Investigating the impact of demand amplification on transport

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Abstract

Transport represents a critical element in the supply chain, connecting nodes to enable the flow of materials to customers. The volume of the movements can be influenced by supply chain dynamics, a phenomenon worsened by the presence of demand amplification which increases the variability of orders up a supply chain. Increasingly, managers are recognising the importance of integrating transport within the supply chain, with the aim of making better use of their available transport fleet. This requires an understanding of the relationship between demand amplification and transport. However, there has been only a very limited investigation into this, with almost no analytical research. This paper aims, through simulation, to quantify the impact of amplification on transport performance. Generally, the results find a negative relationship between transport performance and demand amplification. It is also found that the ratio of vehicle capacity to average demand affects these results.

Key words: Demand amplification, transport, simulation, system dynamics

Introduction

Demand amplification refers to the increase in variability of orders across an echelon within a supply chain. As a phenomenon, it has been recognised for a long period of time (for an early example, see Metzler, 1941). However, it became popularised through the work of Jay Forrester who demonstrated, through difference equation modelling, that the variance of orders could be increased throughout the supply chain (Forrester, 1961). Since then, there have been a large number of studies into the effect. In terms of the impact on the performance of the supply chain, the literature tends to focus upon production, inventory and customer service.

One aspect that has been missing from much of this analysis has been the impact on transport. Indeed, transport only receives limited coverage in the oft cited papers on demand amplification and its consequences (Lee, et al., 1997a, 1997b). Here, it is stated that demand amplification will increase transport costs, due to inefficient scheduling and premium transport rates. However, transport is now becoming increasingly recognised as not only a crucial part of the supply chain, but one that must be integrated more into decision making (Cubitt, 2002). Consequently, there is a need for a more detailed study into the relationship between demand amplification and transport. The paper aims to address this gap in the literature by investigating the impact of demand amplification on transport performance, with a particular focus upon cost and efficiency measures.

The paper proceeds as follows. Firstly, the role of transport within supply chains is outlined, along with current knowledge of the impact of supply chain dynamics on
demand amplification. The method adopted in this research is provided in more detail, before the results from the simulation model presented and analysed. Managerial implications and conclusions are then drawn.

Transport and supply chain dynamics
Within supply chains, transport performs a critical role, enabling products to be made available at the location desired by the consumer. However, the transport function is often regarded as separate from the rest of the supply chain, and has to focus on cost minimisation while satisfying the demands placed upon it by the supply chain (Stank and Goldsby, 2000). This reflects the fact that transport represents derived demand. While such a relationship may be suitable with smooth, predictable demand, in reality transport demand is highly variable and dependent upon the ordering pattern within the supply chain. This variability is worsened by demand amplification (Forrester, 1961). It is also not so easy to buffer against these demand variations, for example it is possible to use inventory to smooth the flow through production.

Figure 1 shows the daily transport demand for one customer of a UK-based haulage company. There are significant daily and weekly variations in the vehicle requirements to service this customer. This makes it difficult for the haulage company to determine their level of investment in vehicles, and how much of the demand should be subcontracted. Boughton (2003) also comments on the impact of these cycles, and the negative impact they have on fleet utilisation. However, because transport is not viewed as an integral part of the supply chain, it is difficult to address these issues. Consequently, many transport managers simply accept that amplification occurs and adjust their operations to accommodate the phenomenon (as evidenced in Steinke, et al., 2003).

In terms of the impact of demand amplification on the supply chain, Kurt Salmon Associates estimated in 1993 that it resulted in excess costs of between 12.5% and 25% (Lee, et al., 1997b). The impact on production, inventory and customer service has been investigated fully elsewhere (for example, Stalk and Hout, 1990, Lee, et al., 1997a, 1997b). Little consideration has been given in the literature to the impact on transport. In addition to the articles above (Boughton, 2003, Steinke, et al., 2003), Lee et al. (1997b) identify that transport costs will increase, citing inefficient scheduling and premium transport costs as the reasons. Inefficient scheduling occurs from the need to provide more capacity to cover for peaks (in much the same way as for production), and this capacity has to be utilised during times of lower demand. Premium transport costs result from the need to use express transport in order to get
products quickly to the customer to maintain service levels. However, quantitative studies on the impact of demand amplification on both transport costs and other performance measures do not appear to have been carried out.

**Method**

In order to investigate the relationship between demand amplification and transport performance, a simulation model is used. The model is the Automated Pipeline Inventory and Order Based Production Control System (APIOBPCS) developed by John et al. (1994). In this model, order decisions are based upon three elements – forecast demand (based on exponential smoothing), a fraction of the difference between target and actual inventory levels and a fraction of the difference between target and actual goods in transit (GIT) levels. A block diagram of the system can be found in Figure 2. Such a control system has been found elsewhere in industry (Anderson, et al., 2000), is contained within MRP systems (Fowler, 1999) and is similar to the basic heuristic used by participants in the Beer Game (Sterman, 1989).

![Figure 2. Block diagram of the APIOBPCS system (John et al., 1994)](image)

Difference equations for a single echelon APIOBPCS are provided in John et al. (1994), and were entered into a spreadsheet package. It is assumed that the lead time between orders and deliveries is fixed at 2 time periods, and that all orders placed are received in full and on time. The model only considers the flow of a single product through the supply chain. Finally, if inventory and/or GIT levels are greater than their target values, then it is possible for the system to place a negative order. This effectively represents a cancellation of future deliveries. An additional column was added in order to calculate the transport demand in each time period. We are particularly interested on the inbound flow into the echelon, as this will be affected by demand amplification within the system. Transport demand is calculated by firstly dividing the volume of products to be moved in a time period divided by the vehicle capacity, before rounding up to the next integer. If the volume to be moved is negative, then transport demand is 0. The model is run for 1,100 time periods, with the first 100 excluded from the calculation of performance measures to allow for the transition phase of the model (Banks, 1998).
Five performance measures were calculated from the model. Demand amplification is ratio of variances between orders placed and received. In terms of transport performance, the measures are:

- **Escapable cost** – this represents the short term avoidable cost associated with making a delivery. A specific value is not allocated to this cost, but instead is equal to the number of vehicles required in each period.
- **Inescapable cost** – the cost of owning a transport fleet which cannot be avoided in the short term. In the simulation models, it is assumed that the total fleet size is equal to the greatest number of vehicles required in a single period during each simulation run. Again, a monetary value is not attributed to this measure.
- **Vehicle fill** – compares the volume of products actually despatched against the transport capacity deployed for the movement. Any capacity not used is excluded from the calculation.
- **Fleet utilisation** – assesses asset utilisation by dividing the number of vehicles used by the total fleet capacity. In effect, this equates to the escapable cost divided by the inescapable cost.

All of the transport measures (except inescapable cost) were calculated for each time period, and then averaged. It is important to address both cost and efficiency as both of these have been identified as critical success factors (van Donselaar, et al., 1998).

In terms of experimental design, the demand signal used was a normal distribution with mean 1,000. A range of standard deviations (d) were tested (Table 1). Because the intention was to investigate the impact of demand amplification on transport, there was a need to generate variations in the level of amplification generated by the system. To do this, two of the parameters in the model were varied – the demand smoothing constant used in forecasting and the time to adjust the inventory error. The values used for these parameters are detailed in Table 1. The initial intention was to increase all parameters in equal steps. However, early simulation runs showed a gap in the range of demand amplification values. Therefore, additional values for the demand smoothing constant (0.2, 0.5 and 1) were introduced. A range of vehicle capacities were tested, from 500 to 2,000 (see Table 1). Providing the ratios between average demand, the standard deviation and vehicle capacity are kept constant, it is be possible to translate the findings to alternative situations. All combinations of parameters were simulated, with 20 simulation runs for each combination. The results represent the average of these. In total, 4,200 data points were generated by the simulation model.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Values simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand smoothing constant</td>
<td>0, 0.2, 0.5, 1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20</td>
</tr>
<tr>
<td>Time to adjust inventory error, Ti</td>
<td>1, 2, 3, 4, 5, 6, 7, 8, 9, 10</td>
</tr>
<tr>
<td>Time to adjust GIT error, Tw</td>
<td>1</td>
</tr>
<tr>
<td>Standard deviation of demand, δ</td>
<td>50, 100, 150, 200, 250</td>
</tr>
<tr>
<td>Vehicle capacity</td>
<td>500, 800, 1,000, 1,200, 1,500, 2,000</td>
</tr>
</tbody>
</table>

**Table 1. Parameter values used in the simulation**

**Impact of demand amplification**

The results presented in this paper only consider demand amplification up to a value of 25. At this value, the standard deviation of orders placed is 5 times greater than
average demand. In addition, only the results for $d = 150$ are included. This helps to improve the clarity of the results shown as graphs in Figures 3, 5, 6 and 7, and therefore identify the trends more clearly. The results for different values of $d$ were also analysed, indicating similar trends but are not presented here. Consideration is given to each of the transport performance measures evaluated.

**Escapable transport cost**

Figure 3 shows the relationship between demand amplification and escapable transport costs. As can be seen, the escapable cost per period decreases as the vehicle size increases. This is a rational result as an increase in vehicle size means fewer vehicles are required to provide the same total capacity.

![Graph showing the relationship between demand amplification and escapable transport costs for different vehicle capacities.](image)

**Figure 3. Impact of demand amplification on escapable transport costs**
Firstly, consider the results where the capacity is a factor of demand (500, 1,000 and 2,000 units). The escapable cost is unchanged, the value being equivalent to:

\[
\frac{\text{Average Demand}}{\text{Vehicle Capacity}} + 0.5
\]

[1]

In order to explain this, consider the situation where vehicle capacity is 500 and average demand 1,000. Orders placed will also be normally distributed, and for this explanation we assume there are no negative orders. The potential values of vehicle capacity are 0, 500, 1,000, 1,500 and 2,000. The scenario is depicted in Figure 4, and shows that the probability of 1 vehicle being required is the same as that for when transport demand is 4. Likewise, the probabilities of the transport demand being 2 or 3 are the same. Therefore, these can be averaged to give a value of 2.5. This corresponds to both Equation 1 and Figure 3.

Turning to the scenarios where the vehicle capacity is not a factor of average demand, a stepped pattern emerges. This is, once again, related to the distribution of orders placed by the system. If there was no variation in demand, the escapable cost each period would be equal to the minimum number of vehicles required to provide sufficient capacity to move the demand. For example, with orders of 1,000 every period and a vehicle capacity of 800, two vehicles would be required to move the products. However, once variation is introduced into the order rate, variability in transport demand increases. Therefore, the escapable cost per period tends towards the average level, which can again be calculated using Equation 1. The rate at which this movement occurs depends upon the difference between the vehicle capacity and average demand. The greater the difference in these values, the slower the rate of movement to the average level (compare vehicle capacities of 1,200 and 1,500 in Figure 3). This is because there is more ‘spare’ capacity that can be used to absorb variations in demand, before requiring additional vehicles. In the case of a vehicle capacity of 800, there is actually a reduction in escapable costs. The probability of orders less than 800 (requiring only 1 vehicle) will always be greater than that for orders over 1,600 (where a third vehicle becomes necessary) as the former is nearer to the mean than the latter. With demand amplification increasing the spread of orders, there is a greater likelihood of transport demand being under 800, therefore reducing the average escapable cost per period.

Inescapable transport costs
Turning to inescapable costs, Figure 5 shows the impact of demand amplification when vehicle capacity is equal to 1,000. However, similar trends are achieved for all
other vehicle capacities. It can be seen that the average inescapable cost per period increases as the level of demand amplification increases. This confirms the views expressed in previously published works by both academics (Lee, et al., 1997b) and practitioners (Boughton, 2003) that smoothing demand reduces transport costs by reducing the level of assets required.

There is a sharp increase in inescapable costs at low levels of amplification. This is because the additional variability introduced soon requires extra capacity to be provided. Once this extra vehicle has been added, there is ‘spare’ capacity to absorb demand variations before the next vehicle is required. The presence of steps in the trend means that, in certain circumstances, a company could see an increase in demand amplification with no corresponding change in inescapable costs. These steps are more perceptible when there is a large vehicle capacity. This is because significant extra capacity is added, which can therefore cope with a larger increase in variability before another extra vehicle is required.

Vehicle Fill

The above measures provide insight into the potential cost impact of changing the level of demand amplification on transport costs. However, a performance measurement system is likely to provide a broader view and consider measures other than cost. Therefore, it is important to understand the impact of changing the level of demand amplification on these measures too. The first measure considered is vehicle fill, with the results presented in Figure 6. Only those for vehicle capacities of 800 and 1,000 are depicted as similar trends are observed elsewhere.

With a vehicle capacity of 1,000, there is an initial decline in vehicle fill. This is common to all the other simulated vehicle capacities, with the magnitude of this fall being affected by the relationship between vehicle capacity and average demand. There is a larger decline when vehicle capacity is 1,200 compared to when it is 1,500. Again, this relates to the ability to cope with variations in demand without requiring additional vehicles. The only exception in the simulation results is where capacity equals 800, which experiences an initial increase in vehicle fill as demand amplification increases. As seen earlier (Figure 3), this capacity results in a decline in escapable costs. This is reflected in the increase in vehicle fill given that on average a similar volume of goods is moved using a reducing quantity of transport.
In order to explain the trends in the graphs, there are a number of aspects that need to be considered. Firstly, the probabilities of different order sizes (and therefore transport demand) vary as the spread in orders increases. This change is variability is due to increased levels of demand amplification. Next, the level of vehicle fill associated with a particular order quantity changes as the order size increases. This change is not linear, but forms a stepped pattern. For instance, fill when transport demand in a period is 1 vehicle can vary between 0% and 100%, but increase this to two and the range is 50% to 100%. Vehicle fill is effectively the fill associated with each individual order, multiplied by the probability of that order occurring. Therefore, the interaction of these two functions results in the observed trends.

**Fleet Utilisation**

The final transport performance measure considered is fleet utilisation. From an operational point of view, this measure calculates the amount of work a vehicle actually does as a proportion of the maximum availability. This is ultimately linked to the financial performance of the transport operation as vehicles only generate income when they are moving with a load. The relationship between demand amplification and fleet utilisation when vehicle capacity is 1,000 and 1,200 can be seen in Figure 7. These graphs are equivalent to the ratio of escapable to inescapable costs, with the trends of each reflected in the overall shape of the graph.

**Figure 6. Impact of demand amplification on vehicle fill**

**Figure 7. Impact of demand amplification on fleet utilisation**
There are four combinations evident which contribute to the complex shape of these results:

- Escapable cost unchanged, inescapable cost unchanged – fleet utilisation remains unchanged.
- Escapable cost rising, inescapable cost constant – there is an increase in fleet utilisation as more vehicles are required but the transport fleet remains the same. Therefore, vehicles are used more intensively. This is more evident for large vehicle capacities (such as 1,200 illustrated in Figure 6) where inescapable costs remain constant for larger ranges of demand amplification.
- Escapable cost constant, inescapable cost rising – this impacts negatively on fleet utilisation as the number of despatches required is the same yet more vehicles are required to deliver them due to greater demand variance.
- Escapable cost rising, inescapable cost rising – fleet utilisation still falls as the rate of increase in inescapable costs is greater than that for escapable costs.

The findings above also tally with empirical evidence. In discussing the variability of transport demand, Boughton (2003) highlights how fleet utilisation decreases on both weekly and monthly cycles. The implication of this is that amplification has increased, leading to a lower level of fleet utilisation, a result achieved in Figure 7.

Managerial implications

Having presented the findings from the simulation model, it is important to identify the main managerial implications arising from the findings. Given that many businesses experience a 2:1 amplification of orders placed when compared against those received (Towill, 1997), it can be concluded that any increase in demand amplification will trigger a rapid increase in inescapable costs irrespective of vehicle capacity, as the transport function needs to deploy extra capacity. There will also be a fall in fleet utilisation. One way around this would be to subcontract transport out to cover these demand peaks, in order to restrict the inescapable costs. In doing this, it would be important to ensure that the rate secured from the third party provider is competitive and does not make it more cost efficient to retain the capability in house.

Of the other performance measures, the changes are more dependent upon vehicle capacity. With escapable costs, there will be sharp changes unless capacity is a factor of average demand, the direction being dependent upon the actual capacity value relative to average demand. Equally, vehicle fill reduces unless capacity is just less than average demand. While this could imply that businesses should select vehicle capacities just less than average demand, it should be noted that there will be a cost penalty in doing this as extra vehicles will be required to cope with average demand levels. The findings in this paper are therefore more useful in assessing the impact of changing demand amplification with a fixed vehicle capacity and average demand, rather than determining the optimal vehicle capacity for a particular flow of products.

Conclusions

To date, the issue of the relationship between demand amplification and transport has only been considered in a qualitative manner (such as in Lee, et al., 1997b, Boughton, 2003). As transport becomes recognised as a critical part of the supply chain, it is important to understand this relationship in more detail. Through simulation, this paper provides an analytical investigation into this area, considering performance measures relating to both transport costs and efficiency.
The main finding is that increasing levels of demand amplification does lead to a reduction in transport performance. Therefore, the analytic results confirm the previously qualitative assessments in the literature. However, the findings also identify some exceptions to this, particularly when vehicle capacity is just less than average demand. In these scenarios, an increase in demand amplification can actually improve transport performance (escapable costs and vehicle fill). This is because there is ‘spare’ capacity within the transport provision to absorb increased variability in the volume of product to be moved. However, this benefit needs to be traded off against changes in inescapable costs and fleet utilisation.

References