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How is freight distribution affected by travel time unreliability?

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Abstract

The impact of travel time unreliability on freight transport has been extensively investigated in the last 20 years with the main focus being placed on mode and route choice (and using mostly stated preference data). In contrast, freight distribution has been very rarely examined in the literature. In this paper, we describe a study on how travel time unreliability affects interregional freight distribution using (revealed preference) data from the last national transport survey carried out in Iran (2015). Through this study, conducted using spatial interaction models and linear and geographically-weighted regression approaches, we found that, globally, travel time reliability is approximately as important as average travel time in determining freight distribution flows, but this importance varies widely across regions. We also found that tardy trip reliability measures describe freight distribution patterns more accurately than statistical range measures (coefficient of variation of travel time).

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Keywords: Freight distribution; Road transport; Travel time reliability; Spatial interaction models; Geographically-weighted regression.

1. Introduction

Travel time reliability has been the focus of many freight transport planning publications notably since the early 2000s. The development of just-in-time logistics, whose efficiency critically depends on reliable deliveries (Mackelprang and Nair, 2010), partly explains this attention. In Taylor (2013), travel time reliability publications are classified into eleven groups. This paper has clearly to do with four of them. We analyze how freight distribution is affected by travel time unreliability ("travel behavior" publication group) using revealed preference data from the latest transport survey conducted in Iran ("use and application"). In contrast, the main attention of existing publications

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is dedicated to mode and route choice (e.g., Danielis, et al., 2005; Train and Wilson, 2008; De Jong et al., 2014; Larranaga, et al., 2017; Zhang et al., 2019), and they are mostly based on stated preference data (Shams et al., 2017). The main reason for the rarity of freight distribution studies probably is the lack of data (Southwork, 2018). In the study we present in this paper study, we considered two different travel time reliability measures ("reliability metrics"), and compared them in terms of the explanation they provide of freight distribution. The elasticities we obtained for spatial interaction models through linear and geographically-weighted regression approaches are key to characterize the global and local importance of travel time reliability for the freight transport sector of Iran ("valuation"). In brief, we contribute to this literature by analyzing, for the first time, the impact of travel time reliability on freight distribution using revealed preference data, and by using a geographically-weighted regression (GWR) approach to analyze the spatial variations of the impact of travel time reliability on freight distribution. This type of regression has been widely used in some transport research areas, like road accident analysis (e.g., Pirdavani et al., 2014) and transit ridership analysis (Cardozo et al., 2012). In contrast, as far as we are aware, the only article published to date where GWR has been applied to freight studies is Lim and Thill (2008), an investigation into the impact of intermodalism on freight accessibility in the United States.

2. Data

Our study relied on data from the most recent freight transport survey (2015) carried out by Iran's Road Maintenance and Transportation Organization (RMTO). Based on RMTO's Statistical Yearbook, road is, by far, the dominant freight transport mode in Iran – its modal share is 93% of the approximately 540 million tonnes of freight moved annually through the Iranian transport network. This type of survey is held every ten years, and concerns both passenger and freight transport on the main intercity road network. It is based on face-to-face interviews with drivers performed on the side of the road with the assistance of police officers and transport experts. In the last survey, the interviews were performed daily between the 5th and 9th May 2015, in three shifts: 6 am to 2 pm; 2 pm to 10 pm; and 10 pm to 6 am. A total of roughly 700,000 drivers were interviewed, of which approximately 200,000 were driving trucks. The data collected are organized into 73 entries and provide detailed information about freight (type, tonnage, etc.), drivers (age, residence, etc.), vehicles (age, capacity, etc.) and trips (origin and destination, length and duration).

The focus of our study was the 31 main freight zones of Iran (out of the total 124), i.e., the freight zones where province capitals are located. These freight zones are identified by their centroids in Fig. 1. In this figure, we also represent the main road network of Iran.

Fig. 1. Main municipalities and road network of Iran (circle sizes are proportional to municipality populations).

The travel time data obtained through the survey are exemplified for Tehran in Fig. 2. It contains a boxplot diagram showing the variability of travel times for the shipments originating in Tehran's freight zone (for each box, the central edge indicates the median travel time, and the bottom and top edges indicate the 1st and 3rd quartiles, respectively). In particular, the figure makes clear that travel time variability severely affects freight sent from Tehran to the peripheral zones of Bandar Abbas (BA) and Zahedan (ZH), in southern Iran.

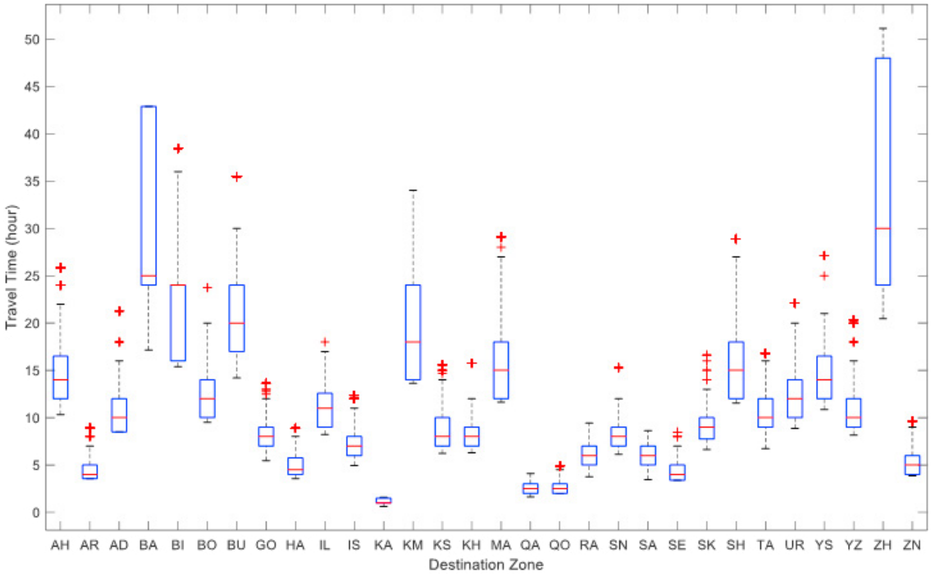

Fig. 2. Variability of travel times for freight shipments originated in Tehran.

Furthermore, in Fig. 3, we summarize the road freight flows produced and attracted by the 31 freight zones considered in our study. As one could expect, Tehran, Mashhad and Isfahan, the three largest population and employment centers (in the latest census their populations were 8.73, 3.37, and 2.24 million, respectively), are naturally the three main freight generation zones. But some other zones also generate substantial amounts of freight. This is notably the case of Ahvaz and Bandar Abbas (where important ports are located), and also of Bushehr, Shiraz, Tabriz and Yazd.

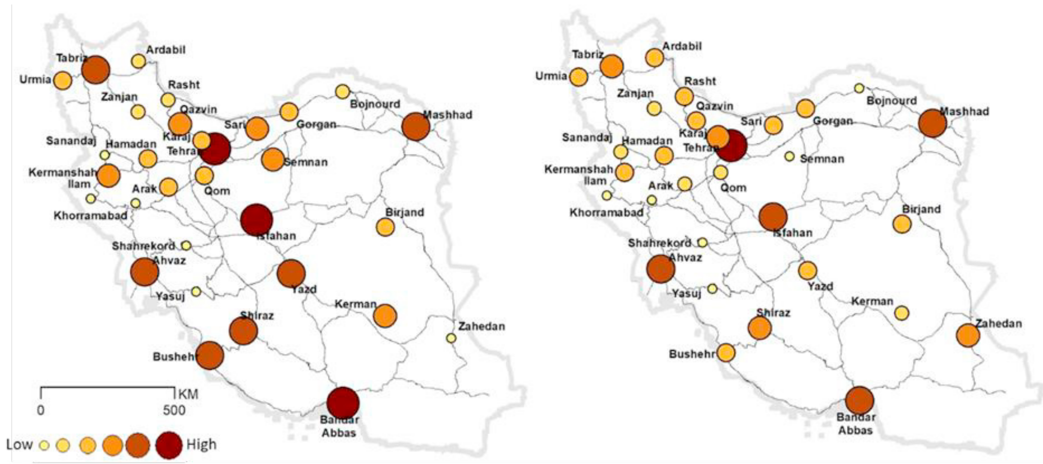

Fig. 3. Freight production (left) and attraction (right) by the main freight zones of Iran.

3. Methodology

In this section, we describe the travel time reliability measures and the modeling approach we have used for studying the impact of travel time unreliability on freight distribution in Iran.

3.1. Travel Time Reliability Measures

The importance of travel time reliability in freight transport planning and operations has been emphasized by several authors, notably Fowkes et al. (2004) and Lyman and Bertini (2008). A wide variety of transport reliability measures (applicable to passengers and freight) has been proposed in the literature; however, as underlined by Wang et al. (2016), different measures capture different components of reliability, and therefore may lead to different conclusions for the same underlying data. According to Lomax et al. (2003) and Van Lint et al. (2008), these measures can be classified into five types: statistical range; buffer time; tardy trip; probabilistic; and skew width. Measures of the first type express the spread of travel time around the expected value using, e.g., the standard deviation or the coefficient of variation. Buffer time measures describe the extra percentage of travel time due to travel time variability that travelers need to take into account to arrive on time to their destinations. Tardy trip measures refer to the number of trips that result in late arrivals. Probability measures express the probability with which a given threshold travel time is exceeded, thus differentiating between reliable and unreliable travel times. Finally, skew width measures depict the leaning of travel time distribution to one side of the mean.

Out of those five types of reliability measures, we focused on the two used more frequently in the literature: statistical range (weighted coefficient of variation of travel time) and tardy trip (tardy freight proportion). The values for both measures were computed based on the information provided by the survey. For every pair (i, j) of the main freight zones of Iran (31 zones), we considered the set of shipments $\boldsymbol{K}_{ij} = \{1, \dots, K_{ij}\}$ registered during the four days in which the survey took place, and for each shipment, $k_{ij} \in \boldsymbol{K}_{ij}$, the freight tonnage ($q_{ijk}$) and the travel time ($t_{ijk}$). The weighted average travel time for shipments between regions i and j (T_{ij}) can be determined by Equation (1), where Q_{ij} represents the total tonnage of freight moved between the zones. Then, using these data, we determined the weighted coefficient of variation of travel time (v_{ij}) and the tardy freight proportion (p_{ij}) for every zone pair (i, j) through Equations (2) and (3). The latter equation includes a parameter $\varphi \geq 0$ (called reliability factor) that defines the threshold above which travel time is considered unreliable. In our study, we assumed $\varphi = 0.10$ based on a recommendation from Vandervalk (2014). Both v_{ij} and p_{ij} are greater than or equal to zero: v_{ij} is zero when all shipments take the exact same time, and increases with travel time variability being unbounded from above (though it will only exceed one if the weighted standard deviation of travel time is greater than the average); p_{ij} is zero when all shipments are made within the travel time reliability threshold, and increases with the shipments whose travel time are above that threshold, but never reaches one.

$$T_{ij} = \sum_{k \in \boldsymbol{K}_{ij}} \frac{q_{ijk}}{Q_{ij}} \times t_{ijk} \,,\; Q_{ij} = \sum_{k \in \boldsymbol{K}_{ij}} q_{ijk} \tag{1}$$

$$v_{ij} = \frac{\sqrt{\sum_{k \in \boldsymbol{K}_{ij}} \frac{q_{ijk}}{Q_{ij}} \left(t_{ijk} - T_{ij}\right)^2}}{T_{ij}} \tag{2}$$

$$p_{ij} = \sum_{k \in \boldsymbol{K}_{ij}} \frac{q_{ijk}}{Q_{ij}} \times \delta_{ijk} \,,\;\; \delta_{ijk} = \begin{cases} 1 \Leftarrow t_{ijk} > (1+\varphi) T_{ij} \\ 0 \Leftarrow t_{ijk} \leq (1+\varphi) T_{ij} \end{cases} \tag{3}$$

The two measures presented above capture travel time reliability in a very different way. We make this clear in Fig. 4, where we characterize the main freight zones of Iran, i, according to the average values of the weighted coefficient of variation of travel time (V_i) and the tardy freight proportion (P_i with $\varphi = 0.10$) of its shipments to all other main zones, j, respectively given by Equations (4) and (5). This is notably illustrated by the positions of Karaj and Urmia in the ranking of travel time reliability: when the measure is V_i, these freight zones are near the top (large dark brown circle in the left pane of Fig. 4); when, instead, the measure is P_i, they are the worst two zones (small light yellow circles in the right pane of Fig. 4). This signifies that the measure chosen to perform this type of analysis can greatly influence its results.

$$V_i = \sum_{j \in \boldsymbol{N}} \frac{Q_{ij}}{Q_i} \times v_{ij}, Q_i = \sum_{j \in \boldsymbol{N}} Q_{ij} \quad (4)$$

$$P_i = \sum_{j \in \boldsymbol{N}} \frac{Q_{ij}}{Q_i} \times p_{ij} \quad (5)$$

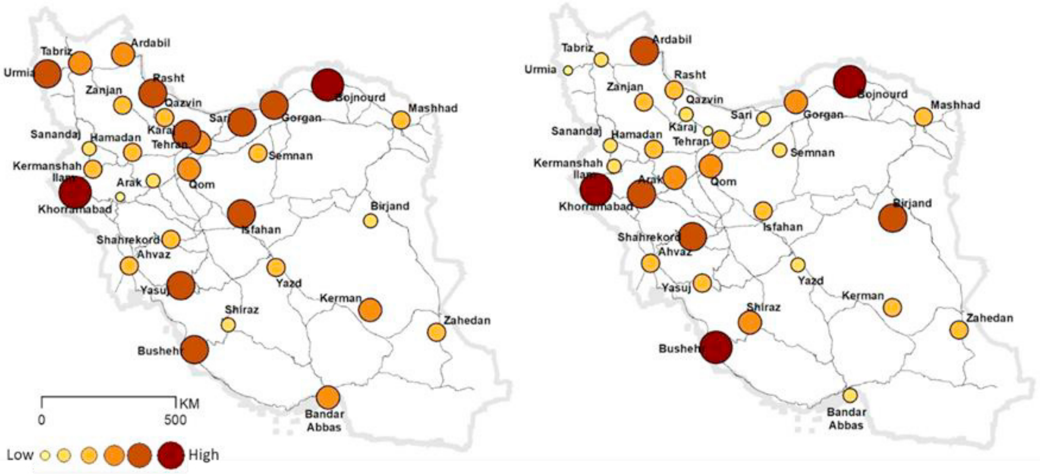

Fig. 4. Average travel time reliability for the main freight zones of Iran as measured by V_i (left) and P_i (right).

3.2. Spatial Interaction Modeling Approach

For our study, we have taken as reference one of the models used more widely in the analysis of spatial interaction phenomena: the unconstrained gravity model; see, e.g., Fotheringham and O'Kelly (1989, Chap. 3) and Ortúzar and Willumsen (2011, Chap. 5). In Equation (6) we present the specific form of the model we have work with. As compared to the classic form, the difference is that travel time reliability is an argument of the impedance function.

$$Q_{ij} = \mu \frac{(E_i E_j)^{\zeta}}{I_{ij}}, \quad I_{ij} = t_{ij}^{\beta} r_{ij}^{\gamma} \quad (6)$$

where Q_{ij} designates the freight tonnage moved between zones i and j, E_i and E_j the employment in zones i and j, I_{ij} the travel impedance between zones i and j, t_{ij} the average travel time between zones i and j, r_{ij} the travel time reliability between zones i and j (i.e., $\boldsymbol{v_{ij}}$ or $\boldsymbol{p_{ij}}$ depending on the measured used), and μ, ζ, β and γ are statistical parameters. The last two parameters are, respectively, the elasticities of freight tonnage with respect to average travel time and to travel time reliability.

For estimating the model using linear regression and GWR, we logged its terms (making it linear in the logged variables) and added errors ε_{ij} with expected value equal to zero to obtain Equation (7). The units of the data used in the estimation were as follows: Q_{ij} - million tonnes; E_i, E_j - million jobs; t_{ij}- hour; r_{ij}- percentage.

$$ln\, Q_{ij} = ln\, \mu + \zeta\, ln(E_i \times E_j) + \beta\, ln\, t_{ij} + \gamma\, ln\, r_{ij} + \varepsilon_{ij} \quad (7)$$

Based on this model, we then applied the methodology advocated in Charlton and Fotheringham (2009), based on Fotheringham et al. (2002): first, we estimated the model (Equation 3) through linear regression (ordinary least squares), and then, to account for spatial correlation effects (which were indeed found to exist), we estimated it through GWR. The difference between these two types of regression can be easily understood by comparing Equations 8 and 9, where y, x_j $(j = 1, \ldots, m)$ and n designate, respectively, the dependent variable, the m explanatory variables and the number of observations. In a linear regression (Equation 8), coefficients (α) do not change over space. In contrast, in a GWR (Equation 9), coefficients change with the geographic coordinates of the places (freight zones in the case of our study), designated by u_i and v_i $(i = 1, \ldots, n)$. Therefore, the coefficients provide information on how the relationship between dependent and explanatory variables vary over space. The latter variables are included in the GWR equation according to a spatially-varying function (kernel) that gives more weight to observations from close places than to observations from distant ones.

$$y_i = \alpha_0 + \sum_{j=1}^{m} \alpha_j x_{ij} + \varepsilon_i, i = 1, \ldots, n \quad (8)$$

$$y_i = \alpha_0(u_i, v_i) + \sum_{j=1}^{m} \alpha_j(u_i, v_i) x_{ij} + \varepsilon_i, i = 1, \ldots, n \quad (9)$$

4. Results

The main results of our study are displayed in Table 1. Therein, we compare the results we have obtained for the best linear regression model we have estimated (BLR) and for the corresponding GWR model. The travel time reliability variable is *Tardy_Freight* (p_{ij}) because goodness-of-fit statistics revealed that it explains freight distribution in Iran much better than *Weighted_COV* (v_{ij}). The variable *Port_Effect* was included in the models because, otherwise, the modelled freight flows would be severely underestimated.

Table 1. Estimation results for the BLR and GWR models.

Variable	BLR model		GWR model			
	Coefficient	t-stat	Coefficients' range	Coefficients' average	Coefficients' std. deviation	t-stat range
Intercept	6.870	31.787	[5.609, 9.999]	7.601	1.067	[2.722, 15.036]
Employment	0.775	19.206	[0.240, 1.382]	0.838	0.277	[1.322, 10.837]
Travel_Time	-0.373	-6.433	[-1.526, 0.113]	-0.568	0.374	[-4.953, 0.622]
Tardy_Trip	-0.526	-5.385	[-1.510, 0.572]	-0.359	0.469	[-3.761, 1.069]
Port_Effect	0.136	8.479	[-0.033, 0.363]	0.159	0.095	[-0.451, 5.974]
R^2_{adj}		0.46				0.61
AICc		1619.9				1458.5
Moran's *I*		0.246				0.004

The analysis of the BLR results reveals that all explanatory variables are clearly significant with a probability of 95% (|t-stat| > 2). The impact of *Tardy_Freight* on freight distribution (elasticity = -0.526) exceeds that of *Travel_Time* (-0.373). However, the goodness-of-the fit of this model is relatively low (R^2adj = 0.46), indicating that predictions made with this model need to be taken with caution. Moreover, Moran's *I* clearly suggests that residuals are spatially clustered (thus correlated), which raises further concerns about model predictions.

These concerns are overcome when the GWR model is applied. It fits the data much better, as attested by the substantial increase of R^2adj (from 0.46 to 0.61) and the substantial decrease of the AICc (from 1619.9 to 1458.5), and makes it possible to discover the spatial pattern of the impacts of *Travel_Time* and *Tardy_Freight* on freight distribution (see Fig. 5). In particular, this figure shows that the northern regions of Iran, the most populated of the country, are the ones where those impacts are stronger. They are also the regions where they are more significant. In contrast, in the southern region, the same impacts are generally weak and often not significant. It should be noted that, according to the GWR model, freight distribution is, on average, less sensitive to *Tardy_Freight* (elasticity = -0.359) than to *Travel_Time* (-0.568). However, it would be the converse if elasticities were calculated considering only the freight zones for which these variables are significant. In this case, the elasticities would be -0.951 and -0.791. That is, overall, the impact of *Tardy_Freight* on freight distribution appears to be quite similar to that of *Travel_Time*.

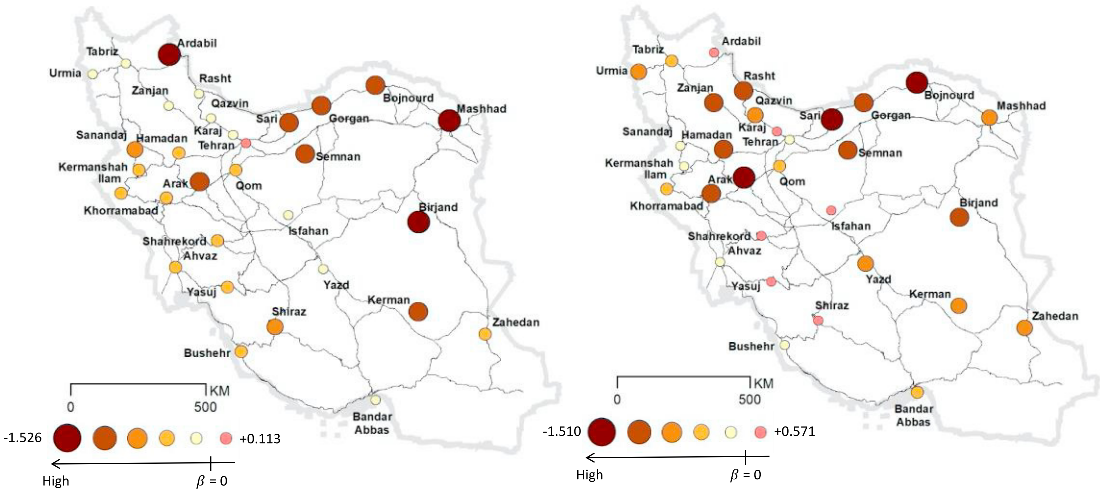

Fig. 5. Local coefficients (elasticities) of freight distribution with respect to *Travel_Time* (left) and *Tardy_Freight* (right).

5. Conclusion

In this paper, we analyzed how travel time unreliability affects road freight distribution in Iran, both globally and locally. Our results reveal that travel time unreliability is a factor practically as important as average travel time in explaining freight distribution, in the sense that their respective elasticities are quite similar, and that freight distribution in the northern part of the country is clearly more sensitive to travel time unreliability than in the southern part. Moreover, they reveal that, at least in Iran, tardy trip measures capture the impact of travel time unreliability on freight distribution more accurately than statistical range measures. These outcomes should be taken into account in the formulation of future freight transport policies and road network plans.

Despite our focus was placed in Iran, we believe that this paper is a significant contribution to the growing literature dedicated to freight transport reliability – to our best knowledge, no previous journal articles have ever examined the impact of travel time reliability on freight distribution (in contrast, articles on mode and route choice are frequent, particularly in recent years). Two other features of our paper should also be highlighted: first, we rely on revealed preference data, whereas most freight transport reliability literature relies on stated preference data; second, we rely on a geographically-weighted regression to analyze freight transport behavior, which only happened before in a single study.

Further research steps in the same area should follow two directions. The first is to improve the goodness-of-fit of the models, e.g., by including some probably missing explanatory variables (in particular, variables describing the types of freight moved between zones), by considering buffer time reliability measures, or by applying other types of modelling approaches (namely, fractional split-distribution models and artificial neural network models). The second, more important in our view, is to investigate the causes of travel time unreliability. A deep understanding of these causes is crucial to establish proper policy measures for improving freight distribution in Iran.

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