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OPTIMAL CITY STREET NETWORK DESIGN UNDER UNCERTAINTY

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Abstract

In this article, we address the problem of city street network design - specifically that of using one-way vs. two-way streets - from a different perspective than existing published literature. While at least one author acknowledges that motorist familiarity should be a factor in network design, this has not been empirically modeled. Instead of implicitly assuming motorists travel optimal paths, we explicitly model motorist unfamiliarity and uncertainty with an area. Furthermore, while the published research uses VMT or similar metrics to evaluate network design, we propose the ratio of actual VMT to optimal VMT as a more appropriate metric, with a target ratio of unity. We develop two simple idealized city street grids: one in which all streets are two-way, and a second of perfectly alternating one-way streets. Motorists are simulated traveling on both grids while varying the level of unfamiliarity and uncertainty. For each motorist, the ratio of actual to optimal VMT is measured and recorded. Our results suggest that travel efficiency for visiting motorists unfamiliar with an area will always be highest for one-way street networks. The policy this suggests is that one-way network city street designs should be preferred when there are likely to be a high proportion of motorists who are unfamiliar with the area. This conclusion goes against the prevailing wisdom, since most analysis evaluates network designs based on minimizing VMT, assuming motorists travel optimal paths.

Keywords: Transportation Modeling, Transportation Network Design, Monte Carlo Simulation

BELİRSİZLİK ALTINDA OPTİMAL ŞEHİR SOKAK AĞI TASARIMI

Özet

Bu çalışmada, mevcut literatürden farklı bir perspektif ile özellikle tek yönlü sokakların çift yönlü sokaklarla karşılaştırılmalı olarak kullanıldığı şehir-sokak ağ tasarımı problemi ele alınmıştır. Literatürde sürücünün bölgeye aşinalığının ağ tasarımında bir faktör olması gerektiğini ifade eden en az bir çalışma mevcuttur ancak bu sonuç deneysel olarak modellenmemiştir. Bu çalışmada motorlu taşıt kullanıcılarının dolaylı yollar yerine en uygun yollarda seyahat ettiği varsayımı altında, motorlu taşıt kullanıcısının bir bölgeye aşina olmaması ve belirsizlik açık bir şekilde modellenmiştir. Buna ek olarak, önceki çalışmada ağ tasarımını değerlendirmek için VMT (bir aracın belirli bir bölgede belirli bir zamanda katettiği mesafenin mil cinsinden ifadesi) ya da benzer ölçüm birimleri kullanılmışken, bu çalışmada daha uygun bir ölçüm aracı olarak, gerçekleşen VMT ile optimal VMT'nin oranlandığı bir ölçüm birimi önerilmiştir. Araştırmada tüm sokakların çift yönlü olduğu ve alternatif tek yönlü olduğu iki adet basit şehir ve sokak çizelgesi geliştirilmiştir. Sürücüler için değişen düzeylerde bölgeye aşina olmama ve belirsizlik durumları iki çizelge için de simüle edilmiştir. Gerçekleşen VMT ile optimal VMT'nin oranı her bir sürücü için ölçülerek ve kaydedilmiştir. Analiz sonuçlarına göre bir bölgeye aşinalığı olmayan sürücüler için tek yönlü şehir ağının her zaman daha verimli olacağı bulgusu elde edilmiştir. Bu doğrultuda bir bölge ile aşinalığı olmayan sürücülerin yoğunlukta olduğu durumlarda tek yönlü şehir ağının tercih edilmesi gerektiği önerilmiştir. Sürücülerin en uygun yollarda seyahat ettiği varsayımı altında, çoğu analiz, ağ tasarımını VMT'yi minimize etme temelinde değerlendirdiğinden, bu sonuç yaygın görüşe farklı bir bakış açısı getirmektedir.

Anahtar Kelimeler : Ulaştırma Modeli, Ulaştırma Ağ Tasarımı, Monte Carlo Simülasyonu

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1. INTRODUCTION

In Walker et al. [3], the authors intimate:

> *One-way streets do not pose a major inconvenience for commuters and regular visitors to the downtown; these motorists have learned the downtown network and know the " best route" to their destination. Rather, it is the occasional visitors to downtown who are often confused and disoriented on encountering a one-way street network.*

Many of us drivers have been stymied by this, and I have often cursed finding the direction I want to turn denied by a one-way street. It is understood that driving in a city that has one-way streets is just as simple as if they are all two-way streets *when the driver knows where he is going* [†]. However, what about these visitors? We are unaware of any published research evaluating this " visitor effect" of path uncertainty on the design of city street networks.

The literature on city street network design, as it relates to one-way vs. two-way streets is rather limited and consistently focuses on different types of analyses than we do in this article. Much of it is at least partially based on the knowledge that "*One-way links, although lengthening some shortest paths, are faster, effectively reducing the travel time in the permitted direction*."[1] In Drezner and Wesolowsky [1], the authors explicitly account for the speed / distance characteristics of both one-way and two-way streets to optimize a transportation network.

In [3], Walker *et al*. explored the apparently contentious issue of converting downtown city streets from one-way to two-way. Their analysis considered multiple facets, such as street capacity, and motorists' trip characteristics. External factors considered were pedestrians' interactions with drivers, public transit, and economic retail. The "measures-of-goodness" related to motorists they used included number of turns and the ubiquitous vehicle miles of travel (VMT). In [4], the authors compared the difference in emissions over one-way and two-way street networks, based again on VMT. They claim their analysis demonstrates that two-way street networks lower emissions over one-way networks, depending on traffic demand.

The final, and most interesting article detailed here, is Gayah and Daganzo [2]. In this article, the authors challenge the belief held by traffic engineers and city planners that one-way street networks handle traffic more efficiently. They developed an idealized network flow model with either one-way or two-way streets and measured the trip-serving capacity. Their results suggest that two-way streets are more efficient, especially for short trips.

The surveyed authors have focused on various measures of city street network design, but most seem to have completely overlooked the fact that motorists do not always follow optimal paths. For any network, there exists an optimal path (possibly many) between any two points, A and B. Adding restrictions to any network will generally increase the length of the optimal path averaged over all origins and destinations; this is so certain as to be nearly axiomatic. Hence, the VMT for a network of two-way streets should necessarily be less (or equal) to the VMT if there were one-way streets. We suggest a more appropriate metric is the ratio of actual VMT to optimal VMT. When a path followed is the optimal, this ratio will be ; a value greater than unity indicates a less efficient path.

To this end, we have developed a city street network model that allows us to simulate traffic flow on either a grid of one-way streets, or a grid of two-way streets. With both networks, we randomly select starting points and use Monte Carlo simulation to simulate motorists driving to a destination, varying the amount of uncertainty and unfamiliarity. For each driver, we measure the ratio of actual to optimal VMT.

Our results suggest that as unfamiliarity increases, this extra-distance ratio increases log-linearly when the streets are all one-way. However, when a network of two-way streets is used, it increases at a higher rate. The variability in the extra-distance ratios shows the same pattern. Our results show that an idealized one-way street network design is basically never worse than a completely unrestricted design.

In Section 2, we describe the city street network model and it's capabilities. We also detail the Monte Carlo simulation used to assess the joint impact of unfamiliarity and street network design on VMT. We describe and interpret the results of our simulations in Section 3, then finish up with some concluding remarks in the last section.

2. THE CITY STREET NETWORK SIMULATION MODEL

2.1. The Model

We begin with a city street network that is a simple grid as shown in the left pane of Figure 1. We use a secondary grid to encode the allowed directions of travel in each block for two possible idealized city street networks:

[†] To the best of our knowledge, however, this has not been empirically demonstrated

- all streets are two-way, with no restrictions
- all streets are one-way, with the direction of travel for parallel streets alternating perfectly

These are shown, respectively in the left and right panes (respectively) of *Figure 2*.

Directions are coded such that U=up, D=down, L=left, and R=right; in *Figure 1*, some of the end blocks are blocked off, since the allowed direction of travel would only lead off the grid. In the grids, we indicate a randomly chosen destination with the highlighted **B**.

The network model is completely malleable; it can be modified to allow any possible travel direction restrictions, and blockages of any shape can be placed anywhere in the network. An example of a complex network is shown in *Figure 1*. After designing the network and specifying the allowed directions, the model automatically checks itself for consistency by verifying that every **A** can reach the specified **B**. It can also automatically identify and record in a tertiatry grid the optimal direction and distance from every **A** to the target **B**. When there are travel restrictions, however, these optima must be manually verified and edited.

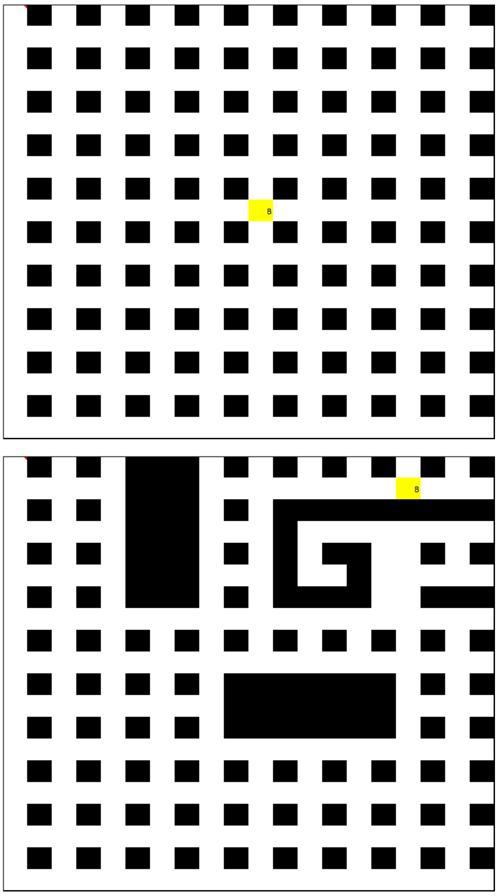

Figure 1. City Street Network Model Grids. First one is a Simple Grid, second is a Sample Complex Grid.

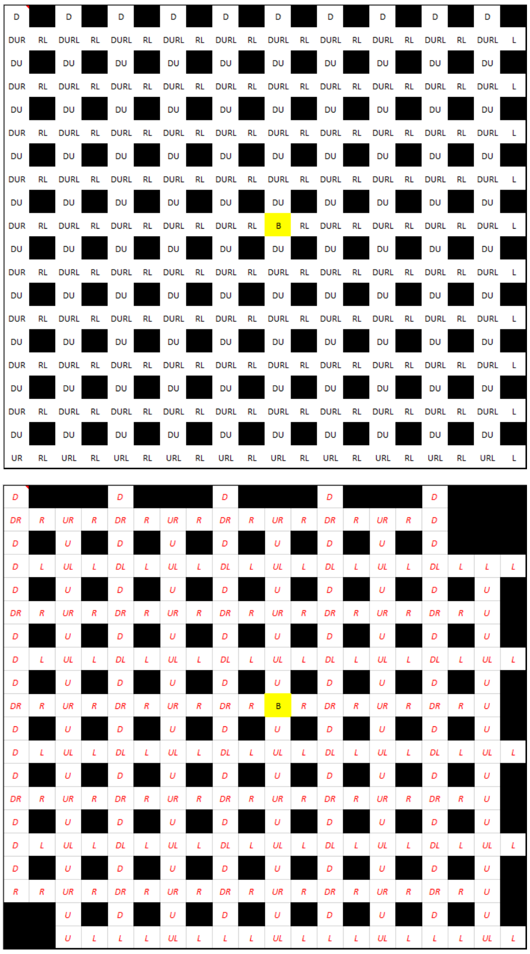

Figure 2. City Street Network Models - Allowed Directions. First Pane is Network O, Second Pane is Network R.

2.2. Simulation

Our Monte Carlo simulation proceeds in two stages. First, an available block is randomly selected as the origin. Secondly, we simulate a motorist following a sequence of paths to drive from **A** to **B**. The complete algorithm is shown here:

I. Randomly select origin **A** uniformly from available blocks

II. Driver begins at A

i. Randomly select the driver's unfamiliarity for this path from three choices: Informed, Uninformed, Completely Wrong using a discrete probability distribution. Probabilities used are specified by the modeler. The resultant travel for this path is generated according to these rules:

- *Informed:* driver travels optimal direction and distance
- *Uninformed:* direction is chosen uniformly from allowed directions, and distance is simulated using a Poisson distribution covering up to the length of the grid, but with a mean of four blocks, and 90% confidence interval of between one and eight blocks
- *Completely Wrong:* driver travels the worst direction until forced to turn

ii. The driver's uncertainty is simulated using a Triangular distribution with minimum of 80%, maximum of 120%, and mode of 100%; this is used to scale the distance traveled generated in *step (i)*

iii. The motorist drives along the path specified by *(i)* and *(ii);* if he has arrived at **B** , go to *III*, else return to *(i)*

III. Record the VMT and number of paths required, compute their ratios to the optimal quantities

IV. If still need to simulate more drivers per **A** , return to II; if number of drivers required is met but still need to simulate more **A**'s, return to *I*; otherwise exit

The simulation parameters which can be set by the user are:

- Number of origins from which to simulate travel
- Number of drivers to simulate driving from selected **A**
- Relative frequencies of unfamiliarity (Informed, Uninformed, Completely Wrong)
- Range of uncertainties for Triangular distribution

The entire city street network simulation model is developed in Microsoft Excel and Palisade's *@RISK*.

3. NUMERICAL RESULTS

For all our results, we model the uncertainty with the default parameters of 80% and 120% for the Triangular distribution. When simulating the drivers' unfamiliarity, we keep the probability of being Completely Wrong at a low 5% to simulate wrong turns, and vary the probability of being Informed between 50% and 90% in increments of 10%. The probability associated with being Completely Wrong is simply the remainder. For each of the ten scenarios (five levels of unfamiliarity for two grids), we generated 100 random origins, and simulated 50 motorists traveling from A to B .

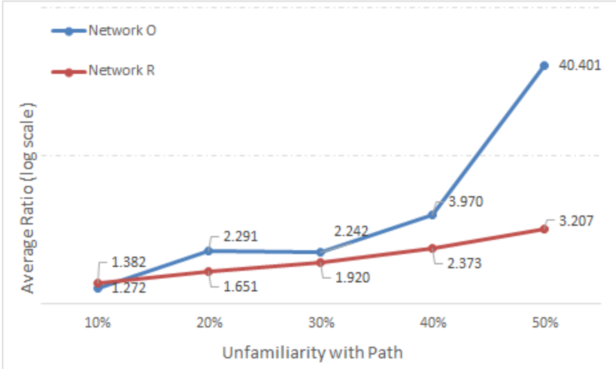

Figure 3. Behavior of Ratio of Actual to Optimal VMT as Unfamiliarity Increases (Averages).

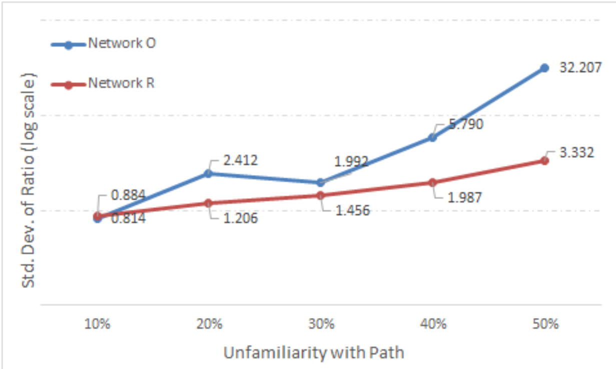

Figure 4. Behavior of Ratio of Actual to Optimal VMT as Unfamiliarity Increases (Standard Deviations).

We first analyzed the affect of motorists' unfamiliarity on the ratio of actual to optimal number of turns, but found no consistent difference between the two network designs. When analyzing the actual to optimal VMT ratio, however, a clear pattern emerged.

Our results suggest that as unfamiliarity increases, the ratio of actual VMT to optimal VMT increases log-linearly under city street network design R. However, when a network of two-way streets is used, it increases at a higher rate. The variability in the extra-distance ratios shows the same patterns. These ratios are plotted in *Figure 3* and *Figure 4*, respectively. Our results empirically support the conventional wisdom that when motorists are very familiar with an area, whether the streets are a one-way or two-way network, they travel close to the optimal path. The extra distance driven over the optimal is relatively low for both network designs.

More importantly, our results show that when motorist familiarity is explicitly modeled, street network design R is basically never less efficient than a network design based on two-way streets. While occasional visitors may become disoriented, they actually end up driving less extra distance over the optimum than if a two-way street network was in place. For example, with 80% familiarity, average VMT may be more than twice as much as optimal when there are two-way streets, while it would only be 65% higher if there were one-way streets. In the case of the two-way network, the average optimal VMT was 10 blocks so the average actual VMT (for 80%) would be 23 blocks. The same quantities for the one-way network design were 12 and 20 blocks, respectively. Hence, the visiting motorist actually drivers further on average, when the streets are all two-way.

4. CONCLUDING REMARKS

In this article, we have addressed the problem of city street network design from a different perspective than existing published literature. Instead of implicitly assuming motorists travel optimal paths, we explicitly modeled motorist unfamiliarity and uncertainty with an area. We developed two simple idealized city street grids: one in which all streets are two-way, and a second of perfectly alternating one-way streets. Motorists are simulated traveling on both grids while varying the level of unfamiliarity and uncertainty. For each motorist, the ratio of actual to optimal VMT is measured and recorded.

Our results suggest that travel efficiency for visiting motorists unfamiliar with an area will always be highest for one-way street networks. The policy this suggests is that one-way network city street designs should be preferred when there are likely to be a high proportion of motorists who are unfamiliar with the area. This conclusion goes against the prevailing wisdom, since most analysis evaluates network designs based on minimizing VMT, assuming motorists travel optimal paths.

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