DYNAMIC WEIGHT CAPACITY UTILIZATION AND EFFICIENCY IN FREIGHT TRANSPORT: AN APPLICATION OF WEIGH-IN-MOTION DATA

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ABSTRACT

Transportation performance is seriously deteriorated by the events in the road network, such as congestion and accidents. Utilization and efficiency are traditional methods to evaluate performance. Both of them are static, and only take input or output of the system into account. With respect to the fact that logistics system shares the road network with other traffic, evaluating transportation performance should take the dynamic freight process in the road network into account. Thus, the objective of this paper is to set up novel approaches to quantitatively evaluate transportation performance from the multiple perspectives. We introduce two new measures of transportation performance based on observable information: dynamic weight capacity utilization and the cost of transportation inefficiency as transportation impact cost. Dynamic weight capacity utilization draws on momentum with the product of weight and speed, comparing with ideal situation of maximal weight and free flow speed. Transportation impact cost fuses truck loads, transportation value and traffic situation to present transportation inefficiency. These two measures can be used for either logistics companies to better understand and evaluate the performance of trucks, or system operators to get insight into the logistics system. Weigh-in-Motion data and loop detector data on A12 motorway in the Netherlands on March 2010 are the main data sources to represent the cargo and traffic information, and further to test the concepts. Based on the result, dynamic weight capacity utilization and transportation impact cost do fuse different perspectives in the freight system and are able to represent dynamic transportation performance.

KEY WORDS: Transportation Performance, Dynamic Weight Capacity Utilization, Transportation Impact Cost, Weigh-in-Motion System
1. INTRODUCTION

Transportation performance of trucks influenced by cargo and logistics characteristics as well as by traffic conditions. Cargo weight or volume below capacity adversely affects a truck’s performance. Also, contractual arrangements about the movement of cargo may influence transportation performance. In addition to these logistics aspects, road and traffic conditions, like accidents, congestion and the weather, may seriously affect transportation performance. In fact, logistics companies are well aware that their transportation performance is at least partly determined exogenously. For instance, Golob and Regan (1) find that trucking companies consider traffic congestion to have detrimental effects on reliability and costs, among other performance dimensions. Moreover, companies act on traffic information as they plan the routing of trucks in view of expected travel times. The intertwining of private logistics sources of variation in transportation performance and public road network sources calls for indicators that take both sources explicitly into account. The objective of the current paper is to develop two such measures, dynamic capacity utilization and transportation impact cost.

Utilization and efficiency are key concepts in performance evaluation and have practical significance for resource allocation among competing entities (2). Existing weight capacity utilization measures are static, measuring the ratio of the weight or volume of the cargo in a truck and the capacity of the truck in terms of maximum allowable cargo weight or volume. Transportation efficiency measures how much it costs (in dollars, time, or energy) to move a certain amount of freight. The concept is relevant for different stakeholders at different levels of aggregation. Logistics service providers would like to conduct efficient transport operations by consolidating freight in time or across routes. Truck carriers may want to judge the transportation performance of individual trucks in their fleet. Freight transport generates value based on the value differential of the use of the goods between origin and destination. In most cases, such value is created only when the goods are delivered in a timely fashion. Additionally, freight transport and private vehicles share the same road network. Research on traffic management abstracts a vehicle as a particle to describe emergent behavior in traffic flows. In this approach, specific characteristics of each vehicle are usually ignored. In freight transport, characteristics such as weight and transportation value are essential. Thus, we introduce the notion of dynamic capacity utilization and transportation impact cost as the cost of transportation inefficiency.

In order to measure heterogeneous characteristics of trucks and behavior of trucks in the road network, multiple data sources are required. Weigh-In-Motion (WIM) is a technology to capture and record axle weights and gross vehicle weights as vehicles drive over a measurement site. Unlike static weigh stations, WIM systems are capable of measuring at normal traffic speeds and do not require the vehicle to stop or drive at low speed, making them much more efficient. Most work based on WIM data deals with bridge design and pavement maintenance (3, 4, 5). Applications of WIM data for transport operations are rare. In addition, loop detectors capture traffic flow and time mean speed to represent the traffic states in the road network, in which freight transport participates.

This paper aims to define and motivate two measures of transportation performance: dynamic capacity utilization and transportation impact cost. These measures bring together two important aspects of transportation performance: the ability of logistic service providers to operate at full capacity and the ability of road networks to support travelling at free flow. We apply these measures to transportation on the A12 highway in the Netherlands, using Weigh-in-Motion data together with loop detector data. The results show among other, that dynamic weight capacity utilization differs between truck types and varies over time. Moreover, we find that transportation impact cost are highly volatile and can be quite substantial even at modest values of transport services.

The remainder of this paper is organized as follows. In the following section, related literature about transportation utilization and efficiency is discussed. In section 3, two innovative
approaches to measure transportation performance are presented. A case study of the A12 highway in the Netherlands is carried out in section 4. Section 5 finalizes the paper.

2. LITERATURE REVIEW

The existing literature provides several approaches to evaluating performance. Adopting a supply chain perspective, Schmitz and Platts (6) identify roles and functions of supplier performance measurement as a management control tool mechanism and as a tool in supply chain management. Yuan and Lu (7) define transportation efficiency by qualitatively exploring the notion in the context of urban transportation structure, urban traffic management, energy reservation, and environmental protection.

Based on the relations between inputs and outputs, Caplice and Sheffi (8) define the performance of activities in terms of utilization, productivity (or efficiency), and effectiveness. Utilization refers to actual input divided by norm input, i.e. the amount of input targeted or planned. In transportation, actual cargo weight divided by the cargo weight capacity of the truck is an important example. Productivity measures efficiency as the ratio of the output produced and the input consumed. An example in transportation would be the ton-km delivered or the number of service hours of labor. Effectiveness refers to actual output divided by norm output. Here, the example could be the amount of deliveries on time as compared to the total amount of deliveries, which is also referred to as service level or reliability. Van Amstel (9) gives a framework of performance indicator in terms of effectiveness and efficiency. The five phases in his control cycle are process description, collection of information, calculation of performance indicators, judgment of performance, and analysis of deviations.

In the nineties, Data Envelopment Analysis (DEA) was introduced to evaluate performance by relating inputs and outputs. DEA has been applied to measure efficiency in many fields, such as port areas (10, 11, 12), transit systems (13, 14), and transportation systems (15). Using DEA, Karlaftis’ (14) obtains efficiency rankings and efficient subsets of transit systems, while Fu et al. (15) analyze the efficiency of para-transit systems. The objective of (15) was to determine sources of inefficiency, and they used regression analysis to identify relationships between efficiency and factors impacting the system performance. DEA can be used to evaluate the performance of transportation systems, but it only considers information about inputs and outputs, and discards information about the process. Features of the transportation process that lead to variation in performance are not taken into account.

Our notions of dynamic capacity utilization in transportation systems consider input, process and output. Dynamic utilization is the actual amount of ton kilometers delivered per time unit divided by maximum attainable ton kilometers per time unit. It incorporates not only the amount of cargo in the truck as an input, but also the process of trucks travelling in the road network with a certain speed. Dynamic utilization reflects the impacts of congestion by indicating unused capacity due to reduced speed. Moreover, it reflects common trade-offs in transportation, such as the decision between early departure with a truck load below capacity to arrive in time and late departure at full capacity but at the risk of arriving too late due to a congested network.

3. MEASURES OF TRANSPORTATION PERFORMANCE

Transportation involves trucks carrying cargoes with value from origin to destination during a certain travel time. During the trip, they share the road network with other traffic. The other traffic interacts with transportation. Transportation performance is defined as cargoes arriving at desired destinations within the expected time. Cargo information is normally represented by weight, volume, surface and contract. Here, we focus on weight measurement since it is the unique value which can be measured while trucks are travelling.

In addition, the transportation process in the road network is as important as it can help us better understand transportation behavior and further explain transportation result. Since transportation combines the perspectives of transportation value and traffic flow, measuring
transportation performance should take both aspects into account. Transportation value is an economic concept, while traffic flow is a physical concept related with movement. There are two proposed approaches to measure transportation performance: dynamic weight capacity utilization based on weight and traffic situation; and the cost of transportation inefficiency based on transportation value and traffic situation.

3.1 Dynamic Weight Capacity Utilization
Transporatation performance is related with various characteristics of cargo and travelling. Larger weights or volumes of cargo, carrying surfaces occupied by the cargo, and even the contractual conditions under which the cargo is moved will affect performance. Likewise, higher speeds and shorter travel times influence the performance of transportation. For practical reasons, we limit the effect of cargo on transportation performance to that of weight. Nowadays, cargo weight, as opposed to other cargo aspects, is commonly available to road network operators as it is routinely captured by Weigh-in-Motion (WIM) systems installed in the road pavement.

Using WIM-data, we define a static measure of weight capacity utilization as the ratio of the observed joint weight of cargo and truck and the inferred weight capacity of trucks. For each truck, this weight capacity is defined as the maximum load per axle, which is 9 ton (16), times the observed number of axles. Denoting captured weight by \( W_i \) and weight capacity by \( C_i \), our static measure of weight capacity utilization (\( CU_i \)) is defined for each truck \( i \) as:

\[
CU_i = \frac{W_i}{C_i} \tag{1}
\]

Here, we abstract from the contribution of empty truck weight. Obviously, \( CU \) provides information about the utilization of truck weight capacity, but not about service times. Two trucks involved in identical cargo shipments, yet revealing different service times, still differ with respect to the utilization of their capacity in favour of the truck with the lower service time. This suggests that travel information should be part of a transportation performance measure. Accordingly, we introduce the concept of dynamic weight capacity utilization, which combines the notions of weight capacity utilization and movement in the road network. Traditionally, ton-km is used to measure transportation performance, which combines cargo weight and travel distance. But ton-km does not represent the speed at which cargo travels through the road network. Trucks with a short travel distance cannot be considered less efficient than trucks with a longer travel distance, if the speed of the former truck is much higher, for instance. Travel time is an essential element of transportation performance. Any condition in the road network, such as congestion, accidents, rain and snow, can affect total travel time, and thus have an influence on weight capacity utilization. Denoting travel time on link \( k \) for truck \( i \) as \( t_{i,k} \), link distance as \( l_k \), and the average speed of truck on link \( k \) as \( s_{i,k} \), we find the ton-km per hour on each link as:

\[
\frac{W_i \cdot l_k}{t_{i,k}} = W_i \cdot s_{i,k} \tag{2}
\]

The notion of a truck carrying a certain weight of cargo on a link with a certain speed, as embedded in this ton-km per hour, is related with the concept of momentum in physics, defined as the product of mass and speed of objects.
In the ideal situation that trucks are loaded at maximum weight capacity \( C_i \) and travel at free flow \( s^0_k \), the ratio of real and ideal ton-km per hour represent the transportation performance. We thus introduce dynamic weight capacity utilization (\( DCU_{i,k} \)) of truck \( i \) on link \( k \) as the ratio of the real and ideal momentum:

\[
DCU_{i,k} = \frac{W_i \cdot s_{i,k}}{C_i \cdot s^0_k}
\]  (3)

The definition of dynamic weight capacity utilization (\( DCU_{i,k} \)) in Equation 3 requires information about space mean speed as input which is typically not available, as opposed to information about point speed. In practice, there is no systematic way to measure space mean speed. Of course, in-truck devices to capture speed data might be used, but the availability of this data for traffic management is limited. Instead we approximate the space mean speed of individual trucks as link length \( l_k \) divided by the average travel time \( t_k \) on that link, \( s_k = l_k / t_k \).

The average travel time on link \( k \) is assumed to be aptly represented by \( t_k = t^0_k \cdot f(q_k, Q_k) \), where \( f \), a function of link flow \( q_k \) and link capacity \( Q_k \), is a markup on the link free flow travel time \( t^0_k \).

Using the expressions of travel speed and average travel time, dynamic weight capacity utilization is reformulated as:

\[
DCU_{i,k} = \frac{W_i \cdot s_{i,k}}{C_i \cdot s^0_k} = \frac{W_i \cdot l_k / t_{i,k}}{C_i \cdot l_k / t^0_{i,k}} = \frac{W_i \cdot t^0_k}{C_i \cdot t_{i,k}} = \frac{W_i}{C_i} \cdot \frac{1}{f(q_k, Q_k)}
\]  (4)

Dynamic weight capacity utilization for each truck \( i \) on link \( k \) connects cargo information and road information into a single measure of transportation performance.

3.1.1 Dynamic Weight Capacity Utilization for Each Journey of Trucks
The dynamic transportation performance measure has been defined for individual trucks on individual links. Different stakeholders may be interested in different aspects of this measure. A logistic company or truck owner, for instance, may be interested in the transportation performance of a particular truck on a specific journey. Assuming that this journey consists of \( K \) links, an aggregate measure of dynamic weight capacity utilization of the truck, \( DCU_i \), is obtained by averaging the \( DCU_{i,k} \) over the links:

\[
DCU_i = \frac{1}{K} \sum_{k=1}^{K} DCU_{i,k} = \frac{1}{K} \sum_{k=1}^{K} \frac{W_i \cdot s_{i,k}}{C_i \cdot s^0_{max}} = \frac{1}{K} \frac{W_i}{C_i} \cdot \frac{1}{\sum_{k=1}^{K} f(q_k, Q_k)}
\]  (5)

Obviously, other summary measures may be considered. An example is the minimum dynamic weight capacity utilization over the links, which would be useful to identify links in the network that contribute negatively to the overall transportation performance.
3.1.2 Dynamic Weight Capacity Utilization for Specific Locations

Opposed to individual truck owners, traffic managers may rather be interested in the operations at a specific link in the road network. The transportation performance at a certain link may be indicated by the average dynamic weight capacity utilization as $DCU_k$ over all $N_k$ trucks observed on link $k$ during a selected time window:

$$DCU_k = \frac{1}{N_k} \sum_{i=1}^{N_k} DCU_{i,k} = \frac{1}{N_k} \sum_{i=1}^{N_k} \frac{W_i \cdot s_{i,k}}{C_i \cdot s_{\text{max}}} = \frac{1}{N_k} \frac{1}{f(q_k, Q_k)} \sum_{i=1}^{N_k} W_i$$

(6)

3.1.3 Dynamic Weight Capacity Utilization for Total Journey of Trucks

In order to evaluate transportation system performance consisting of all the trucks in the road network, dynamic weight capacity utilization is aggregated over links and trucks, denoted as $DCU$.

$$DCU = \frac{1}{K} \sum_{k=1}^{K} \frac{1}{N_k} \sum_{i=1}^{N_k} DCU_{i,k} = \frac{1}{K} \sum_{k=1}^{K} \frac{1}{N_k} \sum_{i=1}^{N_k} \frac{W_i \cdot s_{i,k}}{C_i \cdot s_{\text{max}}}$$

$$= \frac{1}{K} \sum_{k=1}^{K} \frac{1}{N_k} \sum_{i=1}^{N_k} W_i \cdot \frac{1}{f(q_k, Q_k)}$$

(7)

3.2 Cost of Transportation Inefficiency by Transportation Impact Cost (TIC)

Transportation activities generate value for various stakeholders, particularly for logistics service providers. Ideally, trucks travel through the network fully loaded and at maximum allowable speed. If for some reason, trucks are not loaded at full capacity or do not travel at maximum allowable speed, the value generation performance of transportation will slow down, and losses will be incurred. For ease of exposition, we label these costs as transportation impact cost (TIC) to evaluate (in)efficiency.

As with dynamic weight capacity utilization, a parallel with the notion of momentum can be made to model these costs.

We assume that the value for logistics service providers, which is generated by transportation activities, can be expressed in euro/ton-km, and we denote this by $\tau_j$. The higher $\tau_j$, the higher the earnings per ton-km. The rate at which this value is generated is determined by transportation momentum. The higher the momentum, the higher the earnings per hour. This value is bound by a maximum, which depends on truck capacity $C_i$ and maximum allowable speed in the road network $s_{\text{max}}$.

Deviations from this maximum may occur as a result of trucks loaded at less than full capacity, $W_i < C_i$, or trucks driving at less than maximum allowable speed, $s_{i,k} < s_{\text{max}}$. We denote these costs as $I_{i,k}$, where $I_{i,k}$ measures the rate at which these costs are incurred, measured in euro per hour.

Collecting terms, we find the costs of deviations between the actual and ideal momentum as:

$$I_{i,k} = (W_i s_{i,k} - C_i s_{\text{max}}) \cdot \tau_j = (\frac{W_i s_{i,k}}{C_i s_{\text{max}}} - 1) \cdot C_i s_{\text{max}} \cdot \tau_j = (DCU_{i,k} - 1) \cdot C_i s_{\text{max}} \cdot \tau_j$$

(8)

A comparison of this expression with Equation 3 shows its intimate relation with the concept of dynamic weight capacity utilization. The closer actual momentum to its ideal, the closer the dynamic weight capacity utilization to one, and the closer the transportation impact costs to zero.
3.2.1 Transportation Impact Cost for the Road System with WIM Location

From the perspective of network management, there may be an interest in the travel impact cost incurred by all trucks at a particular link in the network. Aggregating the travel impact costs of individual trucks \( i = 1, \ldots, N \) yields for each link \( k \):

\[
I_k = \sum_{i=1}^{N_k} (W_i s_{i,k} - C_i s^{0}_{i,k}) \cdot \tau_i = \sum_{i=1}^{N_k} (DCU_{i,k} - 1) \cdot C_i s^{0}_{i,k} \cdot \tau_i
\]

(9)

It makes sense to think of \( k \) as the link that contains the WIM-locations, as this is about the only point in the network where weight is routinely captured.

3.2.2 Transportation Impact Cost for the Journey of Trucks

Logistics companies may be expected to have a preference for cargoes being transported to destinations as soon as possible with the highest value. Assuming that trucks collect route information along the way, then the transportation impact cost for a journey consisting of links \( k = 1, \ldots, K \) are obtained as:

\[
I_i = \sum_{k=1}^{K} (W_{i,k} s_{i,k} - C_i s^{0}_{i,k}) \cdot \tau_i = \sum_{k=1}^{K} (DCU_{i,k} - 1) \cdot C_i s^{0}_{i,k} \cdot \tau_i
\]

(10)

The \( I_i \) reflects the travel impact costs. If it is negative, then the journey has generated less value than possible as a result of under-utilization of truck capacity or congestion in the road network. If \( I_i \) is positive, then trucks have operated at over-capacity or traveled at speeds above the speed limit, or both.

3.3 Summing up

Considering both cargo weight and traffic situation in the road network, we propose a measure of dynamic weight capacity utilization and a measure of transportation inefficiency cost. Dynamic weight capacity utilization evaluates the utilization of transportation capacity from the perspectives of individual trucks and of the road network. It compares the actual momentum with the ideal momentum attained when driving at full capacity at free flow speed. Transportation impact cost addresses the penalty of under-utilization from three perspectives: cargo weight, transportation value, and link speed compared with free flow speed. Both concepts merge the cargo information and road information to measure transportation performance.

4. CASE STUDY

We illustrate the measurement of transportation performance using WIM data for the A12 motorway in the Netherlands, March 2010. The Dutch Ministry of Infrastructure and Environment collects these data. The A12 motorway is one of the main roads in the Netherlands for freight transport, connecting the Rotterdam port area with the north eastern part of the Netherlands and Germany, via the centre of the country. A picture of a WIM-location is in FIGURE 1. The information system connected with the WIM-location collects data about weight, length, speed, time of passing and number of axles. Based on these data, truck types are identified, such as trailer (T), van (V) and bus (B).
In this section, we provide a summary of the transportation information provided by the WIM system. Additionally, we present results for our measures of static and dynamic weight capacity utilization and of transportation impact cost to evaluate transportation performance at the particular WIM location and in the network.


4.1 Descriptive Summary of WIM Data

The data offered by the WIM system include time, weight, speed, vehicle length and axle loads of passing trucks. Based on the observed characteristics, the WIM system identifies 30 truck types, which are divided into five sub-categories: bus (B), road train (R), trailer (T), van (V), and other (O). Among them, T11O3, V11, T11O11, T11O2, T11O1 and T12O3 are the top six most frequently observed trucks. The other trucks, labeled “others” in TABLE 1, still constitute a substantial number, but their individual shares are small.

TABLE 1 presents descriptive statistics of the WIM-data for this specific location, collected in March 2010. Truck type T11O3 appears to be by far the most frequently passing category with a share of 30.4% in the total number of heavy vehicles. Vans of type V11 represent 14.94% of the passing vehicles, while all other truck types have frequencies below 10%. The average speed of 83.46 km/hour is seen to be quite similar across the truck types. This may be due to the fact that the WIM system is located at a site where congestion is rare. By contrast, the observed weight varies substantially between truck types. For all trucks together, the average weight is 23.52 ton. Vans (V11) are with an average of 10.8 ton much lighter, while T12O3-trailers are much heavier, for obvious reasons.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Frequency Count</th>
<th>Frequency %</th>
<th>Speed (km/hour) Average</th>
<th>Speed (km/hour) Stdev</th>
<th>Weight (t) Average</th>
<th>Weight (t) Stdev</th>
</tr>
</thead>
<tbody>
<tr>
<td>T11O3</td>
<td>49433</td>
<td>30.39</td>
<td>83.58</td>
<td>5.57</td>
<td>27.17</td>
<td>10.62</td>
</tr>
<tr>
<td>V11</td>
<td>24301</td>
<td>14.94</td>
<td>83.67</td>
<td>6.49</td>
<td>10.76</td>
<td>3.62</td>
</tr>
<tr>
<td>T11O11</td>
<td>14602</td>
<td>8.98</td>
<td>83.98</td>
<td>5.20</td>
<td>22.37</td>
<td>5.19</td>
</tr>
<tr>
<td>T11O2</td>
<td>13616</td>
<td>8.37</td>
<td>83.71</td>
<td>5.43</td>
<td>19.54</td>
<td>4.74</td>
</tr>
<tr>
<td>T11O1</td>
<td>7786</td>
<td>4.79</td>
<td>83.70</td>
<td>5.45</td>
<td>17.20</td>
<td>3.67</td>
</tr>
<tr>
<td>T12O3</td>
<td>6621</td>
<td>4.07</td>
<td>83.24</td>
<td>5.60</td>
<td>37.82</td>
<td>10.18</td>
</tr>
<tr>
<td>Others</td>
<td>46293</td>
<td>28.46</td>
<td>83.46</td>
<td>5.59</td>
<td>29.77</td>
<td>8.27</td>
</tr>
<tr>
<td>Total</td>
<td>162662</td>
<td>100</td>
<td>83.58</td>
<td>6.34</td>
<td>23.52</td>
<td>11.53</td>
</tr>
</tbody>
</table>
The observed frequency, speed and weight of passing trucks vary systematically over the days of the week and over the hours of the day. This is illustrated in FIGURE 2, which uses dashed lines for weekends and solid lines for workdays. The patterns of truck flow on workdays in FIGURE 2(a) are roughly similar, with a peak at seven and a bump extending from twelve to sixteen in the afternoon. On Saturdays and Sundays, truck flows are generally limited. On Saturday morning there are still some trucks travelling through WIM, while on Sundays the truck flow is increasing in the evening. From the speed plot in FIGURE 2(b), speeds on Saturday and Sunday are higher than that of working day. The weight patterns in FIGURE 2(c), show that the loadings on workdays are quite stable, especially from 8:00 to 18:00. They tend to be more volatile outside this time window. Particularly on Saturday and Sunday, the weights vary a lot.

If the performance of logistics providers is dependent on the performance of the road network, then we may expect them to shift more intense activities towards times when the road network usage is limited. We explore this proposition by examining the pattern of average transported weight per truck over the hours of the day, and the days of the week; see FIGURE 3. In line with expectations, we find the ratio of weight and truck flow to be much larger during 20:00 and 5:00am of next day than during the rest of the hours. This is supported by interviews with transportation interest groups, stating that during daytime, the commercial vehicles travel on the roads, like vans and light trucks. While during the evening and night time, heavy lorries with full truck loads, such as international transport from and to Port of Rotterdam, travel the network.
4.2 Dynamic Weight Capacity Utilization and Transportation Impact Cost at WIM Location

Static and dynamic weight capacity utilization, and transportation impact cost are presented based on the WIM data and loop detector on A12 motorway, for a particular day, 4th March 2010. We select part of A12 motorway network with four links among which the link with WIM system is the third one.

TABLE 2 presents average static and dynamic weight capacity utilization of trucks in March 2010, by truck type and for all trucks together. Here, we assume that the free flow speed of trucks in the Netherlands is 85km/h. Although the speed limit for trucks is 80km/h according to Dutch law, a margin of 5km/h is employed as a safeguard against any doubts about the speed accuracy in court cases. Static weight capacity utilization differs significantly between truck types (F=635.15, p<0.0001). Except for T11O2-V11 and V11-T11O11, all mean differences between such truck types are significantly different from zeros based on Tukey t-test (α = 0.05). For dynamic weight capacity utilization, the conclusion is almost the same (F = 522.03, p<0.0001). Additionally, all pairwise t-test of the assumed equality of mean static weight capacity utilization and dynamic weight capacity utilization are significant (p<0.001). In addition, based on internet search, we arrive at 0.01 euro per ton-km a reasonable estimate of the transportation tariff to calculate transportation impact cost. V11 has a relative low absolute transportation impact cost, compared with the others.

**TABLE 2 SCU, DCU and TIC of Top Six Categories**

<table>
<thead>
<tr>
<th>Categories</th>
<th>Static Weight Capacity Utilization</th>
<th>Dynamic Weight Capacity Utilization</th>
<th>Transportation Impact Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Stdev</td>
<td>Average</td>
</tr>
<tr>
<td>T11O3</td>
<td>0.68</td>
<td>0.23</td>
<td>0.59</td>
</tr>
<tr>
<td>V11</td>
<td>0.60</td>
<td>0.22</td>
<td>0.58</td>
</tr>
<tr>
<td>T11O11</td>
<td>0.59</td>
<td>0.20</td>
<td>0.60</td>
</tr>
<tr>
<td>T11O2</td>
<td>0.61</td>
<td>0.14</td>
<td>0.53</td>
</tr>
<tr>
<td>T11O1</td>
<td>0.54</td>
<td>0.13</td>
<td>0.62</td>
</tr>
<tr>
<td>T12O3</td>
<td>0.63</td>
<td>0.13</td>
<td>0.68</td>
</tr>
<tr>
<td>Others</td>
<td>0.62</td>
<td>0.16</td>
<td>0.66</td>
</tr>
<tr>
<td>Total</td>
<td>0.61</td>
<td>0.21</td>
<td>0.59</td>
</tr>
</tbody>
</table>
FIGURE 4 shows the patterns of average static weight capacity utilization, dynamic weight capacity utilization and transportation impact cost over time. Several observations can be made from these graphs. First, the differences in volatility of SCU, DCU and TIC on Saturday and Sunday are much larger than on workdays. Second, during the day time from 8:00 to 17:00, volatility of SCU, DCU and TIC is smaller than during the night. Third, these three patterns are quite similar. The main reason is that the speed of trucks measured by WIM has little difference with each other.

4.3 Dynamic Weight Capacity Utilization and Transportation Impact Cost in the Network

Considering the part of A12 motorway with four links from 8:00am to 9:00am on 4th March 2010, dynamic weight capacity utilization and transportation impact cost are presented combined with WIM and loop detector data. In absence of detailed individual truck information, we apply the following procedure. Assuming that the average travel times in these four links within one hour can represent the travel time of the passing-by trucks, Bureau of Public Road (BPR) function in transportation modeling theory (17), which is one of the most commonly used link travel time function, is applied here to estimate link travel time. It relates link travel time as a function of link flow $q_k$ as in Equation 13. In addition, WIM gives the weight information of trucks, and loop detectors offer the traffic flow on A12. With this information, the calculation can be carried out.

$$t_{i,k} = t_{i,k}^0 (1 + \alpha \left( \frac{q_k}{Q_k} \right)^\beta)$$  \hspace{1cm} (11)
where,

- \( t_{i,k} \): estimated travel time of truck \( i \) on link \( k \)
- \( t_{i,k}^0 \): travel time on link \( k \) in free flow situation
- \( q_k \): traffic flow on link \( k \)
- \( Q_k \): traffic capacity on link \( k \)
- \( \alpha, \beta \): parameters (normally \( \alpha \) is 0.15, and \( \beta \) is 0.4.)

### 4.3.1 Dynamic Weight Capacity Utilization in the Network

Dynamic weight capacity utilization on each link, aggregated by all trucks, are 55.65%, 56.25%, 55.80% and 55.95%. Since traffic situation is quite stable in these four links during that time period, dynamic weight capacity utilization (DCU\(_k\)) are almost the same. In addition, if dynamic weight capacity utilization is aggregated along links as DCU\(_k\), the histogram of dynamic weight capacity utilization of trucks that pass by these four links is illustrated in FIGURE 5(a). The total dynamic weight capacity utilization of all trucks in the network of this case is 55.91%. Increasing truck loads and better traffic situation can further improve the utilization.

### 4.3.2 Transportation Impact Cost in the Network

Transportation impact cost (TIC) takes weight, transportation value, and traffic situation into account. FIGURE 5(b) presents a histogram of the total transportation impact cost over the four links for each truck. Most trucks have a TIC between -400 to -200. Some of them have transportation impact cost larger than 0, which means they are overloaded or drive faster than 85km/h. In addition, the aggregated TIC in the four successive links are calculated as: -456.27, -346.70, -445.64, and -473.23. The second link has the highest transportation efficiency. The total transportation impact cost of all trucks passing by these four links is -430.45 euro/hour.

![Histogram of Dynamic Capacity Utilization](a)

![Histogram of Transportation Impact Cost](b)

**FIGURE 5** Histogram of DCU (a) and TIC (b) of Each Truck passing by four links on A12;

### 4.4 Summing Up

In this section, the case study on A12 motorway in the Netherlands on March 2010 is carried out. WIM data is presented category-wise to get insight of transport characteristics. Dynamic weight capacity utilization and transportation impact cost are presented in this case. Based on the results, dynamic weight capacity utilization and transportation impact cost do fuse different perspectives in the freight system and are able to represent dynamic transportation performance.
5. CONCLUSION AND DISCUSSION

Transportation performance is influenced by logistics operations as well as conditions in the road network. Indicators of transportation performance should therefore consider both the logistics and the traffic perspective when evaluating the performance of trucks. The main contribution of this study has been to develop transportation performance measures that take these two perspectives into account, and to begin applying these measures by using Weigh-in-Motion data.

The two performance measures we have presented are dynamic weight capacity utilization and transportation impact cost as a measure of the cost of transportation inefficiency. Both of them take into account the performance of logistics companies and the road network. Dynamic weight capacity utilization draws on the notion momentum, comparing the observed and ideal situation of cargo weight and traffic speed. Transportation impact cost fuses weight, transportation value and traffic conditions to present the transportation inefficiency. In fact, transportation impact cost has an intimate relation with dynamic weight capacity utilization.

The newly developed concepts have been implemented using weight data from a WIM system and traffic counts from loop detectors. A case study of the A12 motorway in the Netherlands shows that dynamic weight capacity utilization and transportation impact cost do fuse different perspectives in the freight system and are able to represent dynamic transportation performance.

Our measures of transportation performance can be used by different stakeholders. Logistics companies can evaluate transport efficiency of an individual truck or a fleet during a particular journey or all vehicles during a certain period. This further improves the performance from the perspectives of cargo load and travel behaviour in the road network. Network operators could better understand the logistics performance in the road network and further optimize the logistics operation.

In the near future when more WIM systems are installed on A12 motorway, several extended work can be done. The index of transportation efficiency on the hourly, daily, weekly and yearly basis could be designed. And if there is loading and unloading during the journal, WIM systems can indicate the weight changing. With this information, freight behaviour can be better represented and the loading on the routes can be identified.

REFERENCE


