

Replacement of Signalized Traffic Network Design with Hamiltonian Roads: Delay? Nevermind

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Abstract

Signal optimisation is essential in traffic engineering. The traffic light control timings should be set as optimum. However, it is challenging because the traffic network is a non-polynomial problem. In this study, the problem is evaluated from a unique perspective. The primary idea is to remove the crossings of the intersections. A Hamiltonian cycle algorithm has been used to design the network. So, vehicles are only able to join or split. Thus, no control mechanism is needed that delays or interrupts the flow. The suggested algorithm and intersection design were tested on Allsop and Charlesworth's widely used sample network. Findings were compared with the literature in the form of delay calculated using the Highway Capacity Manual 2010 formula. The suggested network's delay is calculated to be 98.17% and 95.45% less than the original network and recently published study-based delay, respectively. As a result, Hamiltonian roads seem sustainable in time and fuel consumption and could be used for future designs.

Article Highlights

- The need for signalised intersections is eliminated
- Average delay is decreased up to 98.17% although creating detour
- Novel algorithm is presented in the study to design the network

1. Introduction

With an increment in the population, the city's living areas are expanding, and the number of vehicles is growing (Metz, 2012). It results in building more roads where more intersections occur. The existing network performance must be optimised to meet the additional demand. Since there is no more space left to expand the traffic network in some developed capitals or the construction costs are high, optimising the existing network performance comes to mind as the first solution. Here the intersections are among the critical geometric parts of the urban transportation network because of the crossing of the roads. If no control mechanism applies to these critical parts, conflict points occur. However, a control mechanism causes delays at intersections since the solution of traffic light timings is a non-polynomial (NP) problem. In addition, it is challenging to optimise the green durations. Many studies exist about traffic signal optimisation to solve this problem (Inoue et al. 2021; Yue et al. 2021; Jovanović and Teodorović, 2021; Lian et al. 2021; Li et al. 2022; Wang et al. 2022; Zhang et al. 2022). As can be seen from the literature, the optimisation problem is still an important subject of interest.

1.1. Background of Problem

A study made in 2007 showed that an average of 101 minutes –about 7% of the day – spend by an American a day while driving (Harvard Medical School, 2007). Another study for Europe was made by Pasaoglu Kilanc et al. (2012), revealed that an average of varying between 1 to 2 hours per day for France, Germany, Italy, Poland, Spain, and the United Kingdom –between 4.2% and 8.3% of the day – is spent by people on driving. Alone in the US, considering that about 228,000,000 (FHWA, 2019) people are

licensed drivers and spend 101 minutes daily, it would make 383,800,000 person-hour per day while driving. This would cause 43812.79 person-year per day. When the recent gross national income (GNI) per capita in purchasing power parity (PPP) is considered for the US, which is \$66080 (World Bank, 2019), \$2,895,000,000 PPP per day get lost while driving. This tremendous amount of income gets lost and could be saved by decreasing travel time, which is the aim of this study to decrease delays.

The time spent does not just pass while driving. Drivers encounter delays besides driving in different locations. One is intersections, where the delay is formed because of queuing, stopping, approaching, and departing. Chiou (2016) states that most travel time delays depend on signal control at intersections. Studies are trying to minimise the delay at the signalised intersections and achieve promising results, such as a decrease of 20% (Ghanbarikarekani et al. 2018) in personal delay. Priemer and Friedrich (2009) saved up to 36% of the delay, while Lee et al. (2013) saved up to 34%. Jamal et al. (2020) saved 15–35% travel time delay in their study. The reduction in delay time dramatically impacts the total travel time. However, more studies are exploring whether there are more suitable solutions, as mentioned above. Some studies also investigate a macroscopic model for urban traffic network design (Thonhofer et al. 2018). However, they still used traffic signals, the primary cause of the traffic delay.

1.2. Solution Proposal and Basis

In this study, it is suggested to reform the intersections in a way where no crossing occurs, only joining and splitting. So, no vehicle needs to stop at the intersection, and no queues would be formed because of the red times. The motivation for this study is based on two different studies: Nash equilibrium (Nash, 1950) and Braess's paradox (Braess, 1968). Braess (1968) defined a paradox about increasing the counts of the links on the network as only sometimes the best solution where the total travel time increases, which was aimed to decrease, for the entire network. Building new roads is not always the best solution because of the selfish rerouting decisions made by the drivers to decrease the total cost. However, the numerical analysis shows that it is not the case based on the paradox. A recently published paper (Po et al., 2021) shows that selfish routing degrades the efficiency of the entire network while only a low rate of selfish drivers achieves their aim. A big part of the drivers takes the selfish decisions futilely. Studies published by Spana and Du (2022) aim to reduce network congestion caused by selfish routing decisions. Compliant drivers' travel time increases because of the selfish decisions made. Nash (1950) explained that there is an equilibrium in every finite game in which all players get the optimum payoffs for the game based on the decisions of the other players. Here, the finite game is the traffic network, players are the drivers, and payoffs are the travel costs and travel time in this study. However, the Nash equilibrium is problematic if the drivers are free to reroute. So, redesigning the network in a way where drivers have fewer choices would provide a significant benefit.

Some studies use graph theory for the traffic network to find the shortest path (Guze, 2014; Fan et al. 2020). However, redesigning the whole traffic network using graph theory is new. Here, the Hamiltonian cycle redesigns the network where possible selfish decisions are decreased to near zero or eliminated. Using the Hamiltonian cycle for redesigning the urban network would eliminate the conflict points of the intersections. Therefore, there would not be any intersection control needed. Especially the traffic lights

could be removed, and the delays and queues could be eliminated. Vehicles would no longer stop at an intersection because of the control system, and fuel consumption could be less. Traffic would flow at a uniform speed, and safety would be increased.

In this study, vehicle delay is examined in a well-known and widely used sample network supplied by Allsop and Charlesworth (1977), see also (Ceylan and Bell, 2005; Ceylan, 2013; Dell’Orco et al. 2013; Ozan et al. 2015; Chiou, 2017; Papatzikou and Stathopoulos, 2018; Chiou, 2019a; Chiou, 2019b; Baskan et al. 2019). The network is transformed into a Hamiltonian cycle, and the shortest path is determined using convenient algorithms. The delay that occurred has been calculated. Determined delay results are compared with the literature results, and the results are promising.

In the following section, the traditional and suggested intersection design has been explained. After suggesting the novel intersection design, the algorithm’s theory was given. The base of the algorithm is graph theory. The flowchart and pseudo code of the algorithm are available in the corresponding section. After developing the algorithm, a test network was determined. The network details have been given in the following section. Next, the comparison method and calculation of the values have been explained. Once the developed algorithm runs on the test network, the outputs and the results obtained from the literature are given in the Results and Discussion section. Finally, the last section gives a brief conclusion of the developed algorithm and the gains.

2. Intersection Design

Traditionally, intersections are designed so that two or more roads cross each other (Fig. 1). Thus, part of the traffic flows is expected to pass through each other in a small area while the rest joins. This creates conflict points (Özinal and Uz, 2021; Wu et al. 2022). Control mechanisms, such as traffic signs and lights, are used to overcome the problem. Traffic lights are the preferred control type because they show precisely which flow is in order. However, as mentioned above, they create delays that are still relevant today as a research topic. Another solution is to build multi-level intersections where no flow crosses the other. However, they are costly and need more space. This study suggests reforming the intersection design where no crossing occurs (Fig. 2). Figure 2 is a sample intersection where the North-South route is the main road. The main road will be transformed into a Hamiltonian cycle, explained in the next section. The East-West route is the secondary road of the network. It can be designed as a one-way, as seen in Fig. 2 or a two-way road based on the needs of the network.

3. Algorithm’s Theory

The algorithm developed in this study is based on a Hamiltonian cycle algorithm. A hamiltonian cycle is a variety of graphs. A graph, usually named G , is formed using the (V, E) pairs, where V defines the set of vertices, defined as nodes during this part of the study, while the edges are defined by E . In our study, the edges are the paths between the intersections, and the nodes are the intersections. When a traveller

moves along the graph and visits each node exact once, it is called a Hamiltonian path. Also, a Hamiltonian path ends at the starting point while travelling each other only once.

Moreover, the graph is called the Hamiltonian cycle when the starting node is also the ending node. Since no intersections are desired, a traveller cannot use the same path to return. Thus, it is necessary to provide access from each origin point to each destination in a Hamiltonian cycle. The note is that all nodes will be covered, but the route can go through some edges. In brief, the Hamiltonian cycle ends where it starts and goes through each node, that is, the intersection in this study, making it a convenient methodological choice.

The origin-destination (O-D) matrix must be initialised based on the developed algorithm. A graph is formed based on the initialised matrix. Then, the algorithm generates possible paths in the given graph and checks whether each node has been visited or not. When all nodes are visited, the Hamiltonian cycle has been determined. Since no crossing is desired on the network, the flow should follow only one direction, and the opposite directions should be eliminated. Therefore, the elements of the matrix, which define the opposite directions, are changed to zeros. Thus, the second part of the developed algorithm uses only one direction and calculates the travel times. The general flow of the developed algorithm is given in Fig. 3, and the algorithm's pseudo-code is shown in Fig. 4.

4. Allsop And Charlesworth's (1977) Network

Allsop and Charlesworth's (1977) test network is considered a numerical example since it has been used widely (Papatzikou and Stathopoulos, 2018; Chiou, 2019b; Baskan et al. 2019) to concern the network outputs. Thus, the readers can compare this study's results with those from previous studies and future studies. The network is shown in Fig. 5. The test network has 23 links (edges). The cruise travel times and the saturation flow rates for the network links are given in Table 1. Saturation flow rate is the max vehicle count that could pass through a section of the road in an hour, shown as veh/h. The O-D demand matrix is given in Table 2.

Table 1
Cruise travel times and saturation flow rates of the links

Intersection No	Link No	Cruise Travel Time, s	Saturation Flow, veh/h
1	1	0*	2000
	2	0*	1600
	16	10	2900
	19	10	1500
2	3	10	3200
	15	15	2600
	23	15	3200
3	4	15	3200
	14	20	3200
	20	0*	2800
4	5	20	1800
	6	20	1850
	10	10	2200
	11	0*	2000
	12	0*	1800
	13	0*	2200
5	8	15	1850
	9	15	1700
	17	10	1700
	21	15	3200
6	7	10	1800
	18	15	1700
	22	0*	3600
*Cruise travel times of links between O-D points and intersections have been accepted as 0 since some links are not given.			

Table 2
O-D demand matrix (veh/h)

O-D	A	B	D	E	F	Total
A	0	250	700	30	200	1180
C	40	20	200	130	900	1290
D	400	250	0	50	100	800
E	300	130	30	0	20	480
G	550	450	170	60	20	1250
Total	1290	1100	1100	270	1240	5000

Allsop and Charlesworth's (1977) network can be modelled as an undirected graph. Here, the graph is formed between the intersections since the distance between O-D points and intersections is zero (Fig. 6). The O-D points are associated with the connected intersection. So, the O-D points A, B, C, F, and G are associated with 1, 2, 3, 5, and 6, respectively. Because the fourth intersection connects two O-D points, both are associated with the fourth intersection.

The graph in Fig. 6 comprises six nodes (vertices) and eight edges and is formulated using Eq. 1.

$$G=(V,E)$$

1

$$V=\{v_1,v_2,v_3,v_4,v_5,v_6\}$$

2

$$E=\{e(1,2),e(1,6),e(2,3),e(2,6),e(3,4),e(3,5),e(4,5),e(5,6)\}$$

3

Each vertex v_i in the V set stands for an origin or destination node, and each edge $e(i,j)$ in the E set stands for a weighted edge between the O-D nodes. The weight may be the distance or travel time and a function based on these two parameters between the O-D pairs. The weights for each edge are shown in Fig. 6 as the travel times. Based on Fig. 6, the connection matrix has been figured out as $D_{connect}$. Here, the matrix is a 6×6 size square matrix where each column stands for the destination point, and each row stands for the origin. The matrix elements consist of ones indicating a connection between O-D nodes and zeros indicating that there is no connection.

$$D_{\text{connect}} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 1 & 0 & 0 & 1 & 0 \end{bmatrix}$$

Based on the multiplication of weights and D_{connect} matrix, the input matrix could be figured out as D_{input} .

$$D_{\text{input}} = \begin{bmatrix} 0 & 10 & 0 & 0 & 0 & 10 \\ 10 & 0 & 15 & 0 & 0 & 15 \\ 0 & 15 & 0 & 20 & 15 & 0 \\ 0 & 0 & 20 & 0 & 15 & 0 \\ 0 & 0 & 15 & 10 & 0 & 15 \\ 10 & 15 & 0 & 0 & 15 & 0 \end{bmatrix}$$

When the D_{input} matrix is given to be solved with the Hamiltonian cycle algorithm, the network's matrix is obtained as D_{output} .

$$D_{\text{output}} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 10 \\ 10 & 0 & 0 & 0 & 0 & 15 \\ 0 & 15 & 0 & 0 & 15 & 0 \\ 0 & 0 & 20 & 0 & 0 & 0 \\ 0 & 0 & 15 & 15 & 0 & 0 \\ 0 & 15 & 0 & 0 & 15 & 0 \end{bmatrix}$$

As seen in the D_{output} matrix, the algorithm has created a Hamiltonian cycle for the given network. Based on the cycle properties, the algorithm closed the road sections that allow moving in the opposite direction by changing the corresponding matrix elements to zero. Now, using the D_{output} matrix as input for the shortest path algorithm, the routes for the travellers are obtained. The final network obtained from the Hamiltonian cycle algorithm is shown in Fig. 7.

It is implicitly assumed in Fig. 7 that the O-D points are structures that allow U-turns. Further, $e(2,6)$ and $e(3,5)$ are two-direction edges, but the algorithm never used the opposite direction, as shown in Fig. 7. So, they are shown in one direction. Based on Fig. 7, every travel demand has been met.

5. Comparison

This study suggests a novel approach where traditional traffic network design is replaced with an algorithm where no crossing occurs at the intersections. Based on the suggested algorithm's output,

some travel demands to lengthen the routes. However, since there were no more crossings at the intersections, the safety of the network increased, and the total travel time for the whole network decreased. Therefore, some promising delay results found in the literature are compared with the output of this study. First, the travel time was calculated for each demand by accepting that no control mechanism prevents the traffic flow and that each driver chooses the shortest route. The calculated travel time is the minimum travel time ($t_{\min}$). Second, the travel time was calculated, where each driver chose the best feasible route based on the algorithm's output. The suggested approach's calculated travel time is the total (t_{total}). The difference between the total and minimum travel time is the delay (Δt) because of the network design. Last, delay (d) was calculated using the delay formula (Eq. 4) of Highway Capacity Manual 2010 (HCM2010) (Transportation Research Board, 2010) with the signal parameters found in the literature, which offer promising results. Finally, the comparison flow is graphically represented in Fig. 8.

The travel time for each demand has been calculated by neglecting the intersections, other demands, and the properties of the roads. Each driver chooses the shortest path to their destination. Then, all travel times for each demand are added and divided by the count of total vehicle demand. This is shown as $t_{\min}$, and it is the time when the drivers need to arrive at their destination. Total travel time has been calculated on the output routes of the algorithm suggested in this study and shown as t_{total} . This time is the sum of the $t_{\min}$ and the delay because of the network design. So, the delay in the suggested network can be obtained when the difference between t_{total} and $t_{\min}$ has been calculated. Some results found in the literature are investigated to show the benefits of the suggested network. The signal timing results of the previous studies are used to calculate the delay because of the control mechanism using the delay formula suggested in HCM2010 (Eq. 4).

$$d=d_1+d_2+d_3$$

4

Equation 4 is adopted from Eq. 18–19 in HCM2010 (Transportation Research Board, 2010), where d is the control delay, which is seconds per vehicle (s/veh), d_1 is the uniform delay (s/veh), d_2 is the incremental delay (s/veh), and d_3 is the initial queue delay (s/veh). Since no initial queue is present, d_3 is taken as zero for this study. The uniform delay and the incremental delay formulas are adopted from Equations 18–20 (Eqs. 5) and 18–45 (Eq. 6), respectively.

$$d_1 = \frac{0.5C(1-\frac{g}{C})^2}{1-[\min(1, X) \frac{g}{C}]}$$

5

$$d_2 = 900 T \left[(X-1) + \sqrt{(X-1)^2 + \frac{8 k I X}{c T}} \right]$$

where C is the cycle time in seconds which is the time between the start of the green time of the traffic signal of consecutive phases (s), g is the green time in seconds which is the time when the vehicles are allowed to pass the traffic light (s), X is the volume (vehicles count passing in an hour) to capacity (maximum allowable vehicles count which can pass in an hour) ratio, T is the analysis period duration, say one hour (h), k is the incremental delay factor, and I is the upstream filtering adjustment factor.

6. Results And Discussion

Some of the good signal timings found in the previous studies are used to calculate the delay and compared with the delay of the suggested network in Table 3. The suggested algorithm output has been given as “This Study”.

Table 3
Comparison of the delay results with some previous studies

Reference	Calculated Delay, s/veh	Difference to Allsop and Charlesworth's (1977) Network, %	Difference to this study, %
Allsop and Charlesworth (1977)	1110,99	-	+ 5364.78
Chiou (2017)	914.64	-17.67	+ 4398.97
Baskan et al. (2019)	763,71	-31.26	+ 3656.57
Chiou (2019)	587.29	-47.14	+ 2788.79
This study	20.33	-98.17	-

As seen in Table 3, the suggested algorithm-generated network has a delay value of 20.33 s, which is 98.17% less than the delay value calculated using the original study parameters. The delay value calculated using the original study's signal parameters is high because some of the links exceed their capacity, which is calculated using the green and cycle times. However, no control mechanism is present in the suggested network, so no traffic signals are needed. Thus, the green-to-cycle ratio can be taken as one because no vehicle stops and the saturation flow rate increases. In addition to the time gained in delay, drivers' average travel distances were increased. Since the output route has almost no option for the drivers, the route length has been increased. However, the detour on the designed route still creates almost no delay compared to the design with intersections.

The recently published study by Chiou (2019) showed that the average delay time was 587.29 seconds per vehicle. This is because the intersections are in over-saturated conditions. Compared to the one of the promising result of the literature, this study decreases the average delay per vehicle by about 96.54%. In addition, the calculated delay for this study is generated because of the detouring. So, detouring the vehicles generates about 20 seconds of average delay per vehicle. The whole network with a control

mechanism with optimised signal timings generates about 590 seconds. It should also be taken into account that the average detouring is about 90% of the average travel distance.

7. Conclusion

By bringing a different perspective, the advantages gained by removing intersections from the traffic transportation network were evaluated with an innovative approach. The network has been designed using graph theory, namely Hamiltonian cycles. Thus, the need for control mechanisms has been removed by eliminating the crossing at intersections. An algorithm has been developed to design the network. A well-known network (Allsop and Charlesworth, 1977) has been used to test the algorithm. The network is redesigned using the suggested algorithm given in the manuscript. Afterwards, the delay was calculated and compared with some previous studies. The following conclusions could be drawn from this study.

- Redesigning the intersections in a way where no crossing occurs significantly benefits the entire network. The signal controls caused a significant amount of delay on the original network.
- The Hamiltonian cycle helps design the traffic network since it allows each driver to arrive at their destination—however, the travel distance increases, which should be investigated in detail in future studies.
- The calculated delay is 98.17% less than the original study (Allsop and Charlesworth, 1977) and 96.54% less than a recently published study (Chiou, 2019).
- Based on the World Bank (2019) data given in the Introduction section, considering that per capita works eight hours a day, about \$17915 per hour would be saved. The daily economic gain is tremendous, decreasing the average delay per vehicle from about 590 to about 20 seconds.

7.1. Limitations and Future Work

Redesigning the network using the Hamiltonian cycle seems meaningful, where the average travel distance increases while the delay decreases. Thus, the total travel time decreases. However, the traffic network used in this study is a small one. Nevertheless, based on the extraordinary gains for a small network, it is expected that a more remarkable outcome would be obtained. The suggested algorithm should be investigated in a more extensive network for future studies. As well the travel distance increase would be an exciting topic.

Moreover, people could give up using their vehicles for short distances because of detours. As a result, society may be encouraged to use transport such as public or bicycles rather than personal vehicles. Thus, a significant output in terms of sustainability would also be achieved. These topics could be investigated and would significantly benefit urban transportation planning. Last, the output of the proposed algorithm could be used as input design for a simulation tool in future studies.

Declarations

Ethical Approval: This article does not contain any studies with human participants performed by any of the authors.

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Conflicts of interest/Competing interests The authors report that no potential competing interest.

Informed consent Informed consent was obtained from all individual participants included in the study.

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Figures

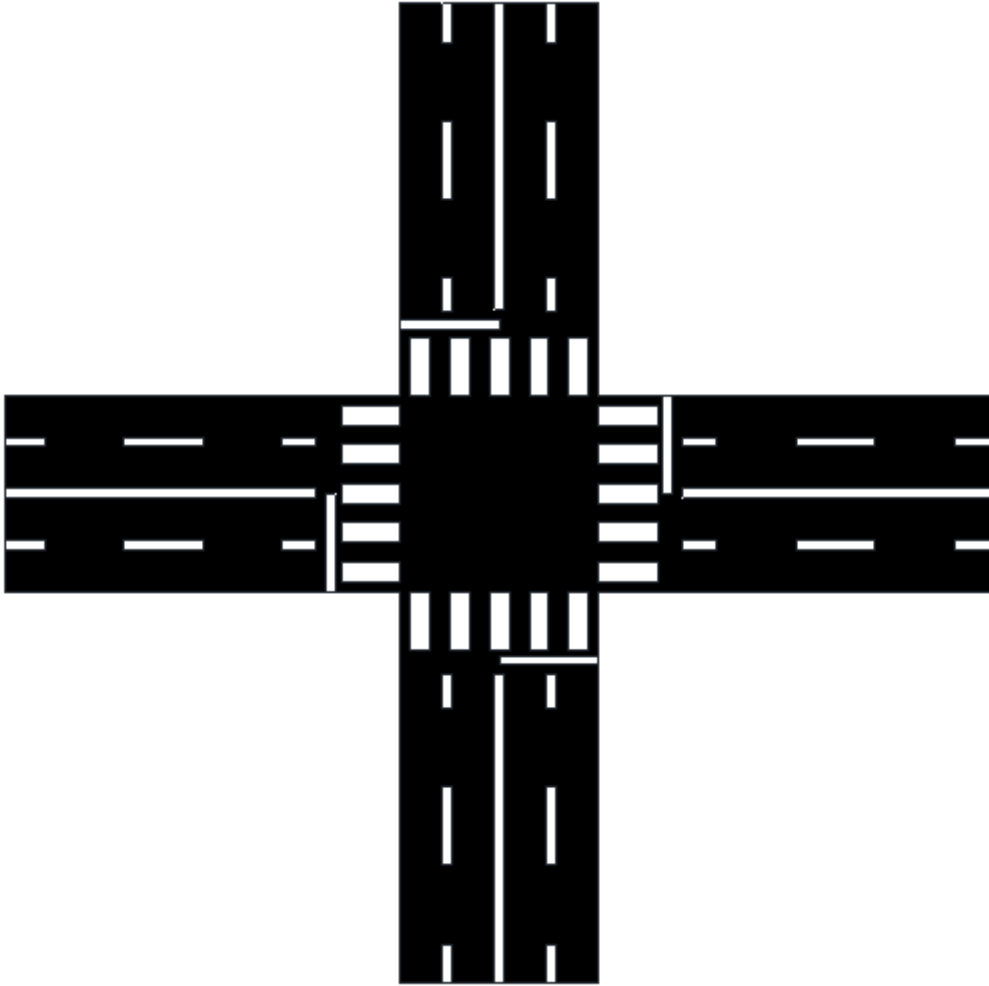


Figure 1

A standard four 4-lane roads intersection

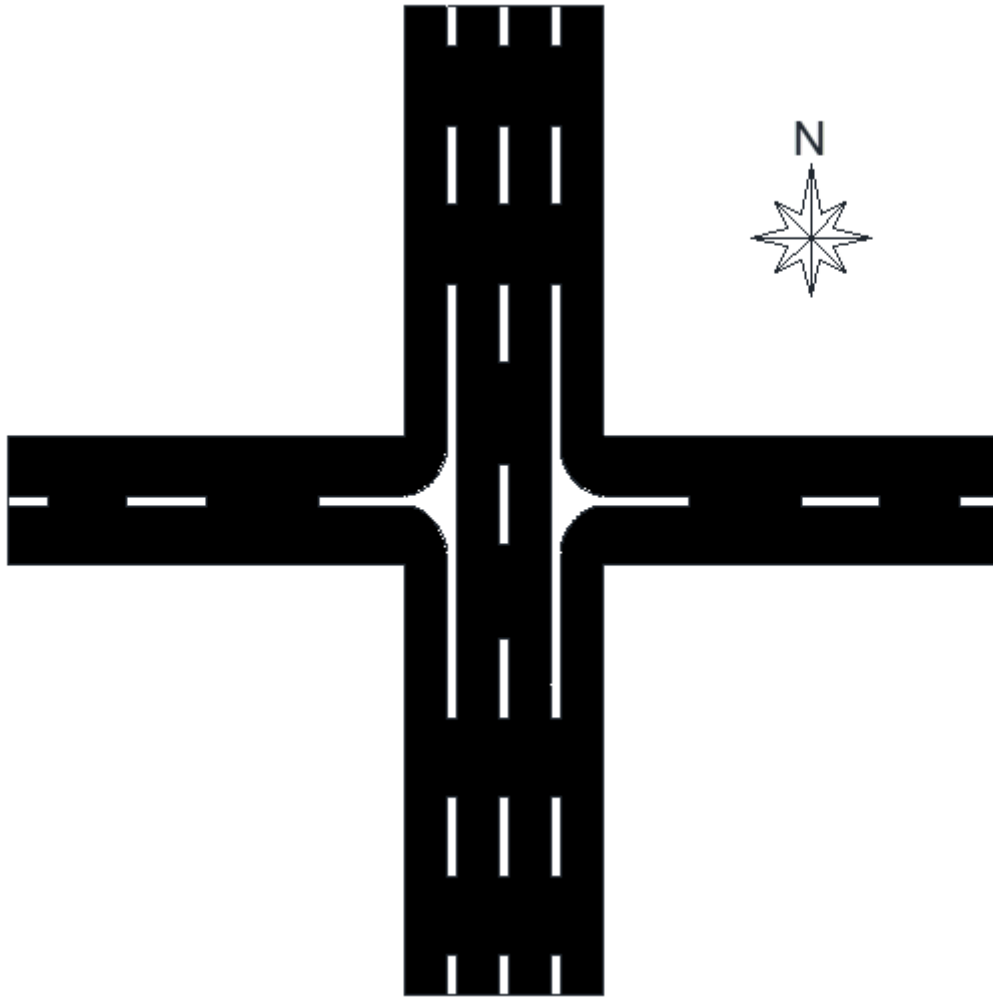


Figure 2

Suggested intersection sample

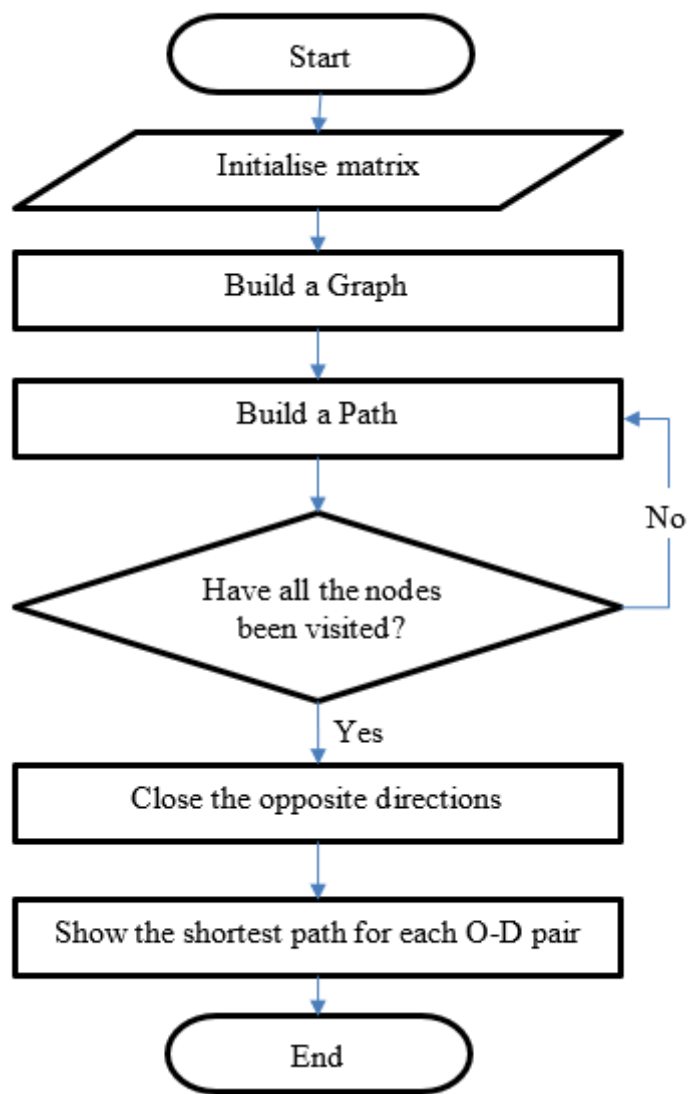


Figure 3

The general flow of the developed algorithm

```

DEFINE CLASS Graph():
  DEFINE FUNCTION _init_(self, vertices):
    SET self.graph TO [[0 FOR column IN range(vertices)] FOR row IN range(vertices)]
    SET self.V TO vertices
  DEFINE FUNCTION isSafe(self, v, pos, path):
    IF self.graph[path[pos - 1]][v] EQUALS 0:
      RETURN False
    FOR vertex IN path:
      IF vertex EQUALS v:
        RETURN False
    RETURN True
  DEFINE FUNCTION hamCycleUtil(self, path, pos):
    IF pos EQUALS self.V:
      IF self.graph[path[pos - 1]][path[0]] EQUALS 1:
        RETURN True
      ELSE:
        RETURN False
    FOR v IN range(1, self.V):
      IF self.isSafe(v, pos, path) EQUALS True:
        SET path[pos] TO v
        IF self.hamCycleUtil(path, pos + 1) EQUALS True:
          RETURN True
        SET path[pos] TO -1
    RETURN False
  DEFINE FUNCTION hamCycle(self):
    SET path TO [-1] * self.V
    SET path[0] TO 0
    IF self.hamCycleUtil(path, 1) EQUALS False:
      OUTPUT("Solution does not exist\n")
      RETURN False
    self.OUTPUTSolution(path)
    RETURN True
  DEFINE FUNCTION OUTPUTSolution(self, path):
    OUTPUT("Solution Exists: Following",
      "is one Hamiltonian Cycle")
    FOR vertex IN path:
      OUTPUT(vertex, end=" ")
    OUTPUT(path[0], "\n")
  SET Get Matrix data from file
  SET g1.graph TO Matrix
  g1.hamCycle();

```

Figure 4

Pseudo-code of the algorithm

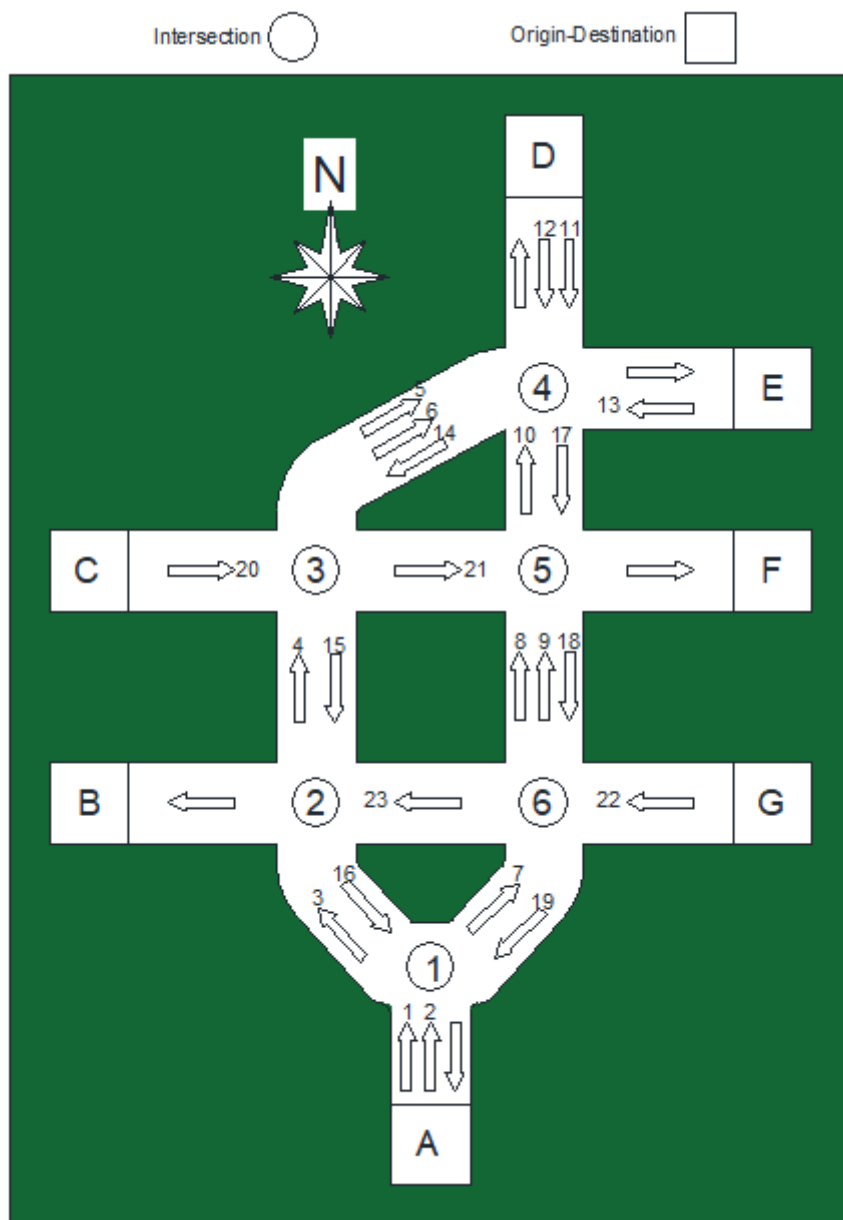


Figure 5

View of the Allsop and Charlesworth's (1977) Network

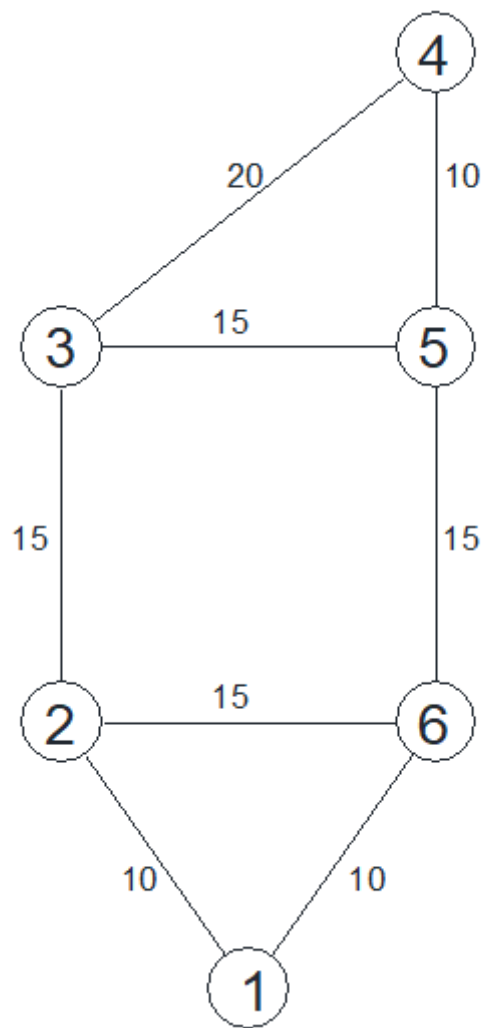


Figure 6

Graph model of the network

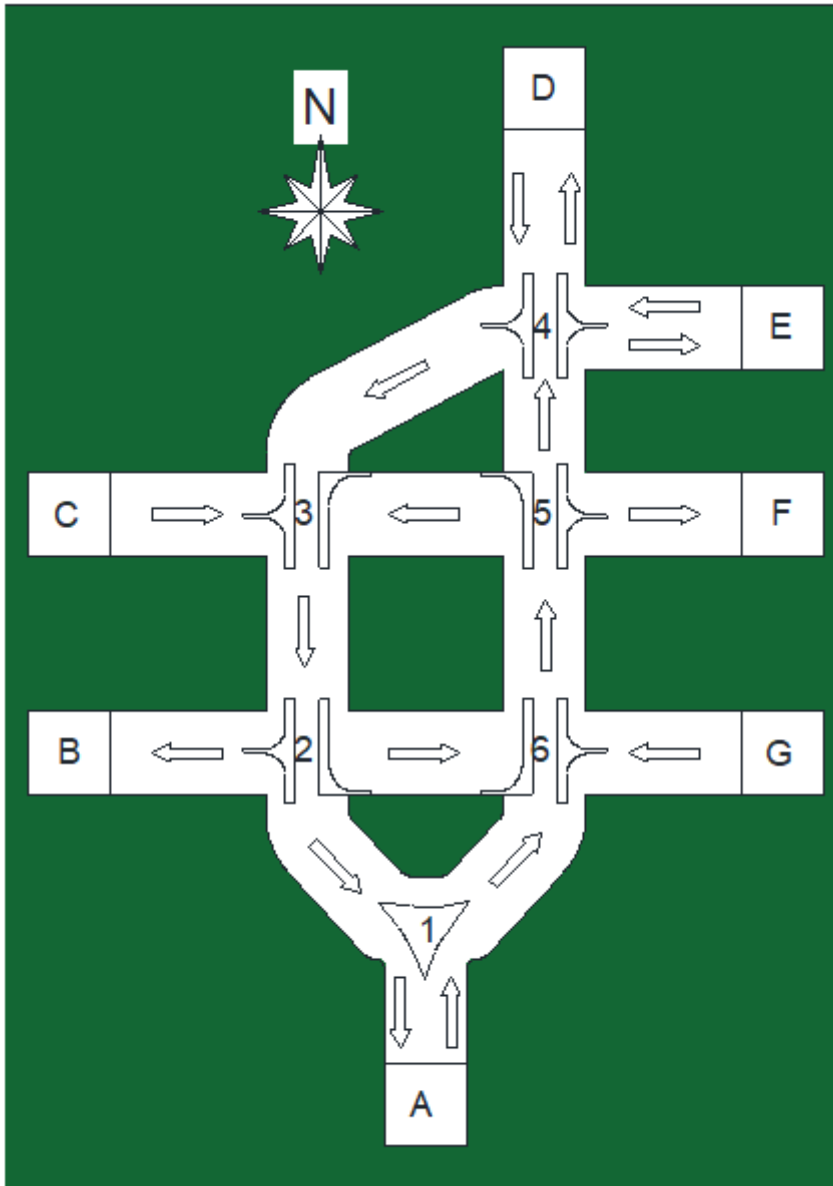


Figure 7

Illustration of the final network to simplify the output of the algorithm

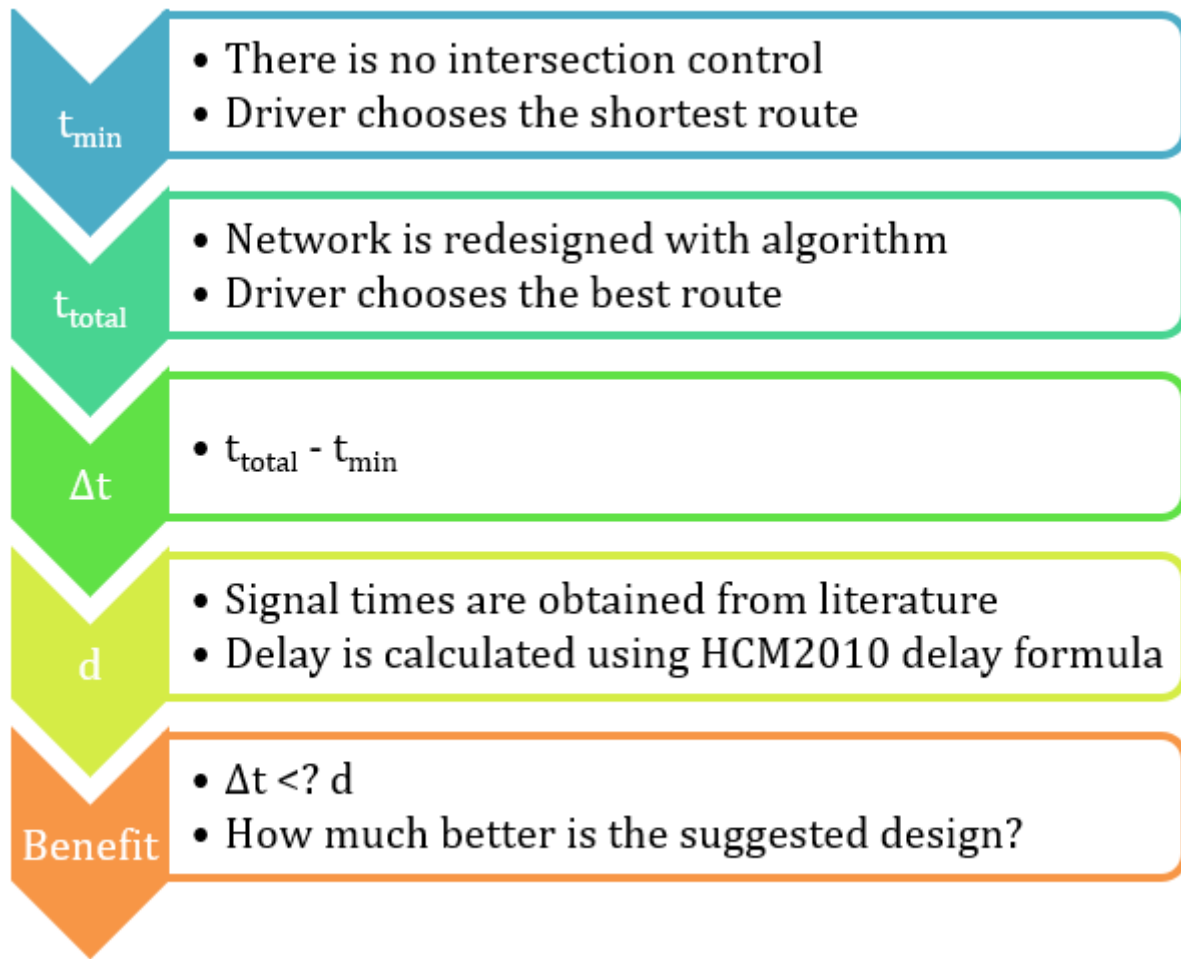


Figure 8

The flow of the comparison method