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Transportation Research Procedia 00 (2018) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

World Conference on Transport Research - WCTR 2019 Mumbai 26-31 May 2019

A New Freight Truck Resiliency Indicator with Connected Vehicle Technology

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Abstract

A freight route resiliency indicator is developed in this paper. Basic characteristics of connected vehicle technology (CVT) which can provide advance traffic information is used to develop the indicator. The indicator is sensitive to route changes that might occur due to detour from an unforeseen congestion downstream of the path of the freight truck. The truck can detour at an appropriate exit on its route. This could be done to maximize the route resiliency. Application of the indicator is shown with a 20-mile stretch of I-710 (interstate 710) freeway of the multimodal freight transportation network in the Southern California Region. I-710 is considered as one of the most important truck route connecting Ports of Long Beach and Los Angeles to other multimodal terminals of California and elsewhere in the United States. It is found that the truck route resilience is maximized if the truck detour occurs at approximately 7th, 6th and 4th exit-ramps downstream from the truck location with probability 0.75, 0.5 and 0.25, respectively. This indicates trucks ability to avoid the downstream congested point with these three probabilities. The resilience indicator developed in this research is extremely useful for resiliency improvements of freight operations in urban regions where congestion occurrence is quite frequent and random.

Keywords: resiliency; multimodal; exit ramp; freeways; travel time; freight;connected vehicle technology;

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1. Introduction and Background

Freight operations are considered important for a sustained economic growth of a region (Fowkes et al., 2004). Several modes of transportation constitute this operation in a freight system (Vis and Koster, 2003). For a freight system to function properly and optimally each of its mode must operate in tandem under certain predicted travel time ranges. The goal for this functionality is to cause minimal delay to any individual component of the system. This is gauged

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by having a reliable and resilient arrival times of commodities at destinations with freight trucks. The importance of punctuality in arriving of commodities at the terminals becomes critical if the terminal point turns out to be the point of origin, termination, interchange, or of transfer. Therefore, delayed arrivals to these terminals cause late pick- ups, delayed deliveries, or delays for the other modes of transportation waiting for the freight, which in turn results in high transportation costs (Rodrigue et al., 2009; Vis and Koster, 2003). Timely arrivals of commodities at the terminal depend on the resilience in transportation exhibited by the freight network system.

Resilience (and also vulnerability) due to its underlying importance have been used quite widely in transportation literatures (Cats and Jenelius, 2012; Reggiani, 2013; Gao et al., 2012). However, in most of the literatures, resilience strategies and principles are not very well tied with multimodal freight performance metrics – a prerequisite to timely arrivals of commodities to the destination. As a recent report by Hughes and Healy (2014) points out that this is mainly because resilience principles differ in their definition and application. Added to the complexity are the uncertainties in types, magnitudes and frequencies of causes and failure modes for freight operations. The National Infrastructure Advisory Council (NIAC) developed a set of recommendations for establishing critical infrastructure resilience goals under four broad categories – of robustness, resourcefulness, rapidity and adaptability (NIAC, 2010). Robustness is the ability to absorb shocks with continuous operations, resourcefulness is the management of disruption as it unfolds rapidity deals with the ability to revert to normal conditions as quickly as possible and adaptability allows absorbing new lessons learned after a disaster. Although the four principles together serve as good performance criteria for resiliency for any general incident response planning purpose, not sufficiently though for freight. Critical to a carrier's and shipper's needs are also the redundancy aspect of freight operations that should be appropriately incorporated within the selected set of resiliency principles.

The freight transportation network in California is large and complex. However, with such a vast and complicated network issues concern timing and unforeseen accidents can cause delays and sometimes result in segments of a network needing to wait for the other parts of the network to improve due to being unable to restart operations after incidents occur. Therefore, a possible method for optimizing the freight transportation network is integrating connected vehicle technology (CVT) in multimodal freight operations. Similar research has been carried out by Chandra et al., (2019) on smart freight operations. CVT might be used to improve the resilience of a multimodal transportation network. By using CVT, it would be possible to become informed of any issue that can result in delays and could even guide users in a direction that can help minimize the effect of any unforeseen event may have had on the system (Golob and Regan, 2001). Furthermore, seeing as how the majority of surface freight transport occurs on roads it is vital that the technology used focuses on trying to improve that section of freight operation. This can be accomplished by improving the communication that occurs between other vehicles to avoid situations that could worsen traffic condition due to the presence of freight trucks and in the same time cause delays throughout the freight transportation network. Additionally, improving the communication occurring between not only freight trucks but also involving the other mode of transportation involved allow decision-making to also become optimized due to the ability to now take into account all delays in every mode involved in the process and thereby plan for situations in which operation may be affected in order to minimize its effect on the system.

A resilience indicator should be able to capture the ability of the link/node to absorb shocks or disruptions and continue to assist in multimodal freight operations. Several literature address network resilience in conjunction with network vulnerability (Mattsson and Jenelius, 2015). For example, Chen and Miller-Hooks (2012) provide an indicator for resilience that quantifies the ability of an intermodal freight network with consideration to negative consequences of disruptions resulting from topological and operational attributes. Variables used in the indicator consist of number of shipments transported and set of candidate recovery activities. Resilience is also closely tied to reduced failure probabilities, reduced consequences from failures and reduced time to recovery (Bruneau et al., 2003). Vadali et al. (2015) note that network disruptions used for truck routes can be approximated by several performance metrics such as travel time measures, percent of population receiving essential services and/or economic costs. And resilience has been described as the ability of the network to internalize minor perturbations. Goods and freight movement is primarily controlled by the private sector market while infrastructure facilities and maintenance are mainly the prerogative of the public agencies. Disruptions to critical networks and nodes can have potential impacts to overall freight movement and have repercussions on the commerce and the economy. Thus, the indicator of resilience should be comprehensive and be able to capture all of four components that underline resilience – robustness (ability to absorb shocks and keep operating), redundancy (back-up resources to sustain operations), resourcefulness (able to manage disruption as it unfolds), and rapidity (quickly get back to normal operations) (Tierney and Bruneau, 2007).

2. Methodology

The resilience indicator developed in this paper is based on the derivation by Chandra et al. (2018). The logic is based on minimizing travel time aftermath a congestion- which might occur due to sudden disruption on the path of travel of a freight truck. The formulation of the resilience developed for a simplistic case is described below:

2.1. Formulation

The sketch in Fig. 1 and Fig. 2, show the location of *n* ramps between points A and B. The area of analysis has a length, *L*, and width, *W*. The travel time between ramps is denoted using *t*.

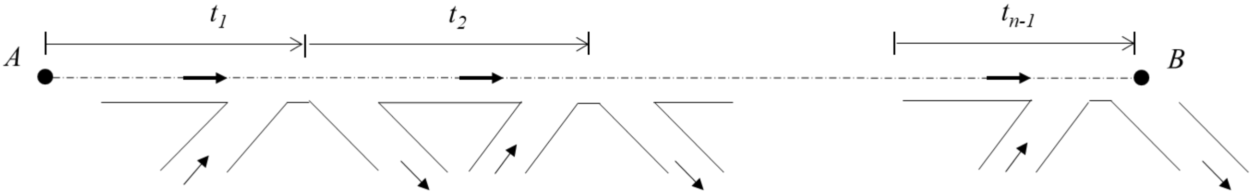

Fig. 1. Set-up for off-ramp and on-ramp freight vehicle travel

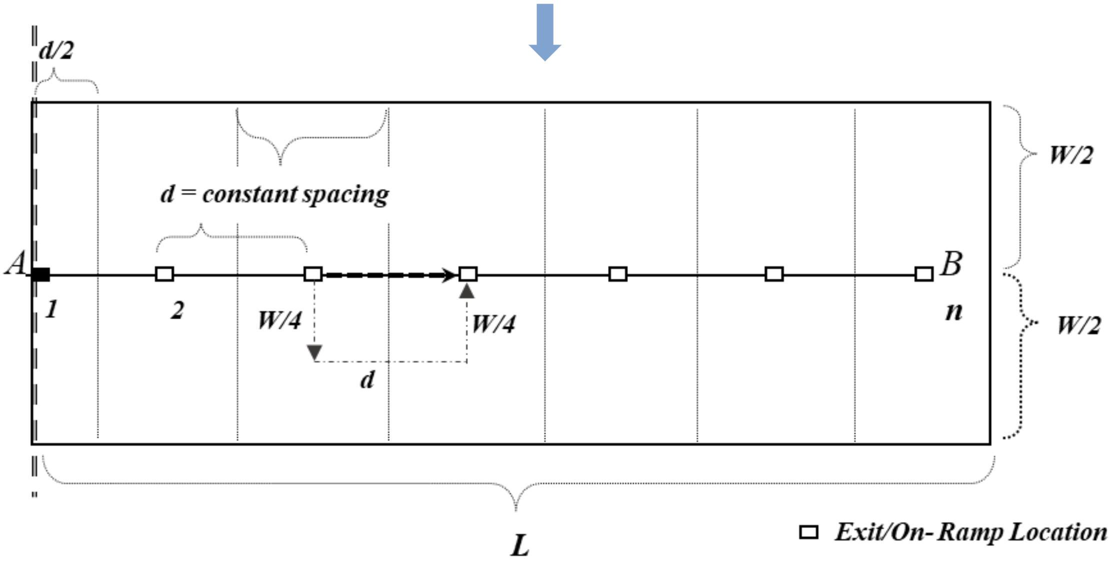

Fig. 2. Simplified set-up for the freeway segment shown in Fig. 1 (Source: Chandra et al., 2018)

The expected travel time, $E\left[\Gamma_1\right]$, from exit ramp 1 to exit ramp 2, is:

$$E\left[\Gamma_1\right] = x\lambda + (1-x)k \tag{1}$$

where,
λ = travel time on the congested link on the freeway between two consecutive ramps,
x = probability of traveling on the congested link on the freeway, and
k = average travel time from exit ramp on to next immediate downstream on-ramp joining to the freeway, expressed using $k = \frac{1}{v}\left(\frac{W}{4} + d + \frac{W}{4}\right) = \frac{1}{v}\left(\frac{W}{2} + d\right)$, with v being the average speed of the freight vehicle traveling from the exit ramp to the next on-ramp.

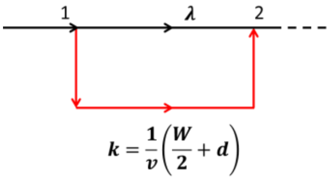

Fig. 3. Detour from exit ramp 1 to join freeway through on-ramp 2

Similarly, the expected travel time, $E\left[\Gamma_2\right]$, from exit ramp 1 to exit ramp 3, if the congestion is between ramp 2 and 3, is:

$$E\left[\Gamma_2\right] = t_1 + x\lambda + (1-x)k \tag{2}$$

Using the sketch in Fig. 4, the expected travel time from exit ramp 1 to exit ramp n, $E\left[\Gamma_{n-1}\right]$, is:

$$E\left[\Gamma_{n-1}\right] = \left[t_1 + t_2 + \ldots + t_{n-2} + x\lambda + (1-x)k\right] \tag{3}$$

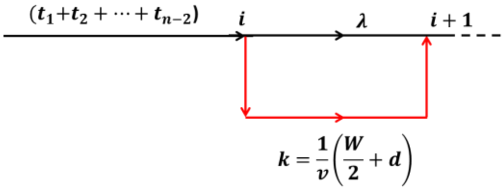

Fig. 4. Detour from exit ramp i to re-join freeway on-ramp (i+1)

The resilience of the path, r_n, will be inversely proportional to the average travel time from A to B and is expressed as follows:

$$r_n = \frac{1}{\left\{E\left[T_n\right]\right\}^{\beta}} \tag{4}$$

where, β is the decay parameter controlling the extent of expected travel time, and

$$E\left[T_n\right]=\frac{1}{LW}\left(\frac{2LW}{2n-1}\right)\times E\left[\Gamma_1\right]+\frac{1}{LW}\left(\frac{2LW}{2n-1}\right)\times E\left[\Gamma_2\right]+\ldots+\frac{1}{LW}\left(\frac{2LW}{2n-1}\right)\times E\left[\Gamma_{n-1}\right] \tag{5}$$

With the assumption, $t_1 \approx t_2 \approx \ldots \approx t_{n-1} \approx \tau$ and $E\left[T_n\right]$ is:

$$\Rightarrow E\left[T_n\right]=\left\{\frac{n\tau}{2}-\tau+x\lambda+(1-x)\frac{1}{v}\left(\frac{W}{2}+\frac{2L}{2n-1}\right)\right\}^{\beta} \tag{6}$$

The expanded form of the resiliency indicator r_n is:

$$r_n=\frac{1}{\left\{\frac{n\tau}{2}-\tau+x\lambda+(1-x)\frac{1}{v}\left(\frac{W}{2}+\frac{2L}{2n-1}\right)\right\}^{\beta}} \tag{7}$$

3. Application Example

Application of the resilience indicator is shown with I-710 which is a prominent freeway truck route in the Southern California Region. The decay parameter, β, and the parameter, α, controlling dispersion in choice of the exit are estimated based on the travel time data collected for approximately 20-miles of continuous stretch of the freeway.

The travel time data and the tonnage information for the links are used for estimating β. The value of β is found to be 12. The tonnage values are obtained from the year 2012 from the Freight Analysis Framework (FAF) data (FAF, 2012). The travel time information is obtained from the Google Maps between 6:00 am to 8:00 pm. Table 1 presents the compiled information for the parameter values. Fig. 5 shows the spatial location of the analysed section of the I-710 used in the application example.

Table 1: Input values to calculate r_n

Parameter/Input Variables	**I-710**
v (mph)	30
d **(**in miles, average between two exit ramps)	1.31
λ **(**mile/mph)	0.131
τ **(**mile/mph)	0.02382
L (miles)	20
W (miles)	2
x	0.25, 0.5, 0.75
β	12

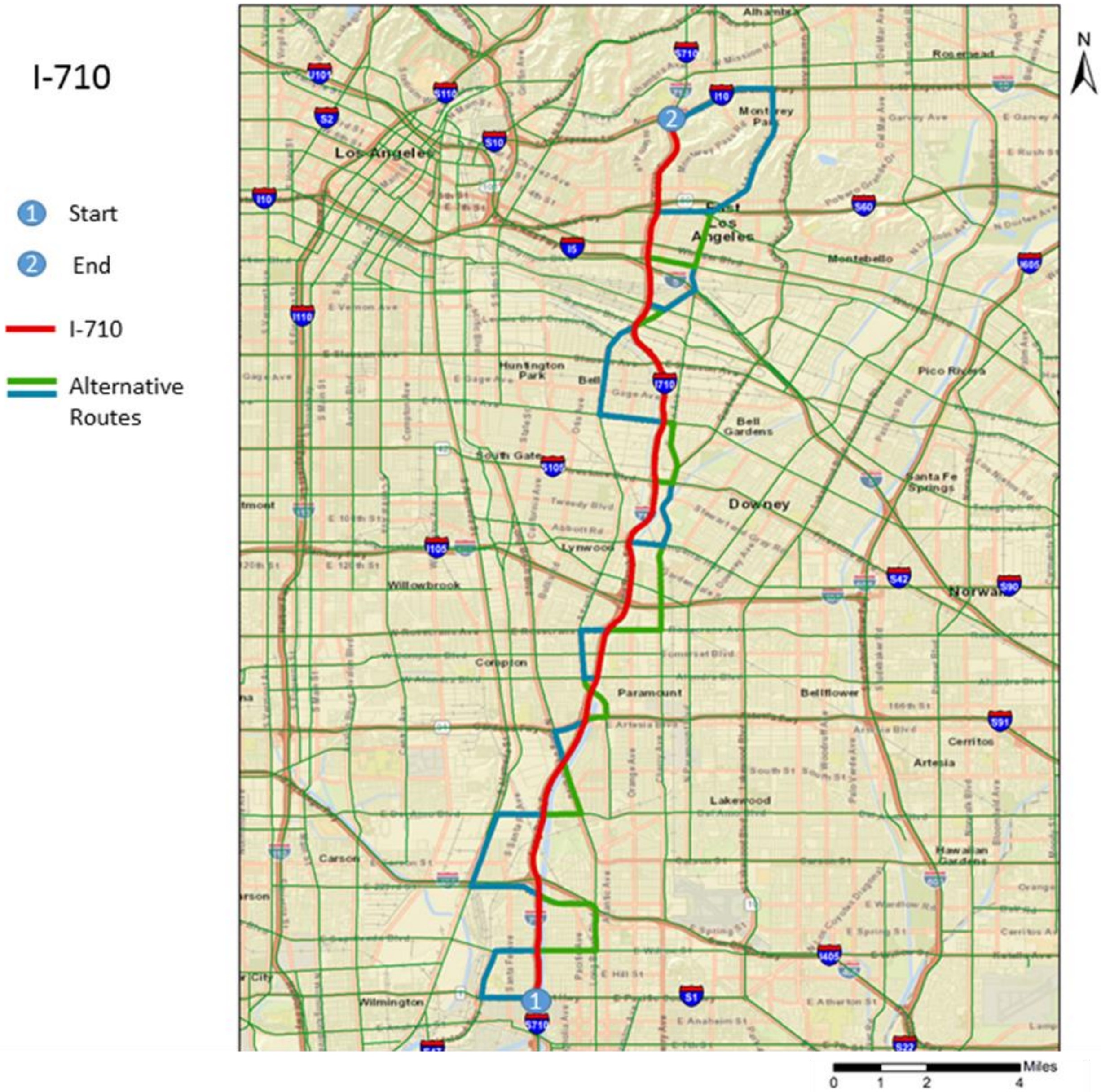

Fig.5. Spatial location of the analysed 20-mile length of the I-710 (Data Source: Caltrans, 2018)

4. Results

By using the expression for resilience indicator in Eq. (7), Fig. 6 shows the comparison of resilience indicator r_n with respect to n for I-710. Three different values of probability x (=0.25, 0.5 and 0.75) were used to make a comparison for the optimal exit ramp. At this optimal ramp exit selection, truck should exit to maximize route resilience.

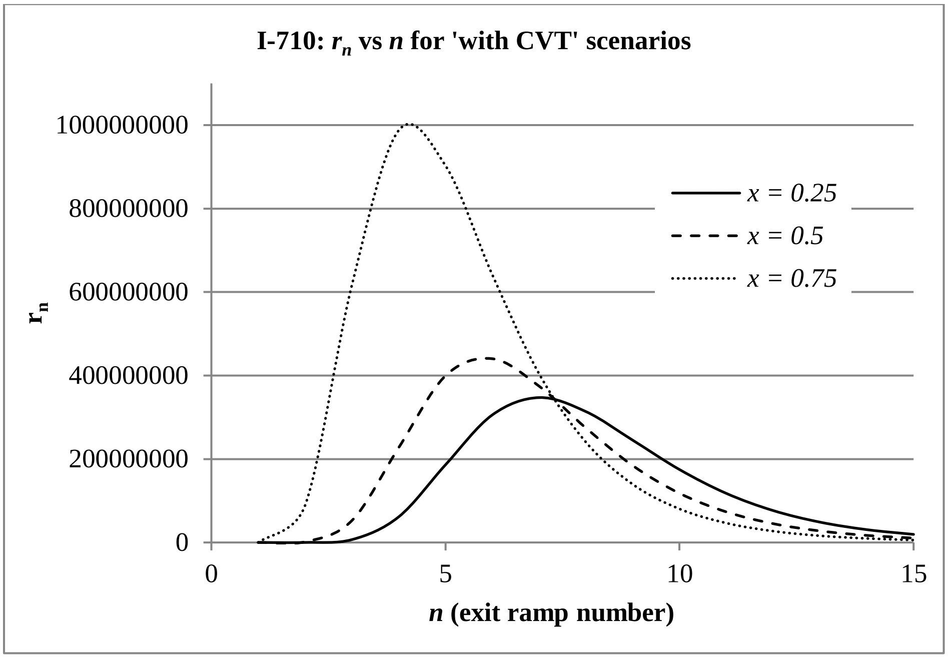

Fig.6. Variation of resilience indicator with number of exit ramps for I-710

Observing the sketch Fig. 6, optimal *n* can we estimated for a given *x*-value such that the resiliency indicator is maximized. The resiliency is maximized for the 20-mile section of I-710 with the optimal values of n = 7, 6 and 4 for truck detour probabilities x = 0.25, 0.5 and 0.75, respectively. Thus, with increase in values of *x*, the value of optimal *n* decreases. The findings suggest that in order to enhance resiliency of I-710, as an important truck route, there might be opportunities for the truck to detour at certain designated exit ramps of the freeway. As I-710 is considered to be an important freeway for transportation of commodities originating at the Ports of Long Beach and Los Angeles, enhancing resiliency of routes can add to sustained economic activity of the Southern California Region.

It can also be noted from the chart in Fig. 6 that with an increase in detour probabilities, *x*, the magnitude of the resiliency indicator increases. This indicates that as the truck travels closer to the downstream congestion point, the truck should make an exit with a high detour probability to maximize its route resiliency.

5. Concluding Remarks

This paper develops a new resilience indicator imbibing the characteristics of connected vehicle technology (CVT) with focus on freight truck operations. Traffic factors such as road speed and infrastructure factors such as location of ramps on a given freeway are used as inputs to the resiliency indicator.

Basic analysis carried out using the 20-mile stretch of the I-710 freeway. I-710 is considered to be an important freeway in the Southern California Region with very high truck volumes. The freeway also connects two of the major sea ports in the United States, namely, Port of Long Beach and Port of Los Angeles, to rest of the part of the nation. Results show that resiliency of truck route is maximized if detour ramps that are located at 7th, 6th and 4th position from the truck location are used. This is applicable if the detour occurs at respective probabilities equal to 0.75, 0.5 and 0.25. The truck detour, if it occurs, from the freeway is governed with information received using connected vehicle technology (CVT) about the downstream congestion. Detours enhancing resiliency of the truck route could saving truck travel time and minimize duration of an already existing delay on downstream freeway traffic.

It is also noted that with increase in probability of a truck being able to exit a freeway (indicated by *x*), it was found that for the ramp to be used to maximize resiliency decreases. This research shows a very useful application of CVT to enhance resiliency of truck routes. Detours are sometimes necessary and feasible due to severe downstream congestion on the route. The outputs of the application example using I-710 in this research can be helpful in enhancing freight operations by utilizing emerging technologies such as CVT to design an efficient multimodal freight network system for trucks.

Acknowledgements

The authors would like to acknowledge the funding support from METRANS for conducting this research.

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