Adaptive Routing Potential in Road Networks

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Abstract. Generally, in biological and ecological disciplines, the concept of adaptation refers to ecosystems evolutionarily changing as system perturbations. This paper extends these concepts to road transportation networks and focuses on the potential for adaptability of commuters to traffic disruptions. Specifically, we apply an Ecosystem Network Analysis (ENA) based upon an information-theoretic framework to demonstrate the potential, calculated as the number of alternate options available throughout a given network, for adaptive routing optimization on road networks. An initial assessment of balanced metrics of resilience and efficiency, calculated from 13 Metropolitan Statistical Area (MSA) road networks, is performed. These metrics are then compared with their respective commuter delay levels, which indicates a correlation between the balance of resilient and efficient networks and the annual commuter delay of each MSA. Whereas road network topologies that demonstrate either a highly efficient or highly resilient network structure show a tendency for higher commuter delay levels, road networks that balance efficiency and resilience suggest a tendency for lower commuter delay levels. This study's novel implication explicitly considers the road network topology as a driver of traffic delay patterns, isolated from commuter decisions.

1 Introduction

Roads, rail lines, and plane routes can be readily viewed as complex networks, where nodes are viewed as intersections, stations, or airports and edges as roads, routes, or flight paths between these nodes. Navigating these networks to optimize travel, both in terms of distance and time, constitutes an ever-evolving area of research. Adaptive routing in transportation networks is a well-researched topic that proposes methods of traffic congestion alleviation [1]. Numerous algorithms have been developed and integrated into various technologies to assess the efficiency of commuter travel. In this study, we explore a new measure to characterize adaptive routing in road transportation networks in cities across the United States.

Primary research has been conducted to optimize congestion avoidance and determine minimum time routing for individual commuters using algorithmic methods such as Dynamic and Stochastic Routing [2] and Dynamic Shortest Path Routing [3]. While some research views routing as a systems-level network assessment [4] most research focuses on traffic equilibrium as the aggregation of individual commuters [5]. Attempting to eliminate the issue of scaling from individual commuters to systemic traffic patterns, real-time monitoring, and probabilistic assessment of routing strategies have also been proposed methods of congestion alleviation [6]. Further, some methods have hybridized

these algorithmic approaches to integrate historical [7] and real-time traffic data [1], to formulate a probabilistically estimated congestion state. From this, the research aims to provide real-time adaptive routing coupled with intersection lighting schemes [8] to better scale local congestion alleviation through system-wide routing. Though less researched and diverging from infrastructure-controlled routing optimization, human decision-making systems, commuter preference, and choice have demonstrated that information conveyed to commuters [9] and choice models [10] produce a highly varied selection determinant. These varied decisions generally create uncharacterizable, subjective driver choices, further complicating congestion alleviation attempts [10].

As cross-discipline research attempts to optimize travel, the effect of system-level road network topology on commuter adaptation to traffic perturbations for routing optimization has seen little discussion. Though commuter-level traffic research is necessary and most applicable to individual commuters, the systems-level properties of road networks, how these properties constrain traffic routing options, and their effect on routing optimization have been less studied. These routing strategies do little to inform and guide road network planning on city or regional road network structures.

As metropolitan areas continue to expand, insight into the integration of existing topologies and how this expansion may affect traffic congestion through system-level topological changes may aid in integrating decades of divergent road structure philosophies.

Here we propose preliminary work on the metric of Adaptive Routing Potential (ARP) to assess the degree of commuter adaptability inherent within the topology of road networks. Our objective is to determine optimal network topologies that allow for the greatest adaptability in commuter actions while balancing the need for efficient travel throughout a road network. The proposed term, adapted from Ecological Network Analysis (ENA) [11] attempts to quantify road networks in order to quantify their balance of resilience and efficiency and assess how this balance may affect traffic delay times in small to medium Metropolitan Statistical Areas (MSA).

Generally, ecosystems, when viewed as a complex network and measured using information-theoretic methods, exist in a narrow window along a spectrum within the opposing structures of resilience and efficiency [21]. In the face of external system perturbations, such as climate change, and internal structural changes, such as species loss, current ecosystems have, by their existence, [17] demonstrated persistence in the face of change. Our hypothesis is that, given that these ecosystems exist, they may have evolved a network topology with the ability to persist through time and that network topology may present properties of optimality that may be useful in varied disciplines characterized as complex networks.

2   Method

Ecological Network Analysis (ENA) is used to analyze the dynamics of the whole ecosystem, assessing food web dynamics and trophic relationships [21] that demonstrate coherent topological properties that have formed over millennia [16]. This analysis method has been applied to various research areas such as economics [13], infrastructure [14], and industrial systems [15].

Here, we consider traffic throughput, or the edge distance between two intersections, as a random variable that indicates the usage level of a length of roadway. Meanwhile, we consider intersections as nodes and roadways as edges in the physical transportation network. In this way, information theoretic measures based on throughput between all nodes in a transportation network reveal aspects of its variability, resilience, and efficiency. We compare measures between cities and against traffic delay statistics for each city to show how they are useful constructs with which to characterize different types of road networks.

We consider that the two system properties of efficiency and resilience are equally important in route travel and adaptation in road networks. Commuters seek the efficiency of a route in that they want to travel from point A to B with a minimal distance, and potentially to a greater degree, minimal time. However, should the route from A to B become unnavigable, alternative routes need to be available to bypass congestion, making the commuters' route resilient in that they are able to adapt to a new route that conforms to their distance and time expectations of travel.

Ecosystem network investigations have led to a number of findings that may inform properties of network topology in general and network adaptability specifically [20]. To better understand the concept of adaptability, with the potential use in road networks, ecosystem definitions may provide a conceptual and analytical method of assessing road network relationships. In ENA, use of the concept of 'Reserve' provides an information-theoretic derived calculation that describes an ecosystem's ability to adapt, or more specifically, the allowable options or food web pathways available for adaptability. The concept and calculation of 'Reserve' accounts for this adaptability, the potential for adaptive routes in a road network.

3   Measures

From ecosystem dynamics research [18–20], the terms and calculations for Capacity, Reserve, and Ascendancy (Eqs. 1–3 [20] respectively) are used and applied to define the properties of adaptability inherent within a network system [20]. Our primary interest is in system throughput ($T.. = \sum_{i,j} T_{i,j}$) and how the scaled properties may quantitatively assess the balance of resilience and efficiency. In ecosystems, system throughput is the amount of nutrients transferred from species to species, with respect to traffic, the number of potential commuters traveling from one intersection to another. In these definitions, T is a 2-dimensional, asymmetric matrix of throughput, where $T_{i,j}$ indicates the throughput from intersection i to intersection j, creating the distance, the weighted edge from the ith to the jth intersection. In this context, the symbol '.' is used as a summation over all i's or j's. So that the term T.. Can be understood as the sum of all edges, potential commuters traveling throughout the road network system. The term T.. Calculates the total distance of all edges within the system, and $T_{.j}$ and $T_{i.}$ Calculate the total distances connecting the respective nodes. These correspond to summation over rows and columns calculated in an adjacency matrix.

Capacity - In information theoretic terms, the capacity is the equivalent to the entropy of throughput for all links in the system. A high capacity indicates that all routes are near "equally probable" since their throughput is similar to a uniform distribution. Whereas

a network with a few links with very high throughput relative to others would have a lower capacity.

$$Capacity = -\sum_{i,j} T_{i,j} \log\left(\frac{T_{i,j}}{T_{..}}\right) \qquad (1)$$

Ascendancy - In information theoretic terms, ascendancy is the scaled mutual constraint. A high value of ascendancy indicates that the throughput $T_{i,j}$ tends to be higher than the product of the throughputs that originate at i and end at j ($T_{i.} * T_{.j}$).

$$Ascendancy = \sum_{i,j} T_{i,j} \log\left(\frac{T_{i,j} T_{..}}{T_{i.} T_{.j}}\right) \qquad (2)$$

Reserve - While Capacity and Ascendency are similar to information theory measures of entropy and mutual information, Reserve is defined as scaled conditional entropy, measure of potential actions characterized by a lack of directed operation.

$$Reserve = -\sum_{i,j} T_{i,j} \log\left(\frac{T_{i,j}^2}{T_{i.} T_{.j}}\right) \qquad (3)$$

The ratio of Reserve to Capacity is calculated and introduced, for road network applications, as the Adaptive Routing Potential, ARP = R/C. Conceptually, this metric assesses the potential adaptability inherent in the structure of a network. Though terms referenced from ENA are suitable for demonstrating network properties, a parallel is useful to demonstrate applicability with more general terms used in varied disciplines. Here a representation of efficiency and resilient networks is undertaken graphically and then mathematically related to ENA terminology. Efficient networks, consisting of long uninterrupted roads, provide direct, unencumbered traffic but are susceptible to perturbations, such as traffic accidents, that can lead to congestion. Resilient networks, consisting of short roads with more intersections, those with numerous alternative routes, require increased network complexity and traffic devices. However, should a road become unnavigable alternative routes are generally available.

The properties of calculated ARP are demonstrated with three example networks analyzed (Fig. 1). We can take a perfectly efficient network (A) to demonstrate a route from the origin (1) to destination (10) consisting of 9 edges of equal length 10. This network is highly efficient, containing no intersections, and demonstrates a Reserve of 0. Should the road become unnavigable at any point in the network from 1 to 10, the route is not traversable, and the potential for adaptation is not present. Though this efficient network ensures a minimal distance, the network is fragile and offers no alternative routes.

The remaining networks would be considered resilient to varying degrees. Network B consists of 9 additional nodes and 18 additional edges with a weight of 8. Should any single node or edge be removed from the network, navigation from 1 to 10 is still possible. This is reflected in the increase in the calculated value of Reserve. In Network C increase resilience, and additional 8 edges are added such that, should any 2 edges be removed, a route from 1 to 10 is still possible. Though Network C provides numerous
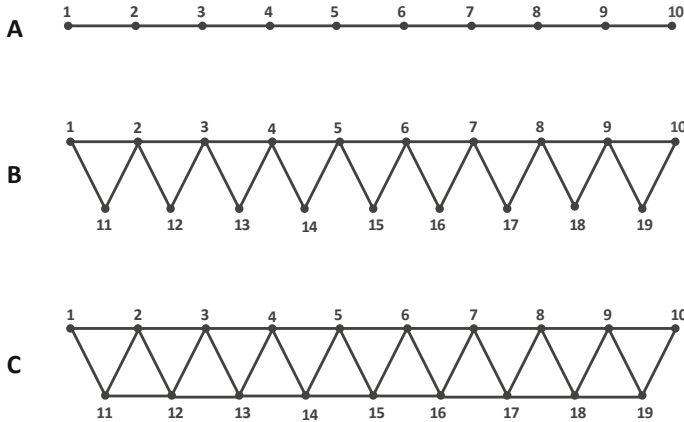
Fig. 1. Example networks with varying resilience

route alternatives, the difference in Reserve and, as a result, ARP does not increase linearly, demonstrating that adding additional resilience measures leads to a diminished return in ARP (Table 1).

Table 1. Example network properties

Property	Network A	Network B	Network C
Edge count	9	27	35
Node count	10	19	19
Capacity	285.29	1110.69	1526.34
Ascendance	285.29	789.58	949.23
Reserve	0	321.11	577.11
ARP	0	0.29	0.38

While efficiency is conceptually simple, resilience is more difficult to demonstrate. To illustrate the system properties of added resilience, a cascading node removal strategy is employed where the added resilient nodes (11-19) and their adjoining edges are removed, and ARP is calculated. The resulting curve demonstrates that added resilience demonstrates initially large payoffs but diminishing returns with added nodes and edges. This over-resilience adds increased traffic signals and other flow-regulation mechanisms that slow traffic, making it far less efficient (Fig. 2).

4   Procedure

Road networks and resultant MSA's were chosen based on reporting indicating the best and worst cities for traffic delays and a random selection of cities for additional
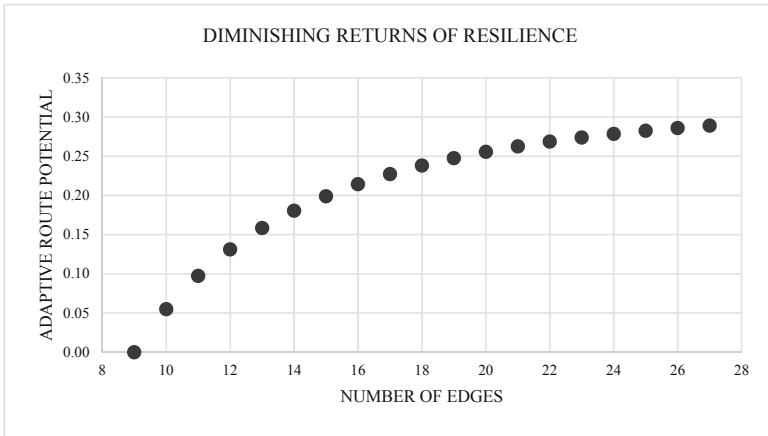
Fig. 2. Edge removal of results of resilient networks

metrics. Road network data were obtained from OpenStreet Maps [21], which produced a street intersection (node, edge) list weighted by node-to-node distance, characterized as road intersections. This list was then converted to an adjacency matrix where Capacity, Ascendency, and Reserve were calculated for each MSA. The ratio of Reserve to Capacity was further calculated to yield the ARP. To assess the relationships between the ARP and traffic delay, MSA level data was retrieved [22] and assessed against 'Annual Hours of Delay per Auto Commuter.'

5   Results

Adaptive Routing Potential was calculated for 13 small to medium MSA's of varied US locations. This calculation was plotted against Annual Hours of Delay per Auto Commuter (Fig. 3). The figure will be broken into 3 subsets: High-Efficiency Networks, High Resilience Networks, and Balanced Networks.

High-Efficiency Networks, with a lower Reserve to Capacity ratio relating to an ARP between 0.14 and 0.165 consists of cities, such as Little Rock, AR and Colorado Springs, CO, demonstrated higher delay hours, with a mean value of 40.20 Annual Hours of Delay PAC. The High Resilience Network consisting of Boulder, CO, demonstrated 35.00 Annual Hours of Delay PAC. The Balanced Networks that fell near the middle of the Efficient/Resilient spectrum demonstrated mean Annual Hours of Delay PAC of 26.14.

The balanced efficiency and resilience networks demonstrate a lower delay rate than the other sections, though the data is inconsistent with outliers such as Salem, OR, and Spokane, WA. Road delays have many causes, and a potential explanation for these cases may be that weather plays a large part in road delays. The Boulder, CO MSA is noticeably on the resilient side of the ARP calculation signifying an earlier assessment that networks with no uninterrupted roads, nearly all roads in Boulder have intersections, will be calculated as high resilience. As a comparison, the MSA with the highest efficiency calculation, Little Rock, contains 6 freeways in its road network.
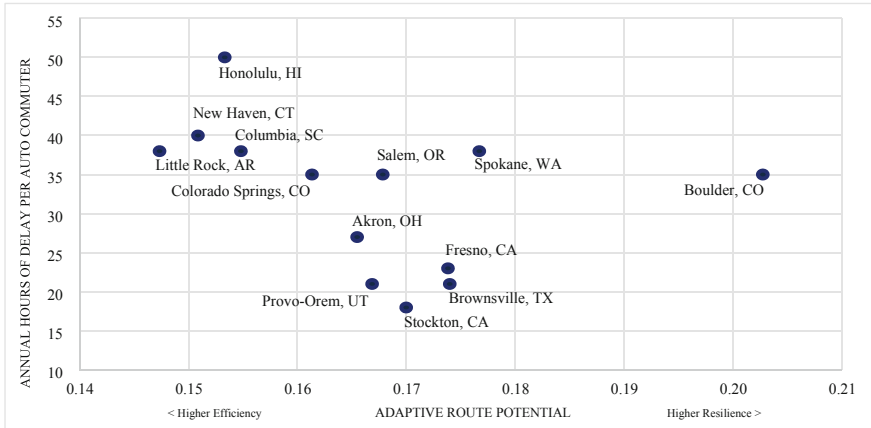
Fig. 3. Adaptive route potential of MSA's vs annual hours of delay per auto commuter.

Fig. 4. Stockton, CA road network

Local, surface streets (Black), Highways (Blue) and Red Roads and Controlled Access Highways (Red).

Mapping road networks (Table 2) of the most demonstrative variables of the road networks (Fig. 3) gives an indication of how network topology may affect commuter delays. The road network maps in Table 2 delineate 3 types of roads: 1) Local (Black), 2) Highways (Blue), and 3) Controlled Access Highways or Freeways (Red). In the context of resilience/efficiency discussion, a general attribution can be assessed:

1) Local roads consist of 2 lanes whose intersections (nodes) may be regulated by stop signs or stop lights and whose distance (edge length) between traffic regulation devices is relatively short. With respect to traffic congestion, these streets may be defined as more resilient. The short distances allow for more options for travel and congestion avoidance.
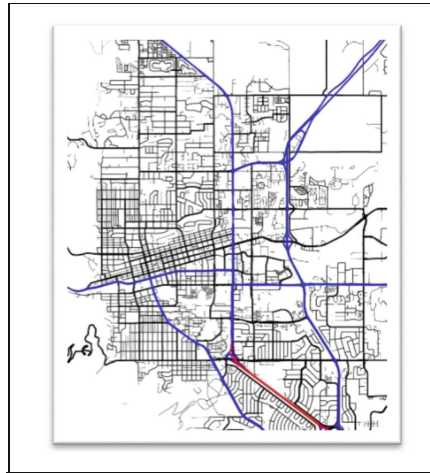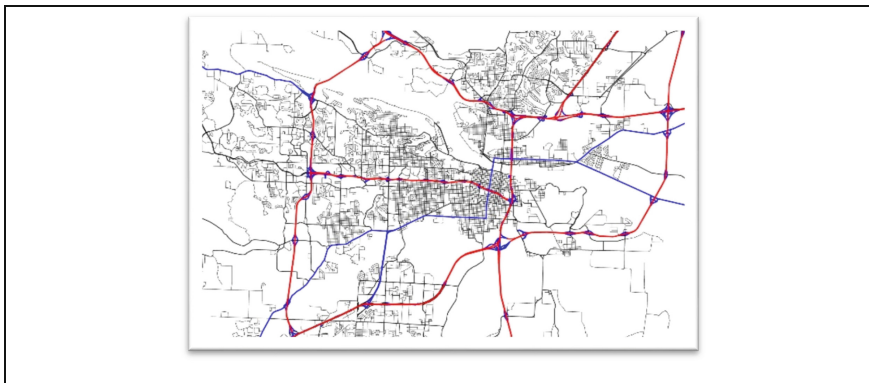
Fig. 5. Boulder, CO road network

Fig. 6. Little Rock, AR road network

Table 2. Selected representative resilience/efficiency edge road networks of Fig. 3

See Fig. 4	See Fig. 5
See Fig. 6	

2) Highways are generally regulated by stop lights at greater distances and are more difficult to enter or exit. Highways generally balance resilience and efficiency by offering commuters longer edge lengths for uninterrupted travel but more difficulty in avoiding congestion and fewer route options during congestion.

3) Controlled access highways, or freeways, do not generally have in-route traffic control devices. Freeways are highly efficient; they offer uninterrupted travel for

the length of the highway. However, during congestion, there are few options for congestion avoidance unless a commuter is near an off-ramp when congestion is noticed.

These three maps demonstrate how the topology of road networks at the MSA level may affect commuter delay times. As can be seen, the Boulder, CO (Fig. 5) road network has no freeways and is composed primarily of local streets with some highways and thus, ranks highly resilient. Little Rock, AR (Fig. 6) conversely shows multiple freeways that are highly efficient but interdependent and, should an accident or congestion occur, leaves commuters with few options for adaptation. Stockton, CA (Fig. 4) ranks in the middle of the efficient, resilient rankings and has the lowest commuter delays of the 13 MASs measured. As can be seen, Stockton has a mix of highways, local roads, and 2 freeways balancing resilience and efficiency.

6   Conclusion

Research on adaptive routing techniques is an active area of research; however the system-level attributes of the networked environment that those methods and algorithms operate in have seen little attention. Research in road networks at the systems level may demonstrate that this environment, the efficiency/resilience balance of road networks, may be an important measure in commuter delay. Due to the availability of road network and commuter congestion data comparisons, localized traffic congestion assessments could not be obtained however, localized congestion assessments are a possible avenue of research.

While initial results allude to an optimal balance of network resilience and efficiency, clearly, a greater number of MSAs require calculation. Further, a more diverse network topology needs to be assessed, especially with respect to high resilience networks. Though outlying balanced networks may be explained, there are surely an innumerable number of variables that may account for delay times, and the effect of potential variables of delay require inclusion.

Adaptability, while it can be viewed and acted upon from a commuter perspective, must account for the system, the networked environment within which it operates. To view that environment, conceptualizing the system network through disciplines where adaptability has been tested and refined through millennia of evolutionary processes may demonstrate optimal network properties.

The metric proposed, Adaptive Routing Potential, could demonstrate that the system-level network topology of roads plays an integral part in traffic congestion. This finding could aid in the development, planning, and integration of future road networks in urban areas. Potentially, the development of road networks may take into account the current state of resilience/efficiency balance and model network additions that move the system-wide network towards more balance, alleviating and preventing a further commuter delay.

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