaces, and in some cases, footways do not exist [14]. In such a scenario, the introduction of a dedicated BLN, using local link roads (avoiding main roads) to connect potential locations, can yield several advantages. Firstly, it may encourage many people to use green mobility for short-distance travel. Secondly, it may alleviate overloaded transport and congestion, which directly reduces environmental impacts and wastage of time. Moreover, the bicycle is less expensive than other forms of transportation; and the use of existing local roads for the BLN might not incur construction costs, as it is a matter of planning and declaring selected roads for use in the BLN. Finally, the BLN would provide a valuable link to the future mass transit system, e.g., the metro rail network, and contribute to shifting the city's mobility paradigm from a congested megacity to a smart megacity.

4.2. Experimental Settings of Proposed BLN Design for Dhaka City

The relevant information is collected from Google Maps for network data preparation, and most road conditions are verified physically. Two different BLNs are investigated in this study: a BLN for the central city area, with 10 km diameter, and a BLN for a broader area with major city locations. Notably, the central area is the most congested and most promising for such bicycle lanes. On the other hand, the entire city is also important and suitable for mobility improvement, especially with electric bicycles. Figure 2 approximately shows the central city area (yellow circle) and broader city (blue rectangle) area of Dhaka taken from Google Maps that were chosen for BLN design in this study.

Nodal pressures (p), link length (L), and hinder values (h) are prepared for each BLN design problem. The value of viscosity (ε) was set to 112; the value of meu (μ) was varied between 0.8 and 1. The threshold value of conductibility (δ) was set to 0.1, and the maximum number of iteration (*MaxItrn*) was set to 100 as the termination criterion. The BLN design algorithm was implemented on Visual C++ of Visual Studio 2013, and the experiments have been conducted on a PC with Windows 10 OS.

Figure 2. Area demarcating a Dhaka city map for two different bicycle lane network (BLN) designs: central Dhaka, marked with yellow circle 10 km in diameter, and all Dhaka, marked with a blue rectangle having area 28 km × 17 km.

4.3. Test Case 1: BLN for Central Dhaka Area

The selected area, central Dhaka city, is amenable to BLN as a person may travel the area in a comfortable bicycle-riding time at an average cycling speed of 20 km/h [44,45]. Figure 3 shows the schematic road network view of the area, with 29 nodes. Table 1 lists the pressures of individual nodes in the area, which were set based on population and importance of the location. For example, Motijheel is the major business and commercial hub of Dhaka city and has more offices and business institutions than any other part of the city; therefore, it holds the highest pressure, nine. A total of 78 linkages' parameters are given as input, which contains links to connect a particular node to its adjacent nodes. The length of a link (L_{ij}), which is not linear, and tubular thickness (r_{ij}) are estimated using Google Maps. For certain cases, the tubular thickness variations are ignored for simplicity. The links' hinder value (h_{ij}) is also measured based on road conditions.

4.3.1. BLN Design Solution for Central Dhaka

Figure 4 depicts the proposed BLN, in blue, for the central Dhaka area on its road network. The numerical values in the BLN map indicate corresponding link lengths in km. As desired, the BLN is designed such that the main roads are not intercepted much, except in a few cases where an alternative is not available or not suitable. For example, the path from node 17 to node 18 (located on opposite sides of the map) is available through 16-23-24-26-29, i.e., without using the main roads. The proposed BLN uses main roads in a few cases, when an alternative is not possible. For example, there is a direct main road sharing with BLN between neighbour nodes 2 and 6, in two small segments, since an alternative route, such as 2-10-7-6, is very long. Such consideration of small portions of main road is sensible to make the network feasible. Another important BLN feature is the several alternative connectivities among nodes, e.g., the optimal route to connect nodes 21 and 28 is 21-24-28, and the alternative routes are 21-23-14-28 and 21-25-22-28. Such feasible alternatives are essential to increase the resilience of the network.

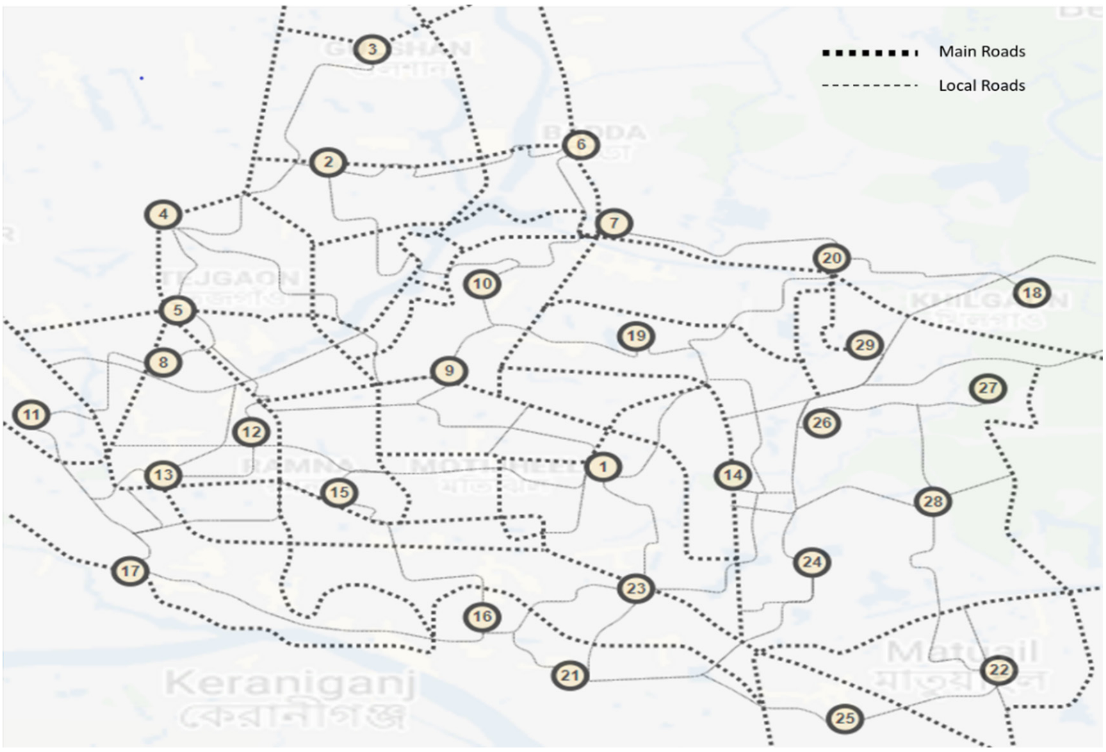

Figure 3. Schematic view of the central Dhaka area's road network, where main and local roads are shown with wider and thinner lines, respectively.

Table 1. The location wise traffic pressure assignment for central Dhaka area.

Sl	Location	Traffic Pressure	Sl	Location	Traffic Pressure
01	Motijheel	9	16	Kotwali	3
02	Mohakhali	8	17	Lalbagh	4
03	Gulshan	5	18	Khilgaon	6
04	Shahinbag	8	19	Taltola	3
05	Tejgaon	9	20	Aftabnagar	4
06	Badda	4	21	Sadarghat	5
07	East West Unv.	5	22	Matuail	8
08	Bashundhara	5	23	Wari	7
09	Mogbazar	5	24	Golapbag	5
10	Mirbag	5	25	Donia	3
11	Dhanmondi	7	26	Rajarbagh	5
12	Shahbag	9	27	Sobujbagh	5
13	Unv. of Dhaka	9	28	Green Model Town	4
14	Kamlapur	8	29	Nandipara	6
15	Ramna	5			

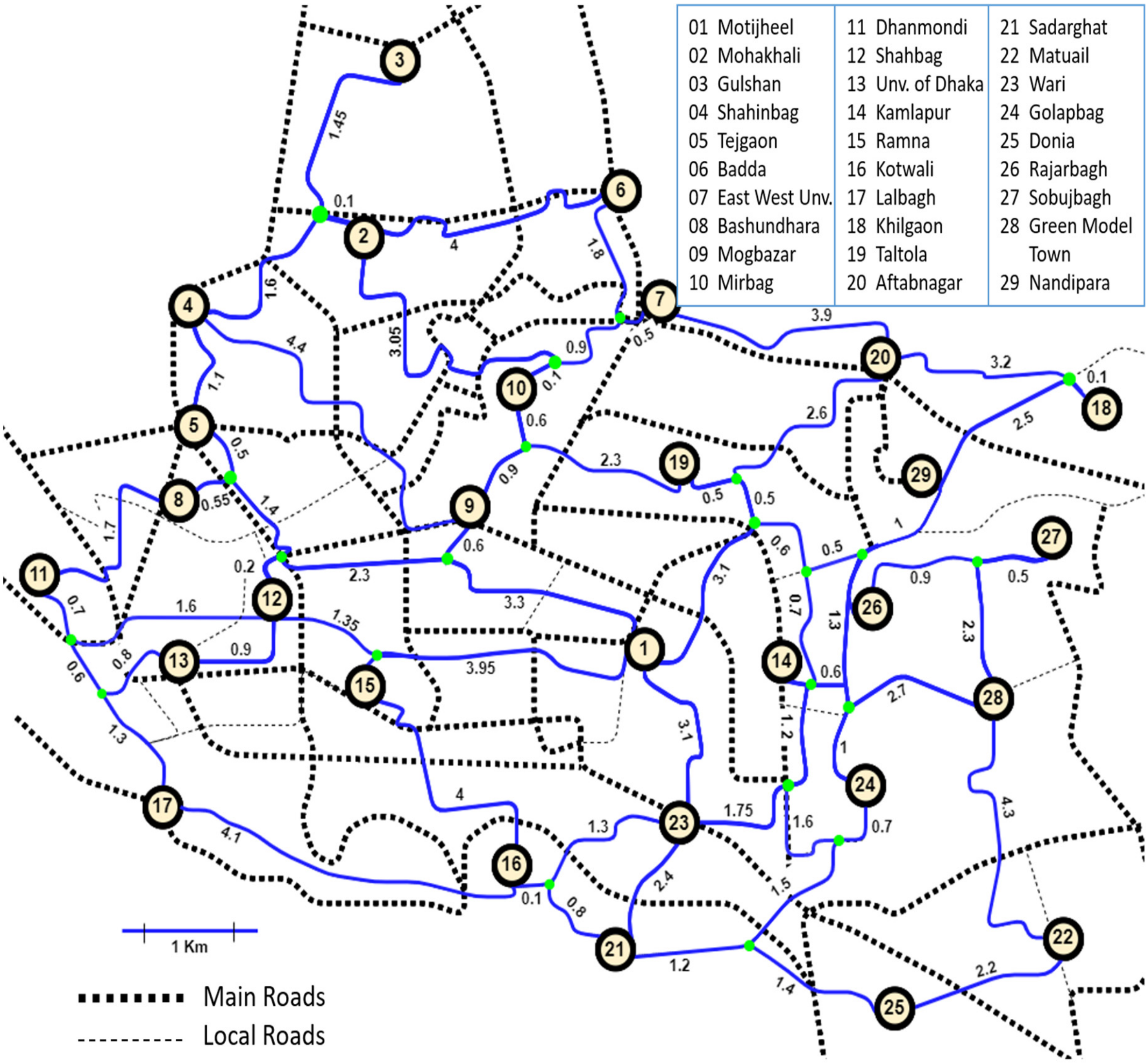

Figure 4. Proposed bicycle lane network (BLN) in the central Dhaka city area, depicted in blue color. Numerical values in BLN links indicate corresponding link's length in km.

Table 2 shows the resulting optimal routes and corresponding distances and travel times from node 1 to other individual nodes, using the proposed BLN shown in Figure 4. Notably, node 1 (Motijheel on the map) is in the centre of the BLN and the most demanding place to visit from different locations, due to its commercial importance. The travel time is calculated considering a standard bicycle speed of 20 km/h [46]. Along with cycling time, 5 min is also added for each main road crossing by bicycle to better reflect reality. According to the proposed BLN, node 3 (Gulshan on the map) is the farthest away from node 1 and route 1-9-10-2-3 (and vice versa) is 9.8 km, which requires 34.4 min including 5 min for travelling across the main road between nodes 2 and 3. The second farthest node is 22, route 1-23-21-25-22 (and vice versa) is 10.3 km and would take 35.9 min. The travel time for any other node is less than 30 min. Node 11 and node 18 are the farthest nodes from node 1 in the left and right directions, respectively, and travel time is less than half an hour using routes 1-12-11 (distance 7.6 km) and 1-29-18 (distance 7.8 km). On the other hand, travel time between two opposite corner nodes might be the sum of two individual routes from node 1. The route between node 3 and node 22 might be 3-2-10-9-1-23-21-25-22 through node 1; it will take more than an hour for a 20.1 km (=9.8 + 10.3) long route. Routes for opposite end nodes might be possible, avoiding node 1, and in some cases, the route might be shorter than through node 1. Note that very few people might travel end to end in the city area, and, at least, it is not usual for daily activity; whereas a visit to and from the centre point is more typical.

Table 2. Optimal bicycle routes, distance and estimated travel time from node point 1 (central point) to different node points through BLN.

Destination Node Point	Optimal Routes	Distance (km)	Estimated Travel Time (min)
2	1-9-10-2	8.6	30.7
3	1-9-10-2-3	9.8	34.4
4	1-9-4	8.3	29.9
5	1-5	7.5	27.5
6	1-9-10-7-6	8.2	29.6
7	1-9-10-7	6.9	25.7
8	1-8	7.6	27.7
9	1-9	3.9	16.7
10	1-9-10	5.4	18.2
11	1-12-11	7.6	33.5
12	1-12	5.3	20.9
13	1-12-13	6.2	23.6
14	1-14	4.4	18.2
15	1-15	4.1	17.2
16	1-23-16	4.5	18.5
17	1-23-16-17	8.1	29.3
18	1-29-18	7.8	28.4
19	1-19	4.1	17.3
20	1-20	6.2	23.6
21	1-23-21	5.5	21.5
22	1-23-21-25-22	10.3	35.9
23	1-23	3.6	10.8
24	1-23-24	7.2	26.5
25	1-23-21-25	8.1	29.3
26	1-26	4.9	19.7
27	1-26-27	6.3	23.9
28	1-14-28	7.9	28.7
29	1-29	5.2	23.3

The proposed BLN includes individual routes close to the optimal distance among different nodes. It is possible to design a BLN to provide the shortest path using main roads with equal probability. In such a case, main roads will be selected in the BLN design in greater percentage since main roads are straight and inter-connected. However, such a shortest-path scenario is avoided due to space constraints for bicycle lanes in the main roads, and for footpaths of the main roads, which are not feasible for bicycling. However, still, in many cases, the proposed BLN is found to achieve the shortest routes when this is available.

4.3.2. Effectiveness Measure of BLN Design for Central Dhaka

Table 3 compares travel times on bicycles through the proposed BLN with the time required by car (taxicab or motorbike) and bus from node point 1 to other nodes on a typical working day. The travel times for cars and buses were estimated from Google Maps and found close to practical values. On the other hand, bicycle travelling time is almost constant all day; travel times for cars/buses are different by time period due to traffic conditions and other issues; therefore, the travel times are presented at 6 am, 10 am, and 4 pm for better realization. Travel by bus to visit a particular location may require several transits due to changing buses and may also require walking a short distance to catch the next bus. At a glance, travel time by bus is the accumulation of the actual travel time, transit time, and walking time to change terminals. The transit time may depend on the frequency of bus trips and available trips at the time, so that travel time by bus at 10 am, a busy office hour with very dense traffic but the highest frequency of buses, is less than at 6 am. Moreover, in several cases, bus routes are not available if marked with '-' in the table.

Table 3. Comparison of travel time using bicycle through the proposed BLN with time required by car (taxicab or motorbike) and bus from node point 1 to other nodes. '-' denotes unavailability of a bus.

Destination Node Point	Distance Using Motor Vehicle (km)	Time Required by Car, Taxicab or Motorbike (min)			Time Required by Bus			Travel by Bicycle through Proposed BLN	
		6 a.m.	10 a.m.	4 p.m.	6 a.m.	10 a.m.	4 p.m.	Distance (km)	Time (min)
2	8.6	18	39	36	62	56	61	8.6	30.7
3	8.9	19	42	39	65	60	65	9.8	34.4
4	7.1	14	33	30	53	50	53	8.3	29.9
5	5.2	12	27	26	38	37	38	7.5	27.5
6	7.6	15	36	36	48	41	48	8.2	29.6
7	7.2	14	34	35	48	41	48	6.9	25.7
8	5.1	11	24	24	32	31	32	7.6	27.7
9	3.6	9	18	15	38	32	36	3.9	16.7
10	4.2	10	20	18	42	35	40	5.4	18.2
11	6.1	12	30	30	41	36	41	7.6	33.5
12	4.2	9	23	23	27	25	27	5.3	20.9
13	4.1	10	24	21	31	29	31	6.2	23.6
14	2.5	5	12	11	21	16	21	4.4	18.2
15	3.2	8	18	18	26	23	26	4.1	17.2
16	3.2	8	27	33	39	34	37	4.5	18.5
17	6.4	13	33	30	52	47	52	8.1	29.3
18	7.2	14	53	48	82	74	82	7.8	28.4
19	3.0	8	21	18	43	37	42	4.1	17.3
20	11.0	24	42	38	64	56	64	6.2	23.6
21	3.9	9	36	36	40	35	38	5.5	21.5
22	8.3	18	33	30	61	56	61	10.3	35.9
23	2.5	6	21	21	30	25	30	3.6	10.8
24	5.1	12	28	27	47	39	44	7.2	26.5
25	5.7	13	29	27	48	42	47	8.1	29.3
26	4.7	11	29	29	-	-	-	4.9	19.7
27	6.4	15	34	32	33	27	32	6.3	23.9
28	5.8	12	42	39	-	-	-	7.9	28.7
29	5.4	12	33	33	72	63	71	5.2	23.3
Sum	156.2	341	841	803	1183	1047	1167	183.3	690.3

According to Table 3, bicycle travel time is competitive with that of cars and much less than by bus. A car takes the least time, at 6 am when traffic is lowest, to visit any place, but a bicycle takes the least time during office hours for the same distance. As an example, the travel distance to visit node 2 from node 1 is 8.6 km and travel time by car at 6 am, 10 am, and 4 pm are 18, 39, and 36 min, respectively. The route distance between node 1 and node 2 on the BLN is 8.6 km and the travel time on a bicycle is 30.7 min, which saves 21% more time than a car at the peak office hour, 10 am. For the same distance, a bus takes 56 min at 10 am, which is almost double that of a bicycle. The bottom of Table 3 shows the sums of the travel distances and required times to travel by bicycle and other vehicles. The total vehicle route distance is 156.2 km, and travel time at 10 am is 841 min by car. On the other hand, the total BLN distance is 183.3 km which is larger than vehicle distance, but total travel time is 690.3 min, which is much less than by car at office hours. Figure 5 illustrates the average travel speed by car, bus, and bicycle through the BLN, based on the data presented in Table 3. The average travel speed of the bicycle is 15.9 km/h, which is only inferior to a car at 6 am (i.e., 27.2 km/h), which is reasonable. At a glance, bicycle speed is almost double that of a bus at any time. Finally, results compared in Table 3 and Figure 5 clearly revealed the time-saving potential of using a bicycle in congested city areas.

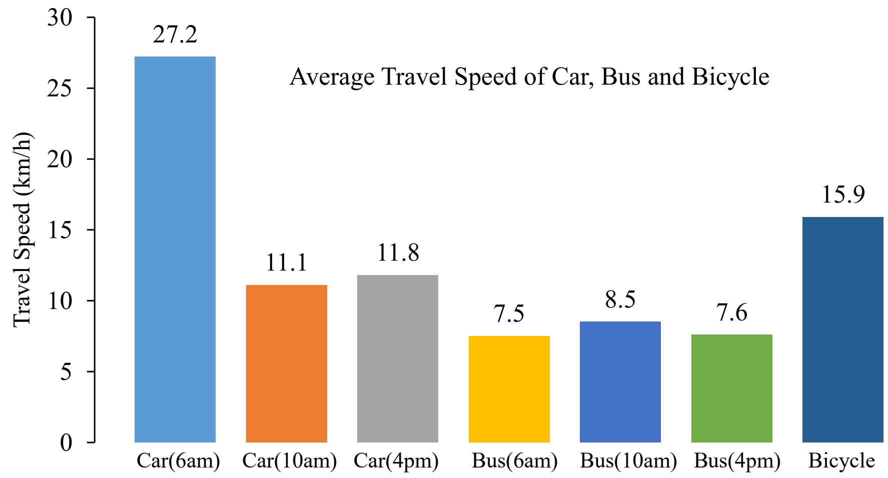

Figure 5. Comparison of bicycle speed on the BLN with car and bus at different times (6 am, 10 am and 4 pm) for the central Dhaka city area.

4.4. Test Case 2: BLN Design for Entire Dhaka City

A BLN for the entire Dhaka city area is promising, due to the heavy traffic in the whole city area. The entire Dhaka city area is around 28 km in the north–south direction and 17 km in the east–west direction. In such extended BLN (eBLN), a person may use an electric bicycle (eBike) instead of peddled bicycle for travelling long distances. Figure 6 shows the schematic road network of the entire Dhaka city from Google Maps marked with important locations. To keep similarity in program for the central area, the entire 29 locations are marked to connect through eBLN. Table 4 lists the pressures of individual nodes in the area. The pressure (p_i) is proportional to its population in that area. For example, Uttara model town is the biggest commercial and residential area of Dhaka city and holds the highest pressure at 10. A total of 89 linkages' parameters were prepared, similarly to test case 1.

4.4.1. BLN Design Solution for the Entire Dhaka City Area

Figure 7 depicts the proposed extended BLN (eBLN), in blue, for the entire Dhaka area bypassing the main roads as much as possible. The eBLN used small portions of main roads where it was necessary. To connect node 8 and node 9, the eBLN considers main road portions because the nodes are closed and connected through the main road link. It is also notable that the eBLN has alternate routes to connect most of the nodes, especially in the central areas.

Table 5 shows the optimal routes and corresponding distances as well as travel times from node 7 (central node) to other nodes on the basis of the proposed network shown in Figure 7. A node may be accessed using different routes and only the shortest one is placed in the table. For example, node 1 can be accessed using the routes 7-6-24-5-1, 7-6-4-26-5-1, 7-21-22-2-24-5-1, and so on; the shortest route 7-6-24-5-1, having a distance of 15.65 km, is shown in the table. The travel time is estimated considering an eBike speed of 30 km/h in the city area, although eBike speed can be 45 km/h on a free road [47]. From the table, the longest route is 22.0 km to visit node 29 from node 7 using route 7-9-28-18-29. The travel time of around 49.0 min seems acceptable for a healthy person using an eBike.

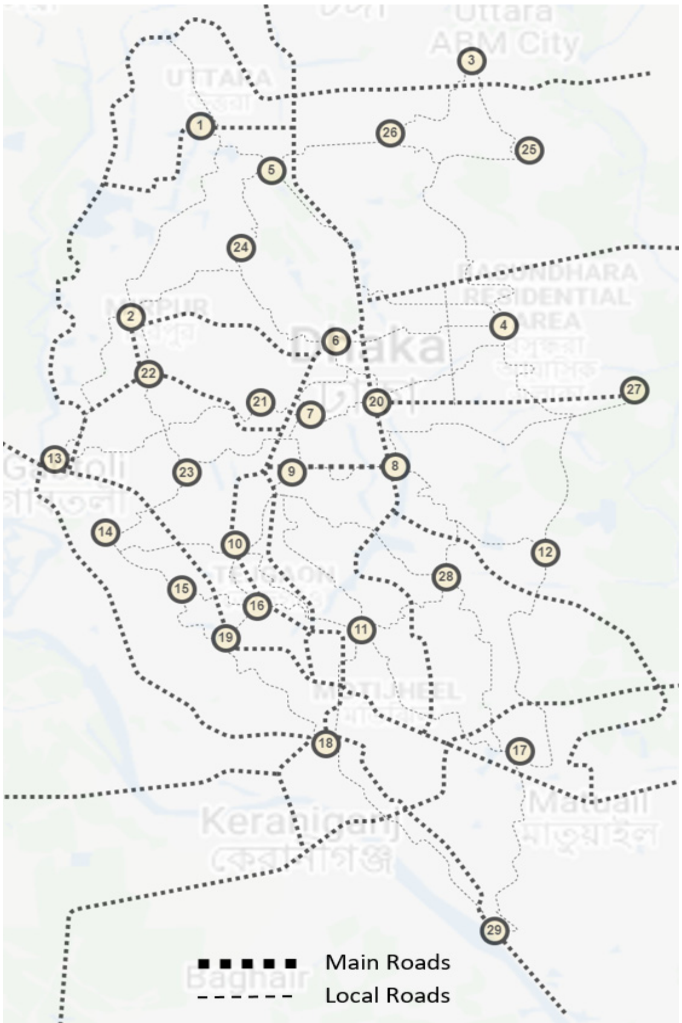

Figure 6. The schematic road network of the entire Dhaka city area with different location identification.

Table 4. The location-wise traffic pressure assignment for the entire Dhaka city area.

Sl	Location	Traffic Pressure	Sl	Location	Traffic Pressure
01	Uttara	10	16	Shahbag	3
02	Mirpur	8	17	Matuail	4
03	Uttara ABM City	5	18	Kotwali/Sadarghat	6
04	Bashundhara R/A	8	19	New Market	2
05	Khilkhet	5	20	Baridhara	4
06	Cantonment	4	21	Banani	5
07	Gulshan	5	22	Monipur	8
08	Badda	5	23	Sher-E-Bangla Nagar	7
09	Mohakhali	5	24	Airport	5
10	Tejgaon	5	25	Poradia	2
11	Motijheel	7	26	Madarbari	3
12	Khilgaon	9	27	Beraid	5
13	Gabtoli	6	28	NutanPara	4
14	Mohammadpur	10	29	Pagla Rail station	6
15	Dhanmondi	5			

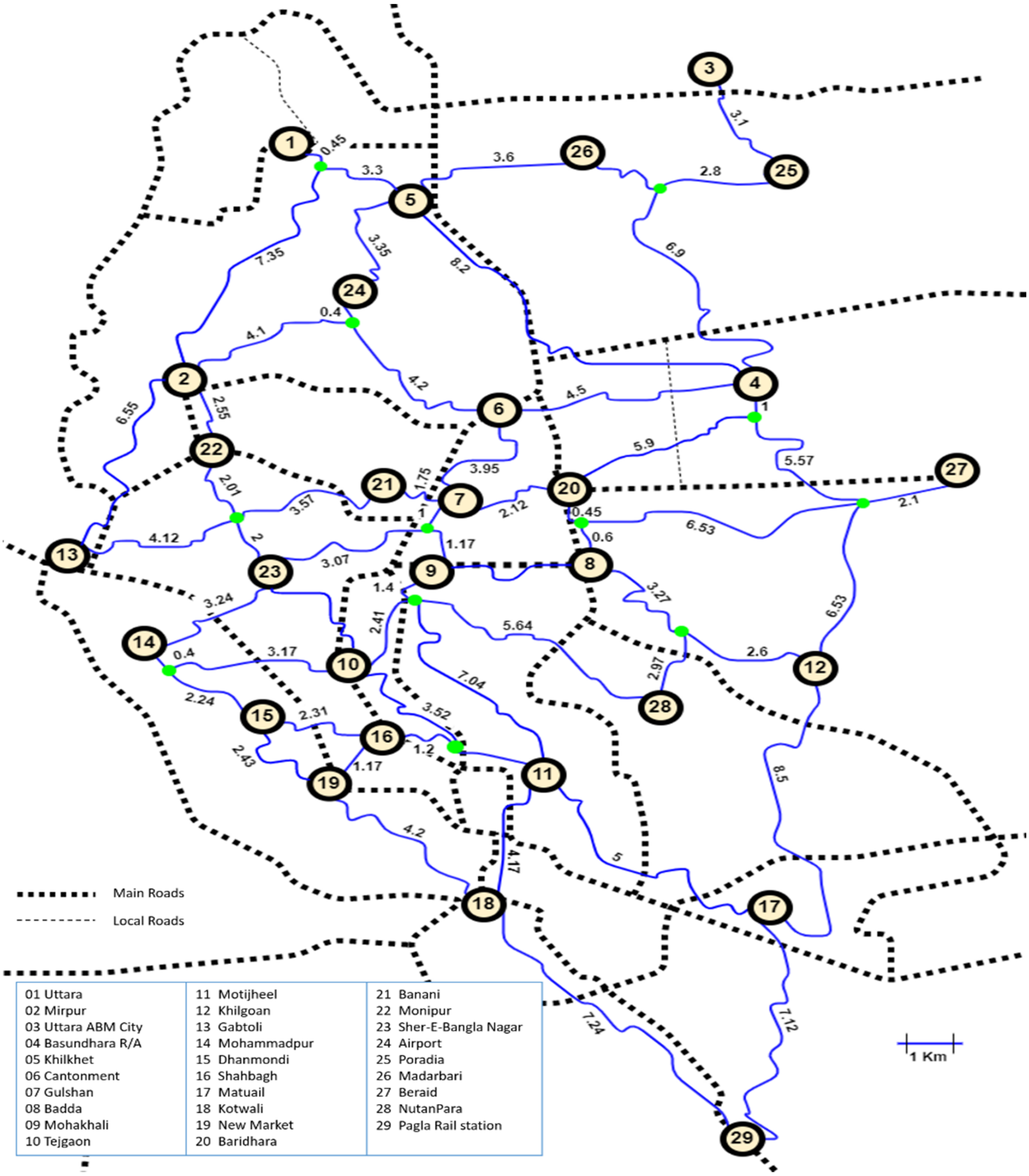

Figure 7. Proposed bicycle lane network (BLN) in the entire Dhaka city area depicted in blue. Numerical values in BLN links indicate corresponding link's length in km.

4.4.2. Effectiveness Measure of eBLN in the Entire Dhaka City Area

Table 6 compares travel time by eBike through the proposed eBLN with the time required by car and bus from node 7 to other nodes on a typical working day. The bottom of the table shows the sums of the travel distances and the required times to travel by eBike and other vehicles. The total vehicle route distance is 263.8 km, and the total eBLN route is 285.2 km; this indicates the eBLN route is close to the optimal route. About travel time, the eBLN is always more efficient by bus and also time-efficient than by car during office hours. At 10 am, the sum of travel time is 1163 min by car, and 1242 min for a bus without several nodes' data, due to the unavailability of a bus. On the other hand, the total travel time by eBike is 681.3 min all day long. Figure 8 illustrates the average travel speed by car, bus, and eBike through the eBLN, based on the data presented in Table 6. The average travel speed by eBike is 24.6 km/h, which is only inferior to the car at 6 am (i.e., 30.9 km/h), which is logical. At a glance, eBike speed is more than double that of a bus for any time. Finally, results are compared in Table 6, and Figure 8 clearly revealed the time savings of using an eBike in the entire Dhaka city area through the proposed eBLN.

Table 5. Optimal bicycle routes, distance and estimated travel time from node point 7 (central point) to different node points through the extended BLN (eBLN).

Destination Node Point	Optimal Routes	Distance (km)	Estimated Travel Time (min)
1	7-6-24-5-1	15.7	36.3
2	7-21-22-2	9.9	24.8
3	7-20-4-25-3	21.8	48.6
4	7-20-4	9.0	23.0
5	7-6-24-5	11.9	28.8
6	7-6	4.0	7.9
8	7-20-8	3.2	6.3
9	7-9	2.2	9.3
10	7-9-10	6.0	17.0
11	7-9-11	10.6	26.2
12	7-20-8-12	9.0	18.1
13	7-21-13	9.4	23.9
14	7-23-14	7.3	19.6
15	7-9-10-15	11.6	28.1
16	7-9-10-16	10.7	26.4
17	7-9-11-17	15.6	36.2
18	7-9-11-18	14.8	34.6
19	7-9-10-16-19	11.9	24.7
20	7-20	2.1	4.2
21	7-21	1.8	8.5
22	7-21-22	7.3	19.7
23	7-23	4.1	13.1
24	7-6-24	8.6	22.1
25	7-20-4-25	18.7	42.4
26	7-6-24-5-26	15.5	36.0
27	7-20-27	11.2	22.4
28	7-9-28	9.4	23.8
29	7-9-11-18-29	22.0	49.0

4.5. Environmental Impacts of a BLN on Dhaka City

Travelling by bicycle through a BLN will not only save time in congested Dhaka city areas, but will also provide other benefits, such as reduced transportation cos, as well as health and environmental benefits. The proposed BLN will aid in CO_2 emissions reduction in Dhaka city in different modes. In addition, a certain percentage of people might use a bicycle for regular daily activity for short distances, even if they can afford a car, when they feel the bicycle ride is comfortable on a well-organized BLN. Many motorbike users might switch to a bicycle or eBike for similar travel performances with better safety and cost-benefits. Although it is difficult to estimate the reduction in car numbers by introducing a bicycle lane, a BLN/eBLN for Dhaka city will be helpful to limit fuel consumption and CO_2 emissions.

Table 6. Comparison of travel time using eBike through the proposed eBLN with time required by car, taxicab or motorbike and bus from node point 7 to other nodes for the entire Dhaka city area. '-' denotes unavailability of bus.

Destination Node Point	Distance Using Motor Vehicle (km)	Time Required by Car, Taxicab or Motorbike (min)			Time Required by Bus			Travel by eBike through Proposed eBLN	
		6 a.m.	10 a.m.	4 p.m.	6 a.m.	10 a.m.	4 p.m.	Distance (km)	Time (min)
1	14.0	24	42	45	79	74	78	15.7	36.3
2	7.5	16	33	36	52	47	52	9.9	24.8
3	18.2	40	75	75	-	-	-	21.8	48.6
4	10.2	22	42	36	-	-	-	9.0	23.0
5	8.7	12	24	24	50	45	49	11.9	28.8
6	4.0	7	21	20	41	33	40	4.0	7.9
8	4.7	8	30	27	40	35	37	3.2	6.3
9	3.5	7	24	22	41	36	41	2.2	9.3
10	5.5	10	25	24	44	38	43	6.0	17.0
11	9.1	18	45	42	73	60	65	10.6	26.2
12	12.0	40	60	57	79	76	79	9.0	18.1
13	9.7	22	44	45	71	60	65	9.4	23.9
14	8.3	14	36	33	57	47	52	7.3	19.6
15	8.7	16	33	36	64	57	62	11.6	28.1
16	8.0	16	39	39	57	52	57	10.7	26.4
17	16.6	30	63	60	111	101	107	15.6	36.2
18	11.4	24	62	60	76	68	73	14.8	34.6
19	8.7	18	42	42	62	55	60	11.9	24.7
20	2.2	5	12	11	28	26	27	2.1	4.2
21	2.3	5	17	15	-	-	-	1.8	8.5
22	6.8	20	36	33	58	53	58	7.3	19.7
23	6.6	12	24	23	52	48	51	4.1	13.1
24	8.7	12	24	24	52	47	52	8.6	22.1
25	15.9	30	68	71	-	-	-	18.7	42.4
26	14.7	30	63	60	-	-	-	15.5	36.0
27	8.5	14	36	33	-	-	-	11.2	22.4
28	10.2	24	63	60	78	75	78	9.4	23.8
29	19.1	35	80	75	119	109	-	22.0	49.0
Sum	263.8	531	1163	1128	1384	1242	1226	285.2	681.3

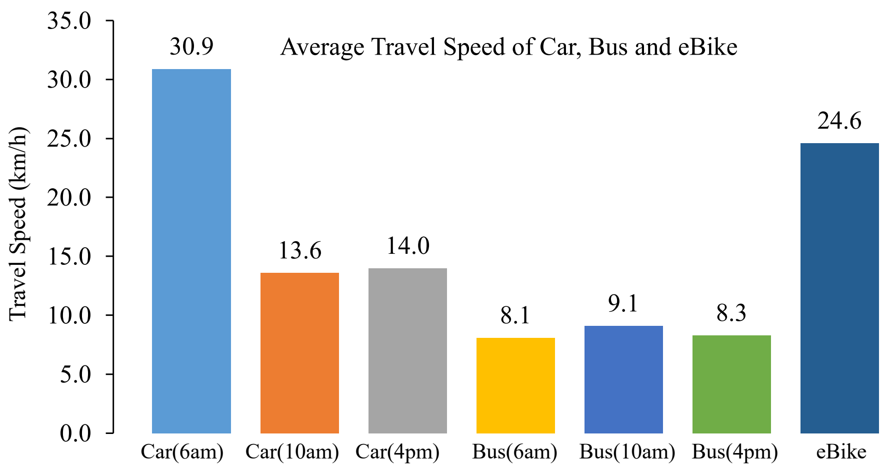

Figure 8. Comparison of eBike speed on the eBLN with car and bus at different times (6 am, 10 am and 4 pm) for the entire Dhaka city area.

5. Discussion

The present study's contributions are two-fold; one, the introduction of Physarum foraging behavior to BLN design that considerers the constraints of a megacity, and two, the implications of the proposed model for Dhaka city, a real-life congested megacity with poor mobility. In this section, we discuss the computational efficiency of the proposed Physarum-inspired method over other bioinspired methods, its ability to obtain the optimal BLN, and improvement in green mobility with BLN by comparing it with existing transport.

Physarum directly represents a single naturally growing network, and in the proposed Physarum-inspired method, a single BLN solution is computed gradually through a simple iterative process. In contrast, the widely used bioinspired population-based methods (e.g., particle swarm optimization, genetic algorithm) require evaluating all the individuals (may be hundreds) in the population, interactions among them, all while updating throughout the iterative process. Therefore, Physarum's method is computationally much more efficient than these other bioinspired methods [48]. This is the motivation behind the Physarum-inspired model development for BLN design—the pursuit of computational simplicity and efficiency.

The developed Physarum-inspired BLN design method was applied to the megacity Dhaka and evaluated the designed BLN. We have compared the optimality under given constraints of its individual routes by taking the samples as described in Section 4.3.1 (BLN for the Central Dhaka area) and Section 4.4.1 (BLN for the entire Dhaka area). Specifically, we verified whether there is a better and/or less costly route for any sample route connecting two arbitrary nodes given in the designed BLNs. In this way, we have confirmed that other (unselected) routes are non-optimal (in terms of travel distance, avoiding main roads). Any other optimization method (if developed) is expected to choose the same optimal routes that our method has selected.

Finally, we have compared the designed BLNs with other modes of transport to verify green mobility by application to Dhaka city. Dhaka is the most congested megacity, with poor mobility from existing transport. The designed BLN was evaluated by comparing its available routes between different locations with the existing vehicle routes of the city in terms of required travel times during different time periods. The BLN routes were found to be suitable alternatives to congested main roads. The expected travel time using BLN is shorter than with other transport (e.g., car and public bus); at a glance, the average travel speed on BLN is almost double that of a public bus at peak hours. Such empirical outcomes justify the optimality of the designed BLN and hence ensures the proposed method's rationality, benefit and efficiency.

6. Conclusions

This paper presented a BLN design to promote green mobility in a congested megacity, employing a bioinspired Physarum method. Taking into consideration existing local routes and avoiding main roads as much as possible in the design of the BLN, the mathematical model of Physarum has been adapted for the case of a congested megacity. The proposed model is applied in designing two BLNs for the megacity Dhaka, which is considered one of the most congested cities in the world. The first BLN is designed for the most congested and busy central city area. The second BLN is designed for the extended area covering the entire Dhaka city, suitable for eBikes given longer travel distances. The proposed BLNs are shown overlain existing networks (Figures 4 and 7); optimal BLN routes for a given node from a reference node, with distance and estimated travel time, are tabulated (Tables 2 and 5) accordingly. Since the proposed BLNs considered mostly local routes, the travel distances between different nodes on the proposed BLNs are often longer than vehicle routes, which is logical and acceptable. On the other hand, the effectiveness of the proposed BLNs is clearly revealed (Tables 3 and 6) when travel time required on the BLNs is compared with the time required by a car, taxicab, and public bus to travel from reference nodes to other nodes. Finally, the average travel speed, using proposed BLNs, is found economical in terms of mileage, time, and cost compared with public transport (e.g., bus) and is almost its double in peak hours (Figures 5 and 8).

Unlike traditional network design approaches that usually consider the shortest routes, the proposed method has obtained both BLNs by avoiding main roads as much as possible. Hence, the proposed BLNs ensure no interference to the city's mainstream traffic. Although

BLNs mainly use the local roads, taking slightly longer travel distance in some cases, the travel time using a bicycle/eBike is found shorter than both public and private transport. The proposed Physarum-based algorithm accomplished efficient identification of highly desirable features in its BLNs of a megacity. As BLNs provide the most cost-effective means to promote green and healthy mobility in a congested megacity, it is expected that many users will choose to use the bicycle as alternative transit, to shorten their travel and to contribute to shifting the transportation paradigm of their city. However, the actual implication of the proposed BLNs requires an administrative decision by city authority; thus, real networks, as well as their performance, may deviate due to practical constraints. On the other hand, the city authority may provide better BLN options, undertaking small–medium construction to enhance its design and exploit its benefits further.

The current work leads to several research directions from motivational outcomes and limitations of this Physarum-inspired study. This study will be encouraging for designing BLNs to promote green mobility in other congested megacities with sustaining constraints. Bicycle parking spaces and some other relevant options should be adopted with a BLN design for better practical prospects, which have not been considered in the present study. For the megacities having organized public transport services (e.g., metro, rapid bus transit), green mobility approaches integrating BLN with public transport services might be attractive, as well as more effective. Moreover, the modifications introduced to the Physarum-inspired method in this study can open new ways of solving other complex real-world network design problems, such as water distribution networks.

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