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Centrality-based lane interventions in road networks for improved level of service: the case of downtown Boise, Idaho

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Abstract

Recent advancements in network science showed that the topological credentials of the elements (i.e., links) in a network carry important implications. Likewise, roadway segments (i.e., links) in a road network should be assessed based on their network position along with traffic conditions at a given geographic scale. The goal of this study is to present a framework that can identify and select critical links in a road network based on their topological importance such as centrality, and the effects of systematic interventions conducted on such links in improving overall system performance (vehicle delay, travel time) to provide an adequate level of service (LOS). A real-world road network (Boise downtown) is investigated by applying lane interventions on roadways experiencing high congestion. Microscopic traffic simulation and analyses are conducted to estimate the traffic flow parameters hence the performance of the road segments. The findings of this study show that interventions applied to critical and congested road segments improve the serviceability from LOS F to LOS E as well as from LOS D to LOS C. Besides, reduced travel time and vehicular delay (after applying intervention on critical components) are also observed for high demand OD pairs of the road network. As such the proposed framework has the potential to incorporate the topological credentials with traffic flow parameters and improve the performance of the road network. This systematic approach will help traffic managers and practitioners to develop strategies that enhance road network performance.

Keywords: Road network, Critical components, Intervention, Simulation, Performance

Introduction

Transportation systems are often considered networked systems (Newman 2003), such as road networks. A network consists of two basic components; nodes, and links (Newman 2002) where the nodes are connected by links, and this connectivity can be directional as well as weighted (Newman 2004). Many new network concepts, properties, and measures have been developed by applying experiments on large-scale real networks (Barrat et al. 2008). Some of these properties, e.g., small world and scale-free property, are common across many real networks such as transportation networks (Albert and Barabási 2002). Small-world Property refers to the existence of relatively short paths between any pair of nodes in networks despite their large size (Milgram 1967; Travers and Milgram 1969; Watts and Strogatz 1998). The small-world effect has significant implications in explaining the dynamics of processes occurring on real networks (Newman 2003). Besides, the scale-free property validates the existence of hubs or a few nodes that are highly connected to other nodes in the network. The presence of large hubs results in a degree distribution with a long tail (highly right-skewed), indicating the presence of nodes with a much higher degree than most other nodes.

It is critical to know which components are most significant to the overall network's success (Mortula et al. 2020), and therefore vulnerable to disruptions (Sadri et al. 2021) when designing and managing networked systems. Even though the reliability of networked systems is extensively studied, few studies have been found to assess the components of vulnerability in the context of enhancing the performance of networked systems (Barker et al. 2013; Baroud et al. 2014; Wan et al. 2018). Networks in which most of the nodes have low degree (number of connections with other nodes) and centrality (topological position of a node in a network) (Derrible and Kennedy 2011) are less susceptible to disruption since these nodes lie on few paths between others (Derrible 2012), whereas a significant reduction in performance is observed due to the disturbance of high degree and central nodes in a large real network is observed (Albert 2000). It is also hypothesized that the topological credentials of the network significantly affect the resiliency of the transportation system (Zhang et al. 2015). In addition, the resiliency of an undirected road network is quantified by implementing graph theory under both random and rank-ordering node removal scenarios (Rouhana and Jawad 2020). But these studies did not consider the implication of interventions to improve the link-level performance of the road transportation system.

For road networks, some critical roadway segments (links) may become congested and inaccessible for adjacent traffic resulting in a significant decrease in the LOS as well as a reduction in the roadway capacity. Hence, the goal of the study is to develop a systematic strategy to improve the performance of road network systems by applying interventions on these critical components. The performance is measured based on vehicle delay, travel time between the pairs of origin–destination (OD) trips, and LOS. The objectives to enhance the goal are as follows:

- Identify the most critical links (roadway segments) of the road network.
- Outline specific interventions (e.g., increasing roadway capacity by adding lane) to implement on critical links (e.g., roadways).
- Estimate and compare (roadways that experience a similar level of congestion) the link-level performance improvements of the road network.

To achieve these goals and objectives, the following research questions are explored as listed below:

- On which network components e.g., congested links (more critical or less critical), interventions should be implemented?

- How much improvement of road network performance can be achievable by applying interventions on critical components?

Figure 1 is representing a hypothetical road network where two roadways (R_1 and R_2) are experiencing a similar level of congestion (e.g., LOS E). Now, lane intervention (e.g., increasing lane width, adding lane) could be applied on either roadway, but may not improve the link-level performance equally. Hence, identifying the critical component based on the network topology (i.e., betweenness centrality of $R_1 = 0.104$ and $R_2 = 0.063$, meaning R_1 is more central hence topologically more critical) and implementing lane intervention on that (R_1) could better improve the performance of the road network rather than applying intervention on other roadways.

The core contribution of this study is to develop a methodology to improve the performance of the road network by implementing lane intervention on critical components. The research will help to decide on which roadways (having a similar LOS) lane intervention should be implemented, by using complex network metrics (Boccaletti et al. 2006; Strogatz 2001). The study has developed a systematic strategy to enhance road network performance which will help traffic managers and practitioners to establish efficient plans for transportation system development, operations, construction, and recovery works.

Literature review

In urban environment, traffic flow demonstrates the dynamic movement of vehicles, generally autonomous in nature, except transit trips are guided and predictable. With the advent of dynamic network theory in the last decade, research on transportation

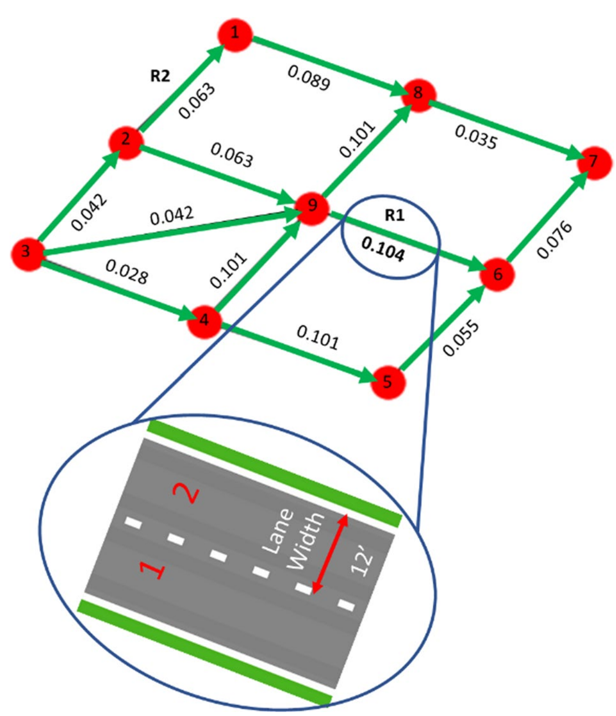

Fig. 1 Hypothetical road network for lane intervention to improve performance of the system

network systems has advanced dramatically. Most highways, roads, and railways are built out in a network pattern, with connection flows, travel time, and geographical distance acting as weights (Lin and Ban 2013). Kazerani and Winter explain the dynamic nature of the urban movement as spatiotemporal distribution of trip origin and destination, flexible but not random movements (Kazerani and Winter 2009). Researchers questioned the interdependencies between the heuristic traveler behavior and the static physical structure as well as the topology of the network. They found that rather than the traditional one, time-dependent weight to Betweenness Centrality (BC) has the potential to characterize the traffic flow in the street network. Similarly, Akbarzadeh investigated the correlation between traffic flow, node centrality, and node criticality (Akbarzadeh et al. 2019). This study suggested that the network topological properties have a strong effect on traffic flow.

Furno et.al. adopted graph-based approach to detect the critical spots in a transportation network (Furno et al. 2018). They proposed a framework to capture the correlation between Betweenness Centrality (BC) and global efficiency, also rank the nodes based on BC to evaluate network vulnerability in case of any disruption, hence the study evaluates the network resilience. Similarly, Gauthier et.al. identified and ranked the links most critical to the overall performance of the road network, considering the dynamic properties of road traffic i.e., demand, congestion, and overall link importance as a function of travel cost (travel-time weighted betweenness centrality for this study) and estimated resilience as robustness index focusing on day-to-day disruptions (Gauthier et al. 2018). They argued that topological metrics in connection with the dynamic weight are computationally efficient than demand or congestion-based models.

Cheng et.al. introduced delay flow centrality that captures the commuter flow and time delay in measuring transportation network centrality (Cheng et al. 2013). They found delay flow centrality acts like degree centrality and betweenness centrality and conclude that delay flow centrality can be a useful tool to capture critical nodes in the transportation network. Liu et.al. analyzed Nanjing's transportation network and proposed a weighted (based on road grade) complex network (Liu et al. 2019). The study uses an approximate algorithm to calculate BC and proposed a key node identification model, hence rank the most critical nodes in the transportation network. Zhang et.al. developed a relationship to capture the road network pattern of traffic analysis zones (TAZ) based on graphical and topological features (Zhang et al. 2011). They found that betweenness centrality best describes and distinguishes the TAZs and their boundaries.

Many studies have acknowledged that the transportation networks' topological credentials have the potential to identify and classify critical locations. Henry et al. studied the disruption, hence resilience of Lyon transport network through degree centrality, degree distribution and shifting, heterogeneity, density, and symmetry (Henry et al. 2021). Saberi et al. describe the urban travel pattern can be viewed as a weighted directional graph on a large scale (Saberi et al. 2017). Ayden et.al. developed a fast and effective methodology for transportation network resilience by combining stress testing and graph theory metrics (Steinfeld et al. 2015). They use unweighted betweenness centrality to evaluate spatial resilience. But these literatures lack the application of network theories to the improvement of traffic flow, especially the studies did not include the strategies that can incorporate the improvement interventions and design alternatives of critical nodes or links from design perspectives.

In transportation planning and forecasting, microscopic simulation is considered as a credible technique for traffic study (Arafat et al. 2020). Moreover, microscopic models are in close vicinity to represent the real-world scenarios and simulations are the most cost-effective way to implement any design improvement, alternative route, network performance in disruption, etc. hence becomes a very popular way of model testing. VISSIM, the state-of-the-art microscopic traffic simulation tool is used for different studies in transportation domain such as for automatic signal timing decisions to reduce traffic congestion (Tariq et al. 2020), prediction of traffic diversion due to incidents on the freeway (Saha et al. 2020a, b), and active traffic management for connected vehicle (Saha et al. 2020a, b). Besides, transportation system operation and management (TSMO) and intelligent transportation system (ITS) related studies have also used microscopic simulation extensively (Saha 2019). Real world road network is developed and experimented by researchers as well as the developers of simulation software to understand the dynamics of traffic flow, travel demand (Zhao et al. 2010), and the walkability of pedestrians (Speck 2014). These networks have also been tested for disruption due to traffic incidents (Hurlburt et al. 2019) as well as for transportation system criticality (Abdel-Rahim et al. 2006). As such microscopic simulation, e.g., PTV-VISSIM simulation environment, has the potential to implement the design improvements interpreted from topological metrics.

Evaluation of a significant number of real road networks showed that congestion locations moved farther from the city center when the number of larger metropolitan areas increased, resulting in abrupt spatial transitions (Lampo et al. 2021). Furthermore, network analysis of eight urban road networks worldwide (North America, Europe, Australia, and Asia) showed that the betweenness centrality of nodes (urban intersections) followed power-law distribution, however, the degree distribution for weighted and unweighted road networks showed completely different results (Akbarzadeh et al. 2018). Investigation on the applicability of a group of matrix function-based centrality metrics is conducted to the more general urban multiplex framework, which has recently been adapted from single-layer networks to layer-coupled multiplex networks (Bergermann and Stoll 2021).

The extensive literature review reveals that the existing studies are inconclusive to the application of networks' topological credentials to ensure the improvement of transportation vulnerability. A certain number of studies developed methodologies to identify critical nodes, links, and zones in the networks but the real applications to improve the performance of these network components are limited and lack clear directives. Moreover, there is a lack of proper initiatives to guide the traffic network planning and design to adapt and improve the criticality of traffic flow in vulnerable locations. It is also unknown how the transportation network will behave for any improvement when the design interventions are viewed from the bigger picture, i.e., from the local or global scale of the network. All these unanswered questions are the motivation for this study.

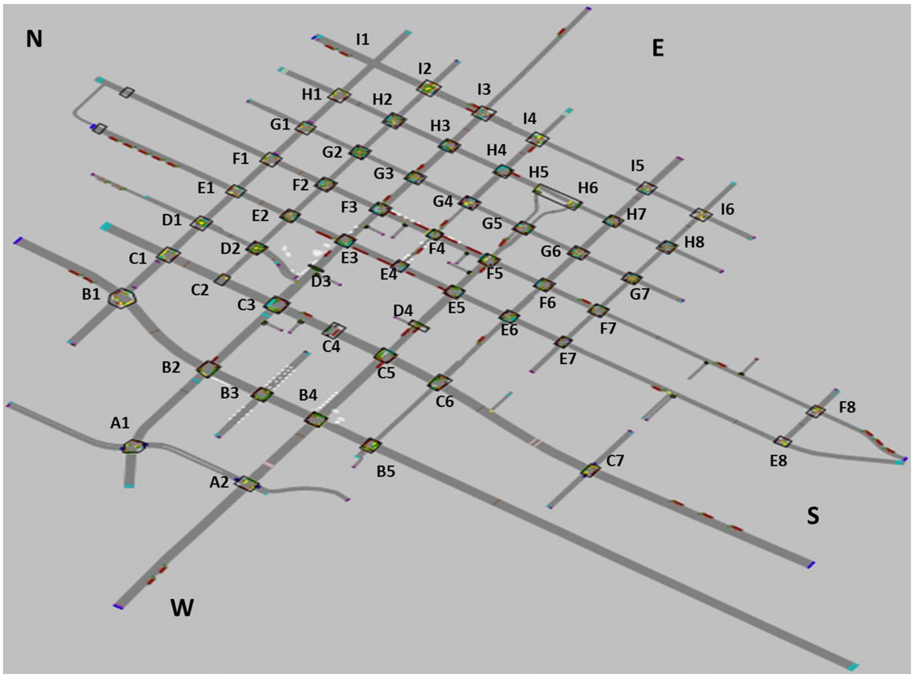

Fig. 2 Boise downtown road network with hypothetical labeling

Road network data

For this study, a real-world road network (downtown Boise) is considered for network analyses and traffic simulation studies, which was already created by state-of-the-art microscopic traffic simulation software (VISSIM) developers. In following Fig. 2, the Boise Road network is shown with hypothetical labeling on intersections. The whole network has 55 nodes (intersections) and 112 links (road segments). Most roadways are one way in this network as it represents a road network of a downtown city area of Boise, Idaho. The signalization system for this network is ring barrier controlled (RBC), and some of the intersections are actuated. Besides, vehicles are assigned among 140 origins and 363 destinations using the Static Traffic Assignment STA) method. For this study, this exemplary road network of VISSIM software is used (including STA) to ensure the consistency among all the different experimented scenarios. Although the Dynamic Traffic Assignment (DTA) may represent the congestion scenario of a road network realistically, use of actuated traffic signal control system along with static traffic assignment can also quantify the road network performance (i.e., travel time, vehicle delay) similar to DTA (Farhan and Martin 2011). Besides, Static Traffic Assignment can provide analytical solutions clearly as it is difficult to derive such solutions applying DTA even for a medium size network due to the computational expense and the iterative nature of the process (Kohler and Strehler 2012).

Methodology

Network analysis and traffic vulnerability assessment (by microscopic traffic simulation and analysis) for a real-world road network (Boise Road network) are conducted in this study. First, the link-level network metric (i.e., edge betweenness centrality) of roadways are computed. Next, those centrality values are prioritized to identify the most critical roadways. Then, different design interventions are applied on roadways to improve the link-level performance of the road network, leading to enhanced efficiency. Finally, the system performance is measured in terms of total travel time, and total vehicle delay. According to Highway Capacity Manual, the level of service is defined as a qualitative measure of the level of quality of traffic flow, and the quality is measured based on performance measures that attempt to assess the comfort of the road users. LOS is categorized into six classes (LOS A to LOS F); where LOS A is the free-flow condition, LOS E is the congested situation when traffic flow is at the roadway capacity (maximum traffic flow), and LOS F is over-capacity (Elefteriadou 2016).

In this study, the basic network metric, i.e., edge betweenness centrality (Fig. 3) values are used to identify the critical components (i.e., road segments) of the road network (Table 1). Betweenness centrality defines a central node (for the link it is edge betweenness) which lies mostly on the shortest path of other pairs of nodes. A summary of these metrics is explained in Table 2 as follows.

Results

With the help of the state-of-the-art microscopic traffic simulation software VISSIM, a real-world road network (Boise downtown road network) (Abdel-Rahim et al. 2006; Zhao et al. 2010) is analyzed by computing travel time, vehicle delay for high demand origin–destination pairs, and LOS. Besides, network analyses of the same road network are performed to identify the critical components. After implementing different interventions on these critical components, the travel time, vehicle delay, and LOS are calculated again and finally compared with the congested case to identify the improvement of LOS of the road network. As Boise Road network is already a well-established and tested road network in PTV-VISSIM, hence the calibration and validation of this road network were not required.

Road network analysis

The network analysis for the Boise downtown road network is conducted for the link (roadway) level property. Figure 2 shows the hypothetical labeling on the Boise downtown road network for the analyses. The results for weighted and directed graph analysis of the Boise Road network are listed below for different link (Table 3) properties. Traffic volume (vph) is used as the weight for this analysis (Table 1). This is logical as it combines the traffic flow parameter with the network analyses hence the results are more representative. Existing literature shows that different traffic volume parameters (i.e.,

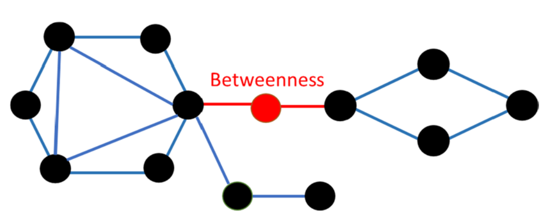

Fig. 3 Networked representations of betweenness centrality

Table 1 Boise roadway characteristics

From node	To node	Link type	Traffic flow direction	No of lanes	Traffic volume (vph)	Vehicle speed (mph)
B1	B5	One-way	Southbound	5	2208	35
C7	C1	One-way	Northbound	5	2460	35
D1	D2	One-way	Southbound	1	101	30
D2	D1	One-way	Northbound	1	116	30
D3	D2	One-way	Northbound	2	229	30
D2	D3	One-way	Southbound	1	275	30
E1	E3	One-way	Southbound	3	764	30
E3	E5	One-way	Southbound	4	764	30
E5	E7	One-way	Southbound	3	764	30
E7	E8	One-way	Southbound	2	764	30
F3	F1	One-way	Northbound	3	355	30
F5	F3	One-way	Northbound	4	355	30
F7	F5	One-way	Northbound	3	355	30
F8	F7	One-way	Northbound	2	355	30
G7	G1	One-way	Northbound	1	299	30
G1	G7	One-way	Southbound	1	186	30
H5	H1	One-way	Northbound	3	258	30
H8	H5	One-way	Northbound	2	258	30
I1	I4	One-way	Southbound	2	670	30
I4	I1	One-way	Northbound	2	486	30
I4	I6	One-way	Southbound	1	670	30
I6	I4	One-way	Northbound	1	486	30
E7	I6	One-way	Eastbound	2	267	25
I5	E6	One-way	Westbound	3	969	25
E6	B5	One-way	Westbound	2	969	25
A2	C5	One-way	Eastbound	4	2019	25
C5	F5	One-way	Eastbound	3	2019	25
F5	H5	One-way	Eastbound	1	1009	25
F5	H6	One-way	Eastbound	1	1010	25
G4	I4	One-way	Eastbound	3	406	25
G4	E4	One-way	Westbound	1	64	25
E3	A1	One-way	Westbound	4	800	25
I3	E3	One-way	Westbound	3	800	25
C2	I2	One-way	Eastbound	1	78	25
I2	C2	One-way	Westbound	1	93	25
C1	B1	One-way	Westbound	2	97	25
B1	C1	One-way	Eastbound	2	173	30
E1	C1	One-way	Westbound	1	133	25
C1	E1	One-way	Eastbound	2	173	30
E1	F1	One-way	Eastbound	3	227	25
F1	G1	One-way	Eastbound	3	280	25
G1	I1	One-way	Eastbound	3	540	25

AADT, vph) were successfully used to identify the topological credentials of the roadway network (Rinaldi and Viti 2020; Ahmed et al. 2022). Links are ranked based on their weighted centrality value in the network.

Table 2 Summary of complex network metrics

Network metrics	Definition	Equation	Remarks
Betweenness centrality	The number of times a node acts as a connecting point along the shortest path between two other nodes is measured by betweenness centrality. Out of a number centrality measures, betweenness centrality of node k is the sum of the fraction of all-pairs of shortest path that pass-through node *v* (Brandes 2001, 2008; Brandes and Pich 2007)	$C_B(v) = \sum_{a \neq k \neq b \in Z} \frac{\sigma_{ab}(v)}{\sigma_{ab}}$	Where Z is the set of nodes (v) in the graph, σ_{ab} is the number of shortest paths from node *a* to *b*, and $\sigma_{ab}(v)$ is the number of paths that pass-through nodes other than *(a, b)*
Edge betweenness centrality	Compute betweenness centrality for edges. Betweenness centrality of an edge *e* is the summation of the fraction of all-pairs shortest paths that pass-through *e* (Brandes 2008)	$BC(e) = \sum_{x,y \in Z} \frac{\theta(x,y\|e)}{\theta(x,y)}$	where Z = number of nodes, θ (x, y) = quantity of smallest (x, y) routes, and θ (x, y |e) = number of routes which traverse to link *e*

Traffic simulation results

To quantify the network performance improvement of the road network in terms of travel time, vehicle delay, and LOS, the state-of-the-art traffic simulation software VISSIM is used for this study. VISSIM is a microscopic traffic simulation software that facilitates to create traffic simulation environment and evaluating traffic conditions. It's particularly useful for comparing multiple traffic management scenarios before settling on the right alternative and optimization steps (Lin et al. 2013).

Initial simulation criterions

To understand the effect of different interventions on the road network, initially, a congested road condition is created for the Boise downtown road network by increasing the traffic volumes (base traffic volume shown in Table 1) at some specific road segments. The basic simulation parameters are explained below (Turner 2015):

Period

The period of time to be simulated. Including the initialization period.

The simulation is considered to run for 4500 s (1.25 h) and the initial 900 s is considered as the initialization period (as the whole network requires this time to show the competing effect of the traffic while measuring the travel time and vehicle delay).

Simulation resolution

The number of times the vehicle's position will be calculated within one simulated second (range 1 to 10 parts of a second). The higher the value the smoother the simulation. A value of 10 is used for this study.

Table 3 Link property (edge betweenness centrality) analyses

Rank	From node	To node	Edge betweenness centrality	Rank	From node	To node	Edge betweenness centrality
1	G2	G3	0.2394	31	B4	C5	0.0845
2	F2	G2	0.2327	32	C3	B2	0.0845
3	G3	G4	0.2327	33	F7	F6	0.0828
4	E2	F2	0.1958	34	D2	D1	0.0816
5	D2	E2	0.1946	35	C6	C5	0.0808
6	E5	E6	0.1758	36	E6	C6	0.0791
7	F2	E2	0.1710	37	H2	I2	0.0768
8	H2	G2	0.1609	38	I6	I5	0.0684
9	E2	D2	0.1577	39	D1	D2	0.0616
10	G4	F4	0.1549	40	I2	I3	0.0606
11	I2	H2	0.1498	41	G5	G6	0.0593
12	C2	D2	0.1461	42	H4	I4	0.0579
13	E4	E5	0.1394	43	I5	I4	0.0572
14	E6	E7	0.1320	44	G7	H8	0.0569
15	C3	C2	0.1316	45	H8	I6	0.0569
16	F4	E4	0.1300	46	B2	B3	0.0512
17	C5	C4	0.1290	47	B3	B4	0.0512
18	C4	C3	0.1290	48	F7	G7	0.0492
19	F3	F2	0.1172	49	G6	F6	0.0488
20	I3	I2	0.1152	50	G5	G4	0.0475
21	F4	F3	0.1145	51	G6	G5	0.0451
22	I4	I3	0.1125	52	E5	F5	0.0428
23	G2	F2	0.1024	53	H7	G6	0.0424
24	D2	D3	0.1007	54	I5	H7	0.0424
25	E7	F7	0.0966	55	I3	I4	0.0401
26	F6	F5	0.0963	56	C5	D4	0.0364
27	G4	G5	0.0902	57	D4	E5	0.0364
28	F5	F4	0.0896	58	A1	A2	0.0354
29	G2	H2	0.0879	59	E7	E8	0.0354
30	D3	C3	0.0872	60	F6	E6	0.0354

Random seed

Simulation runs with identical input files and random seeds generate identical results. For this study, an initial value of 70 is used and an increment value (random seed increment) of 5 is considered for simulating different scenarios. Besides, 10 simulation runs are performed for each scenario.

Simulation speed

The number of simulation seconds to a real time second. Maximum simulation speed is used here to obtain the results quickly.

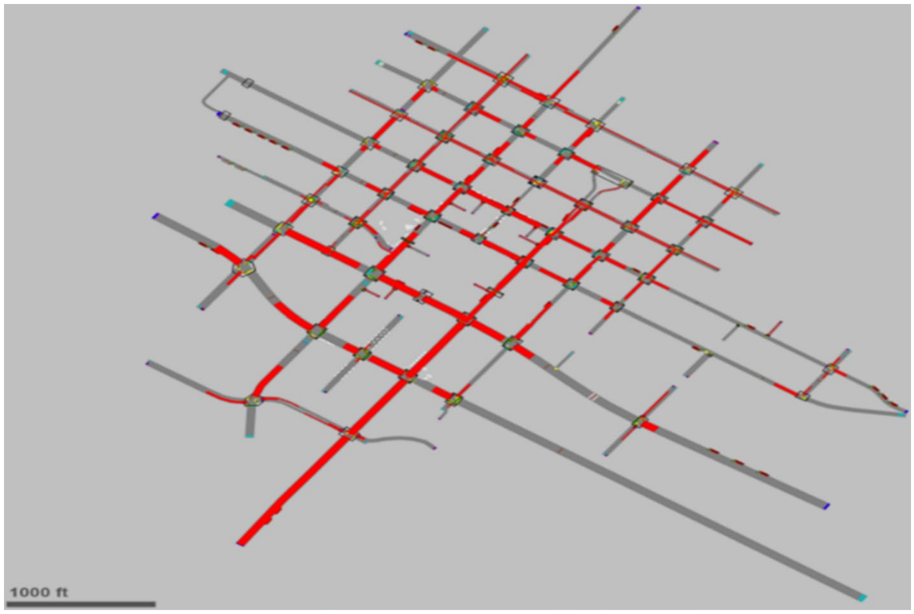

Fig. 4 Boise downtown road network (congested case)

Table 4 LOS criteria for the urban street facility (HCM 2016)

LOS	Travel speed threshold by base free-flow speed (mph)						
	55	50	45	40	35	30	25
A	> 44	> 40	> 36	> 32	> 28	> 24	> 20
B	> 37	> 34	> 30	> 27	> 23	> 20	> 17
C	> 28	> 25	> 23	> 20	> 18	> 15	> 13
D	> 22	> 20	> 18	> 16	> 14	> 12	> 10
E	> 17	> 15	> 14	> 12	> 11	> 9	> 8
F	≤ 17	≤ 15	≤ 14	≤ 12	≤ 11	≤ 9	≤ 8
F	Any						

Intervention to improve system performance

Different interventions for roadways may contribute to improve the total travel time and vehicle delay, hence the LOS of the road network. The design intervention i.e., increasing number of lanes, applied only on roadway segments (link-level) in this study. The implementation of the intervention is focused on the following criterions:

1. Interventions should be applied on the roadway segments having similar LOS (e.g., LOS F/E/D) to compare the before and after scenario of implementing design interventions.
2. Equitable improvement (e.g., for the same length of the roadway, add an equal no of lanes) should be considered for all the modified scenarios.

Scenario 1 (both roadway segments are along the OD routes and same direction)

Initially, a congested scenario (Fig. 4) is generated by increasing the traffic volume of the road network. The traffic simulation is performed using VISSIM by following the *initial simulation criterions* mentioned earlier. The congestion level of roadways (D4-E5, E5-F5) are identified after simulating the base case. For motorized vehicles, travel speed is used to characterize vehicular LOS (Table 4) for a given direction of travel along with an urban street facility (Elefteriadou 2016). Besides, the central roadways are determined based on the edge betweenness centrality values (Table 3) as all the interventions are applied at the link level.

The average travel time and vehicle delay are computed for the four OD pairs between zone 1 to 3, zone 1 to 4, zone 2 to 3 and zone 2 to 4 (as shown in Fig. 5). The four OD pairs are selected based on the high demand and flow of traffic from the origins to destinations. The design intervention, i.e., increasing (adding one lane) the number of lanes is applied on congested roadways. For this scenario, the intervention is applied on two adjacent roadways experiencing the same level of congestion. The roadways D4-E5 (rank = 57, BC = 0.0364, less central) and E5-F5 (rank = 52, BC = 0.0428, more central) are found experiencing the level of service F and these two connected roadway segments (Fig. 2) are considered for equitable improvement (for the same length of the roadway, adding one lane). Here, D4-E5 and E5-F5 are one-way roads (eastbound) having 4 and 3 lanes respectively. After adding one lane, the roadway D4-E5 became a 5-lane eastbound road, and E5-F5 became a 4-lane eastbound road. Besides, all the signalizations of ring barrier-controlled intersections are updated accordingly. All the left and right turns are also adjusted with adjacent roadways. The traffic simulations' results (percent change in

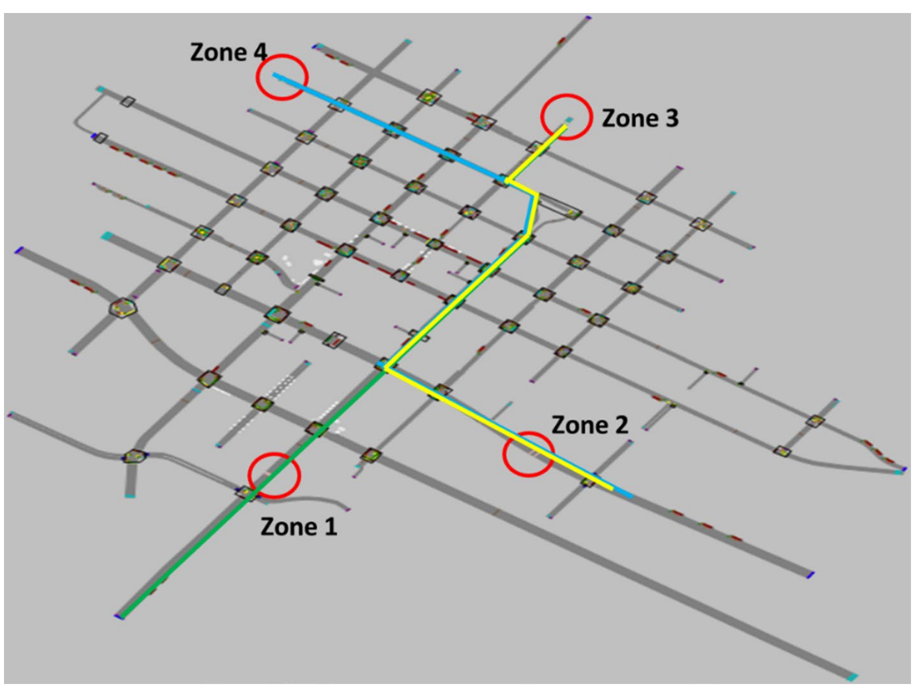

Fig. 5 Boise downtown road network (Zones)

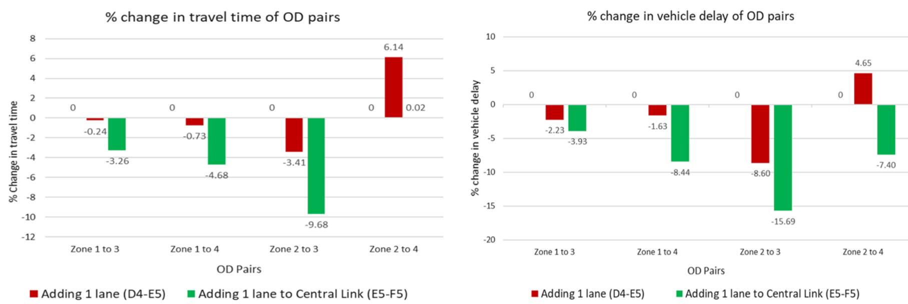

Fig. 6 Percent change in travel time and vehicle delay for OD pairs (scenario 1)

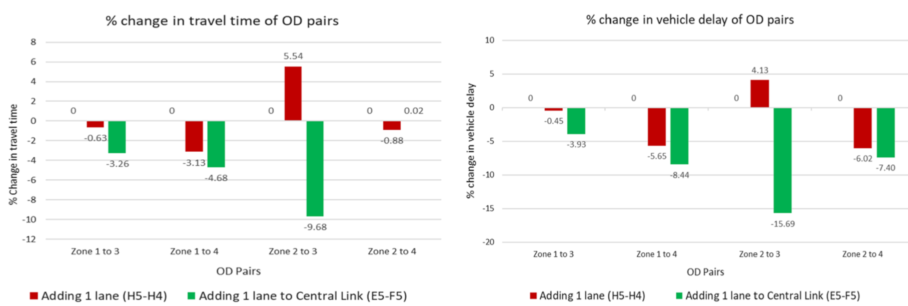

Fig. 7 Percent change in travel time and vehicle delay for OD pairs (scenario 2)

travel time and vehicle delay) for all three cases (congested base case, adding one lane to central roadway E5-F5 and other roadway D4-E5) are plotted in Fig. 6.

From Fig. 6, it is observed that the percent change in travel time based on the initial congested condition (left bar chart) is higher for most of the OD pairs for central roadway E5-F5 (i.e., 10% reduction for zone 2 to 3) whereas the improvement is less on the other D4-E5 segment. Similar results are also observed for the central roadway (i.e., 16% reduction for zone 2 to 3) in case of the percent change in vehicle delay (right bar chart). Besides, the LOS improved from LOS F to LOS E after adding one lane to the central roadway E5-F5; on the other hand, LOS did not improve for the same intervention implementation on less central roadway D4-E5.

Scenario 2 (both roadway segments are along the OD routes, but in the cross direction)

In this case, the roadways E5-F5 (rank = 52, BC = 0.0428, more central) and H5-H4 (rank = 63, BC = 0.035353, less central link) are considered for applying design intervention (adding one lane). Here, E5-F5 (eastbound) and H5-H4 (northbound) are one-way roads having 3 lanes. After adding one lane, the roadway E5-F5 becomes a 4-lane eastbound road, and H5-H4 becomes a 4-lane northbound road. Besides, all the signalizations of RBC intersections and the static traffic assignments are updated accordingly.

From the network analyses of link (Table 3) properties of the Boise Road network, it can be said that the roadway E5-F5 is more central than the roadway H5-H4. The results (percent change in travel time and vehicle delay) of the traffic simulations for all three cases (congested base case, adding one lane to H5-H4, and adding one lane to central roadway E5-F5) are plotted in Fig. 7.

From Fig. 7, it is observed that the percent change in travel time based on initial congested condition (left bar chart) is higher for most of the OD pairs for central roadway E5-F5 (i.e., 10% reduction for zone 2 to 3) whereas the other roadway H5-H4 shows less improvement (i.e., 3% reduction for zone 1 to 4). Similar results are observed for the percent change in vehicle delay (right bar chart), where the central roadway also showed better results (i.e., 16% reduction for zone 2 to 3) compared to the other roadway (i.e., 6% reduction for zone 2 to 4). Besides, interventions applied on both roadway segments improved the LOS marginally (for roadway H5-H4, from LOS D to LOS C and for roadway E5-F5, from LOS F to LOS E).

Scenario 3 (one roadway segment is outside of the OD routes and opposite direction)

For this scenario, the roadways E5-F5 (rank = 52, BC = 0.0428, more central and along the OD routes) and F3-E3 (rank = 99, BC = 0.0097, less central and outside of the OD routes) are considered for applying design intervention (adding one lane). Here, E5-F5 and F3-E3 are one-way roads having 3 lanes. After adding one lane, the roadway E5-F5 became a 4-lane eastbound road, and F3-E3 became a 4-lane westbound road. Besides, all the signalizations of RBC intersections are updated accordingly. All the left and right turns are also adjusted with adjacent roadways. The traffic simulations' results (percent change in travel time and vehicle delay) for all three cases (congested base case, increased number of lanes to central roadway E5-F5 and to other roadway F3-E3) are plotted in Fig. 8.

From Fig. 8, it is observed that the percent change in travel times (left bar chart) is higher for most of the OD pairs for central roadway E5-F5 compared to the other roadway F3-E3 based on the initial congested condition. Similar results are also observed for the central roadway in case of the percent change in vehicle delay (right bar chart). Besides, the LOS improved from LOS F to LOS E after adding one lane to the central roadway E5-F5; on the other hand, LOS (LOS D) did not improve for the same intervention implementation on less central roadway F3-E3. Here, as the roadway segment F3-E3 is outside of the OD routes, hence the observed percent change in travel time and vehicle delays are minimal which may cause due to the stochasticity nature of the microscopic simulation.

System performance comparison

To compare all the three scenarios explained before, total travel time and total delays are determined from the simulations. Then, the improvement is defined as the reduction in total travel time and total delays in minutes (after lane intervention applied) with respect to the base case for different scenarios.

In Fig. 9, improvements in total travel time (left bar chart) and total delay (right bar chart) in minutes are plotted for all the three scenarios (scenario 1- both roadway segments are along the OD routes and same direction; scenario 2- both roadway segments are along the OD routes, but in the cross direction; scenario 3- one roadway segment is outside of the OD routes and opposite direction). These observations show that lane intervention applied on more critical roadway segments improves the system performance more than two times compared to implementing lane intervention on less critical roadways (having similar LOS) in terms of travel time and vehicle delay.

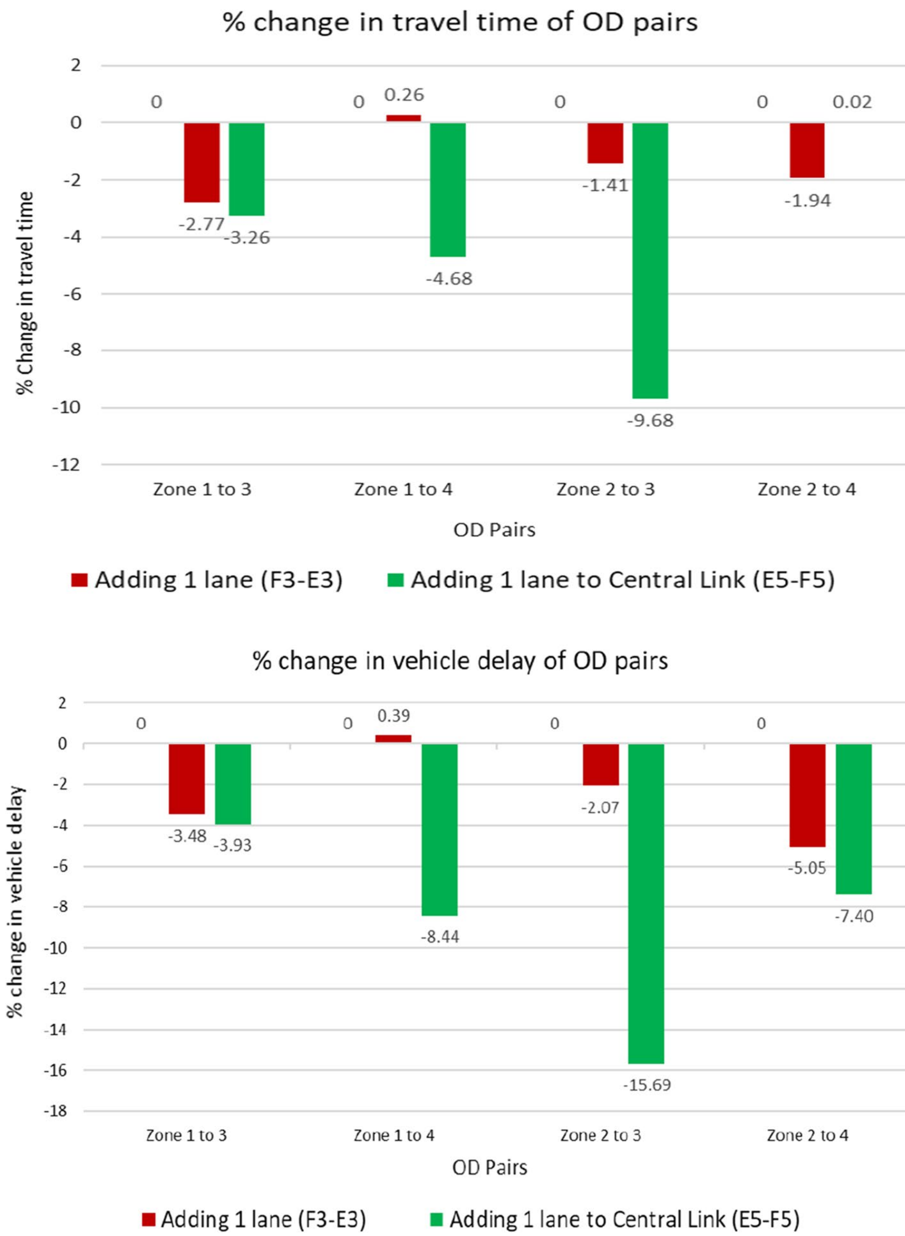

Fig. 8 Percent change in travel time and vehicle delay for OD pairs (scenario 3)

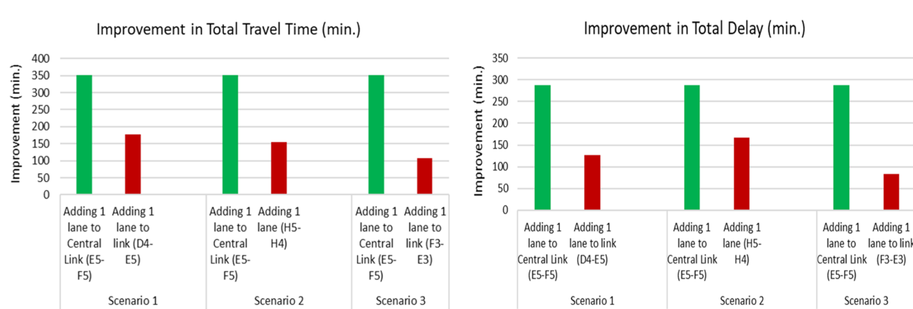

Fig. 9 Improvement in total travel time and total delay of different scenarios

Discussion and conclusion

This study proposed a strategy for improving road network performance by implementing interventions to critical components (roadways segments). The systematic approach combines traditional traffic simulation studies with complex network metrics to improve the performance of road networked systems. With growing attention to risk-based operation and maintenance of transportation systems, accurate knowledge and importance of the vulnerabilities, as well as consideration of implementing design interventions on roadways in a network becomes crucial. Traffic engineers and managers often tend to improve the performance of a roadway that experiences the worst LOS by implementing different interventions (e.g., increasing the number of lanes, increasing the roadway capacity, and so on) without considering the cascading effect on the surrounding road network. This way of traffic management may improve the LOS for a specific roadway locally but cannot solve the traffic congestion problem for the surrounding network. When different network components experience similar congestion level, the proposed systematic approach of implementing interventions could be applied which may help traffic engineers to decide on the network component alternatives to enhance the system performance. Besides, network position or topological credentials should be considered along with the traffic flow parameters while implementing any measures on network components to improve the roadway performance.

The main goal of this study is to develop a systemic approach to improve the road network performance by implementing interventions on the critical components, which are identified through complex network metrics. A real-world road network (Boise downtown) is analyzed in this study by computing network metrics that identified the critical components of the network. To quantify these phenomena, the link-level property of the network is evaluated by the edge betweenness centrality. After that, traffic simulation is performed to identify the network performance in terms of travel time and vehicle delay for high-demand zones' OD pairs as well as the LOS. Finally, a before and after scenario of applying interventions on different network components is simulated to find the effectiveness of the proposed strategy. The findings of this study are listed below:

- Traffic performances improve for lane interventions made on more critical or centrally located roads that are equally congested or experience similar level of service (i.e. LOS F) improves the LOS of critical roadway link (from LOS F to E).
- Better performance improvements (reduction in travel time and vehicle delay) for high-demand OD pairs are observed for lane intervention applied on more critical roadways. Such as, in scenario 1, the vehicle delay was reduced by 15.7% from the base case when lane intervention was made on the more critical roadway, whereas the vehicle delay was reduced by 8.6% from the base case while lane intervention was applied on the less critical roadway.
- Noteworthy performance improvements for the entire network are also observed for lane intervention applied on more critical roadways as compared to less critical roadways. For example, after lane intervention was applied on more critical roadways, the total system travel time (TSTT) reduced twice as much from the base case as compared to the lane intervention applied on less critical roadways.

The proposed strategy to improve road network system performance based on topological credentials will guide traffic managers and practitioners to decide on which roadways (having a similar LOS) lane intervention should be implemented and establish an efficient plan to enhance transportation system efficiency. The application of this study could be further extended in the future by performing a multiresolution, iterative analysis such as Dynamic Traffic Assignment (DTA) to capture the network-level performance through simulation of traffic networks. Future research may use graphical network models along with network parameters to conduct multidimensional analysis. Different external variables (e.g., traffic volumes, travel times and LOS) may also be considered to embed centrality measures in linear causal model (Giudici et al. 2020b). Besides, a comprehensive network model can be used for multidimensional experiment to understand overall operational losses which may correspond to LOS (Giudici and Bilotta 2004). Application of DTA is crucial to capture the traffic dynamics for congestion pricing as DTA has the ability to account for variable demands (Boyles et al. 2006). Moreover, DTA can manage traffic in a road network through real-time measurement, hence often ensures better traffic planning and management scope (Saw et al. 2015). To derive centrality measures, future studies may consider different correlations among traffic volumes at different timestamps and implement the correlation networks to analyze the traffic network performance. Existing literature developed network centrality measure based on adjacency matrix extracted from multilayer network (Giudici et al. 2020a; Avdjiev et al. 2019), which can be implemented to analyze interdependent and multivariate transportation networks (i.e., roadway, utility, water distribution).

Besides, node-level analyses (i.e., closeness centrality, node betweenness centrality) can be performed and node interventions may also be considered such as, adding two critical intersections with a new roadway, optimizing the signal timing of critical intersections, diverting traffic to critical intersections among others in future research. This study showed improvement in road network system performance by applying intervention on critical roadway segments for day-to-day congestion scenarios; future studies may consider applying similar methodology for disruptions due to extreme events (i.e., hurricane, flood, wildfire), which could enhance the resiliency of the transportation system. Moreover, traffic volume (vph) is used as a weight in this study to measure betweenness centrality of roadway segments; future research may explore different weights i.e., percentiles of traffic volumes, travel time, vehicle delay, LOS, lane width (given data availability) to ensure more robust betweenness centrality in ranking. The limitation of the study is tied with the network analysis, which is conducted only for one scale of the network. As network credentials change at different scales (i.e., city, county, state level) of networks (Ahmed et al. 2021), future studies may also explore possible scaling effects of network design interventions.

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Author contributions
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Declarations

Competing interests
The authors have no known competing interests with the data source, results and the outcome of this study.

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