# THE BULLWHIP EFFECT ON CARRIERS: INVENTORY POLICY CONSIDERATIONS

Michael A. Haughton
School of Business & Economics, Wilfrid Laurier University
Waterloo, Ontario, Canada N2L 3C5, Telephone:  (519) 884-0710
Email: mhaughton@wlu.ca

## 1. Introduction

The "Bullwhip Effect" (BWE) depicts how distorted customer demand creates disproportionately wilder demand fluctuations by successive echelons further back in the supply chain.  While there has been much research on adverse BWE outcomes (e.g., ballooning inventories in the supply chain) for supply chain members that make, store, and trade merchandise, little attention has been paid to BWE problems for the chain's freight delivery carriers.  It appears that only the practitioner literature has qualitatively discussed how shippers' demand distorting actions can complicate and destabilize carriers' capacity plans and cause capacity allocation inefficiencies (e.g., Stiles, 2005).

The purpose of this paper is to move beyond qualitative coverage by providing a rigorous quantitative analysis of BWE problems from a carrier perspective.  A related purpose is to show how the cost impacts of distorted demands for transportation service might be attenuated or mitigated by the timing and magnitude of shippers' delivery requests. To provide a point of reference for examining the impact of capacity flexibility, baseline findings are presented for the standard service provider context where a carrier invests in the capacity required to meet peak demand.  This context, which is characterized by limited ability to make short-term capacity adjustments, will be contrasted with the cost impacts if carriers have some flexibility to quickly add and reduce capacity instead of having to make heavier financial outlays to acquire permanent staff and purchase vehicles.  The quantitative findings provide a basis for asserting that, in the presence of seasonal demands, retailers' replenishment policies and capacity flexibility strongly influence a carrier's BWE costs.  The material that clarifies the findings as well as that assertion appears in section 5 of the paper, and is preceded by, in order of appearance in the paper, a literature overview (next section), discussion of the study’s supply chain context (section 3), and its methodology (section 4). Section 6 contains the summary and conclusions.

## 2. Literature Overview

Several studies have undertaken the combined tasks of (a) estimating the supply chain inefficiencies and costs resulting from the BWE and (b) assessing strategies to mitigate the BWE. Mitigating strategies have been based on work to deepen understanding of the potential causes of the BWE, including behavioral causes (e.g., Sterman, 1989; Croson and Donohue, 2003). These studies have all focused on the supply chain members that, at one point or another own inventory (either in finished or unfinished state) that is ultimately made available to the end customer. As such, inventory-related costs such as holding and shortage costs have dominated the analyses with no explicit treatment of the unnecessary costs incurred by the transportation intermediary. BWE mitigating strategies have also featured the role of inventory as Baganha and Cohen (1998) show that inventory can be used to dampen the BWE.

However, for the carrier function, inventory is neither an outcome of the BWE problem nor a controllable factor to solve that problem. Thus, the costs that carriers incur relate to service capacity instead of inventory; e.g., costs of having excess capacity and adjusting capacity. Few BWE studies focus on service providers. The earliest of these (Anderson and Morrice, 2000) was a behavioral experiment in which MBA students simulated the processing of mortgage applications. The findings showed that, along the application processing (supply) chain, upstream access to true downstream information on the applications dampened the BWE, and thus led to more cost-effective capacity plans. The work by Akkermans and Vos (2003) was also motivated by the intuitive observation that the BWE peculiarities caused by the intangibility of services require analysis and remedies that cannot simply be replicas of what one sees in manufacturing. In two later studies, Anderson, Morrice, and Lundeen (2005, 2006) build on the initial work of Anderson and Morrice (2000) to further clarify the heightened relevance of capacity as the focus of analysis in non-manufacturing supply chains.

The present study’s seeks to further extend the literature’s coverage of service settings by addressing the specific case of transportation as an intermediary service function that is directly influenced by a product supply chain. A defining feature of this extension is that for carriers, capacity resources cover both drivers and vehicles. Acquisition of the latter typically involves a capital investment so capacity changes are not always as inexpensive or as relatively straightforward as adding or subtracting workers (the approach in Anderson and Morrice, 2000; Anderson, *et al.*, 2005). A second important feature is that the well documented problem of driver shortage (e.g., Kilcarr, 2005) might reduce flexibility in staff-related capacity adjustments since carriers may be reluctant to lay off drivers and risk being unable to rehire them. Therefore, the BWE costs for some carriers will be more in terms of costs that are inelastic with respect to short-term demand fluctuations; i.e., costs that are irreversible in the short term.

## 3. The Logistics System

This study considers a hypothetical logistics system in which 10 suppliers each serve 50 retailers, and all 10 suppliers (wholesalers) rely on the same carrier to collect merchandise from the suppliers and deliver to the 500 retailers. So the logistical flow is that the retailers' end-customers' demands are translated into replenishment orders to the wholesalers, who in turn, assume the role of shippers in ordering transportation service from the carrier. These activities drive the carriers' capacity plans and operations. Starting with the retailers' operating context as a key network element, the foregoing description of each element is done with a view to clarifying the BWE factors of interest in the study.

### The Retailers' Operating Context

This study considers cases where retailers face time varying (or non-stationary) demands resulting from the pronounced seasonality of end-customer buying patterns. With a stream of forecasts based on these patterns, the retailers' decision problem is to determine the optimum schedule and size of replenishment orders that satisfy a specified service level. For this paper, the service level metric is the cycle service level (*CSL*), which is the probability of no stockout during the replenishment cycle (see, e.g., Silver, Pyke, and Peterson, 1998; p. 245). The following additional features apply to each retailer:

- The retailer's *CSL* is 0.99
- Unmet end-customer demands on any given day, *t*, are lost.
- Next-day delivery of the replenishment order is 'guaranteed' in so far as the carrier's service level target is concerned (the

carrier is assumed to also have a 99% *CSL*: a 0.99 probability of being able to deliver all replenishment orders).

- Order cost ($A$) and cost to hold a unit of inventory for a day ($h$) are assumed to be \$100 and \$1.50 respectively.
- Customer demand faced by each retailer on day $t$ is normally distributed with $(\mu, \sigma) = (q_t, q_t/3)$ (*i.i.d.* across retailers); $q_t$ can be viewed as the multiplicative seasonal index for day $t$ because in a $T$-day year because $q_1 + q_2 + \ldots q_T = T$.
- With highly seasonal demand considered here, the retailer's replenishment decision should be based on methods for time-varying demand. Since a reasonable assumption is that it is natural for retailers' to act in their own self-interest (i.e., to minimize their total inventory cost), the retailer's first choice among available methods is one that provides (near) optimal solutions but is fairly easy to implement. The assumed first choice in this study is a method due to Silver (1978), in which the standard Silver-Meal heuristic for non-stationary demand is adapted for probabilistic demand.

### Planning Transportation Capacity: Process and Outputs

Consider a carrier with a multi-year history of delivery requirements from its 10 customers (the wholesalers) –a history with disaggregated data; e.g., annual demand data on which the carrier bases next year's capacity plans can be disaggregated into period-specific requirements (daily, weekly, etc.). With this data the carrier can aggregate daily forecasted demands across retailers to develop each day's rough-cut delivery plans, which can then be converted to capacity requirements.

It is assumed that for this planning process, the carrier's ability to forecast any given day's requirements is limited to making a point forecast equal to that day's long-run mean (and carrying slack (excess) vehicle and driver capacity to assure a 0.99 probability of being able to deliver all of the day's orders: $CSL = 0.99$). Total vehicle and driver capacity required to satisfy each day's *CSL* are, denoted as, respectively, $K_t$ and $L_t$ . Given the already noted obstacles to short notice acquisition/disposal of capacity, capacity planning for the year ahead might involve determining the fleet size and staff size to satisfy peak requirements; i.e.,

$$K = \max\{K_1, K_1, \ldots, K_T\} \text{ and } L = \max\{L_1, L_1, \ldots, L_T\} \quad (1)$$

This reflects a case of (virtually) zero flexibility in day-to-day capacity acquisition/disposal of delivery resources (capacity). However, *some* flexibility may exist; e.g., through use of independent vehicle owner-operators to help handle surges in delivery requirements. That is, the capacity planning process might include determining which owner-operators to select, and its outputs might include short-term contracts with the selected operators. The underlying details of those tasks are beyond the scope of the present paper.

Instead, the paper's focus in discussing the research findings is on assessing the extent to which such options of limited flexibility to adjust capacity can mitigate the carrier's BWE costs. This involves comparing BWE costs under the flexible capacity conditions of being able to rely on those options with BWE costs under the inflexible capacity conditions of having to own the required capacity. In order to simplify subsequent exposition after (1), a one-to-one matching of driver and vehicle is assumed; i.e., $K_t = L_t$. Relaxation of that assumption will be considered later.

Transportation Capacity Planning Inputs: Demand History

Because it translates into the essence of the carrier's BWE –unsound and unduly costly capacity plans– one source of erratically fluctuating input data can be very troubling for the carrier. That source is that the network of retailers and wholesalers may use inventory replenishment policies that distort the carrier's view of the network's delivery needs. Again, the distortion is in terms of delivery requirements that are more erratic than the underlying end-customer demand, and results in flawed and unduly costly capacity plans.

One gets closer to the utopian state of minimizing BWE costs if the network adopts the most carrier-friendly replenishment policy. Using this ideal as the benchmark, this study will use the expression in (2) to gauge how the BWE on the carrier is affected by deviations from the ideal. In this expression, $TC(R^*)$ denotes the carrier's mean daily transportation capacity spending (cost) in the benchmark scenario ($R^*$ indicates the most carrier-friendly replenishment policy); the corresponding cost if the replenishment policy deviates from the ideal is $TC(R)$.

$$\text{Carrier BWE} = \frac{TC(F,R)}{TC(F^*,R^*)} - 1 \qquad (2)$$

A BWE value of, say, 2 means that the carrier's expenditure on transportation capacity is 200% above what it would have been under ideal circumstances (= 2+1 = thrice as high). Evaluating (2) requires cost coefficients for the daily cost of providing a unit of driver capacity (daily wage of each driver on staff) and a unit of vehicle capacity (per-day amortized cost of each truck in the fleet). Empirical values of these coefficients from actual carrier operations will be used to compute the BWE. An additional (non-cost) measure of the carrier BWE in this paper focuses on the instability in the carrier's delivery operations: day-to-day activity level changes (equation 3).

$$Carrier\ BWE_{change} = \frac{\delta(F,R)}{\delta(F^*,R^*)} - 1 \qquad (3)$$

In this expression, $\delta(R^*)$ is the average absolute day-to-day percentage change in the carrier's level of operations activity (level of operations measured as the number of vehicle-driver dispatches) in the benchmark scenario. For the scenario involving deviations from the ideal, $\delta(R)$ is the equivalent metric.

Minimizing the BWE on the Carrier

A retailer's myopically optimal replenishment method produces erratic delivery patterns for the carrier –a clear indicator of the BWE. To help mitigate the BWE, a retailer can suppress its self-interest by eschewing its myopically optimal replenishment method for a carrier-friendly alternative. The studied alternative here is a fixed $\overline{p}$-day replenishment interval with replenishment orders being received on pre-determined days; e.g., every other Monday. $\overline{p}$ is calculated as:

$$\overline{p} \cong \frac{EOQ}{Mean\ daily\ demand} = 12$$

The fixed $\overline{p}$ policy is often labeled as the period order quantity (POQ) model since it converts the EOQ as a time supply. Under this POQ policy, the retailers replenishment deliveries would be coordinated with a view making the stream of total replenishment deliveries as smooth as possible by dividing the $N$ (= 500) retailers into $\overline{p}$ (= 12) subsets averaging $N/\overline{p}$ per subset. The first subset of retailers would commit to scheduling their replenishment deliveries for days $1, 1+\overline{p}, 1+2\overline{p},$ etc., a second subset would do so one day later than those in the third subset, and so on. Each retailer's order quantity would be the amount required to bring its inventory to the level that provides a 99% *CSL* over the next 12 days. This policy will be referred to as the *coordinated POQ* policy in subsequent discussions.

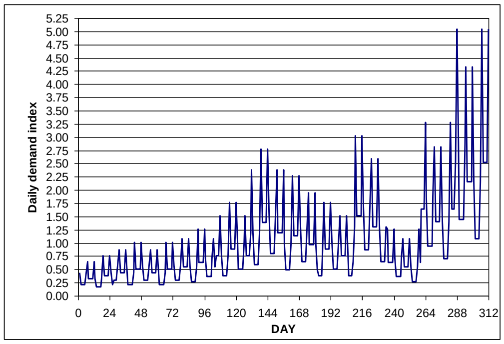
Retailers' sacrifice of using this policy for a carrier's benefit translates to quantifiable inventory costs. This paper considers these costs in order to assess each policy's efficacy more fully; i.e., in addition to the carrier's BWE comprising transportation considerations, the logistics network BWE, comprising both transportation and inventory considerations (to include the retailers' perspectives) is also covered here. Consistent with the notation for transportation capacity cost, *IC*(*R**) denotes the total inventory cost (across all retailers) for the ideal scenario from the perspective of the network and *IC*(*R*) denotes the corresponding value for cases of deviation from the ideal, so the network BWE is:

$$Network\ BWE = \frac{TC(F,R) + IC(F,R)}{TC(F^*,R^*) + IC(F^*,R^*)} - 1 \qquad (4)$$

## 4. Simulation Experiments

The simulation experiments featured a seasonal end-customer demand pattern that might apply in the consumer retail goods sector (Figure 1) and involved studying how the retailer's choice between the more carrier-friendly policy (a coordinated POQ policy based on a fixed 12-day replenishment interval) and the myopically optimal Silver-Meal replenishment policy impacts the carrier's BWE. The experiments reflected the planning process described earlier; i.e., end-customer demands that are translated by the retailers into replenishment delivery orders, which the carrier then converts into daily capacity plans. The simulation covered a continuous run of 93,600 days (essentially 300 replicates of a 312-day year).

FIGURE 1: End-Customer Demand Pattern



The software used to find the most cost-efficient capacity levels for drivers and vehicles was Roadshow®. The geographic network used in the experiments comprised 511 actual business addresses (the 500 retailers, 10 wholesalers, and one carrier) in a 100x100 kilometre region in southwestern Ontario, Canada. Simulated vehicle capacities were 10, 20, and 30 units. Split orders were not allowed so a retailer's replenishment order for, say, 11 units would be assigned to a delivery vehicle with a capacity of 20 units instead of being split across separate delivery trips involving vehicles with a 10-unit capacity.

Subsequent conversion of the driver and vehicle requirements into cost drew on empirical labour and vehicle cost coefficients from the Transport Canada study titled "Operating Costs of Trucks In Canada". These are \$154/day in driver wages and \$60.32/day in vehicle cost (including depreciation). Transportation cost calculations were done for both the case of the carrier having no flexibility to adjust day-to-day capacity, and for the case where the carrier has some flexibility. The more flexible case was depicted by the carrier having a full-time driving staff and an owned fleet equaling 70% of peak requirements, and a part time staff equaling 10% of the peak. With this baseline of owned capacity, the flexible carrier would, on days when total delivery requests exceed 70% of the peak, first call on part-time staff, and then on independent owner-operators if the requests exceed 80% of the peak. Relaxation of the assumption of equality between total fleet size and total staff size (unlike the case of zero flexibility) fits with the practice that a vehicle can perform "double-duty" within a day; e.g., complete a morning route with one driver who then returns it to the depot for a second driver to run an afternoon route.

## 5. Results and Discussion

### Replenishment Policy and the BWE

Table 1 presents the mean daily carrier cost and network cost for each replenishment alternative. Table 2 does likewise for the non-cost BWE measure but is structured differently from that of Table 1: it shows only one set of driver-vehicle dispatches values instead of different sets depending on capacity flexibility. That is because regardless of whether the carrier has capacity flexibility or not, the required driver-vehicle dispatches will be the same.

Together, both tables depict that the impact of retailers' replenishment policy choice on the carrier's capacity cost, network cost (inventory and transportation), and the carrier's operational stability can be very substantial. More importantly, the retailers' choice of the myopically optimal replenishment based on the Silver-Meal heuristic over the more carrier-friendly coordinated *POQ* leads to significantly adverse outcomes for both the carrier and the network as a whole.

TABLE 1: Mean daily cost with and without capacity flexibility

| | Flexibility to make daily capacity changes: | | | |
|---|---|---|---|---|
| | No flexibility | | Some flexibility | |
| **Replenishment Policy** | Carrier Cost | Network Cost | Carrier Cost | Network Cost |
| Coordinated POQ | $28,436 | $39,867 | $20,245 | $31,006 |
| Silver-Meal heuristic | $148,826 | $163,418 | $104,472 | $114,421 |

TABLE 2: Stability of vehicle-driver dispatches

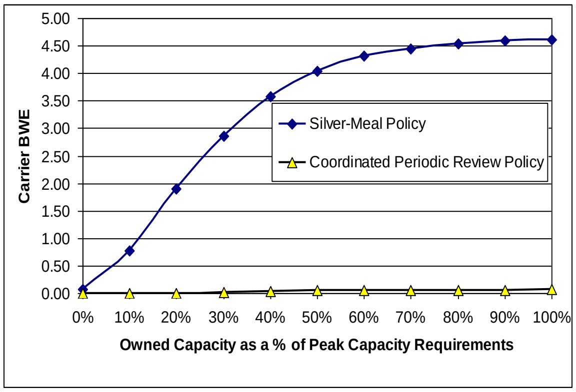
| **Forecasting Capability** | **Replenishment Policy** | Mean daily % change in driver-vehicle dispatches |
|---|---|---|
| None | Coordinated POQ | 4.75% |
| None | Fixed quantity (EOQ) | 77.27% |
| None | Silver-Meal heuristic | 119.65% |

### Capacity Flexibility and the BWE

Table 1 shows that with the analyzed capacity flexibility scenario (full-time driving staff and an owned fleet equaling 70% of peak capacity requirements, and a part time staff equaling 10% of the peak) the capacity cost is typically less than under the inflexible case by roughly just under 30%. This is consistent with results by Garrod and Miklius (1984) who show that flexibility to sub-contract the services of owner-operators is economically superior when demand is highly seasonal or cyclical.

Figure 2 further clarifies the influence of capacity flexibility on costs. In the figure, the theoretical extremes of minimum and maximum capacity flexibility reflect, respectively, complete ownership of the capacity required to handle peak-period delivery requirements, and no ownership of transportation capacity. The graph shows that unless retailers adopt the coordinated POQ replenishment policy, the BWE will become significantly more problematic as the carrier's capacity flexibility lessens. The shape of the graph for the Silver-Meal replenishment policy shows that to guarantee a BWE below 1 (i.e., capacity cost less than twice the lowest observed capacity cost), the required level of flexibility would have to be at a seemingly implausible level: the carrier owning no more than 10-20% of peak capacity requirements but is able to readily procure the remaining 80-90% on the day that required capacity reaches its peak (then dispose of whatever is not needed on day after). This is the crux of the BWE dilemma for service organizations such as carriers: those lacking the capacity flexibility suffer more from the BWE than those with flexibility yet the high level of flexibility required to appreciably mitigate the BWE might be impractical.

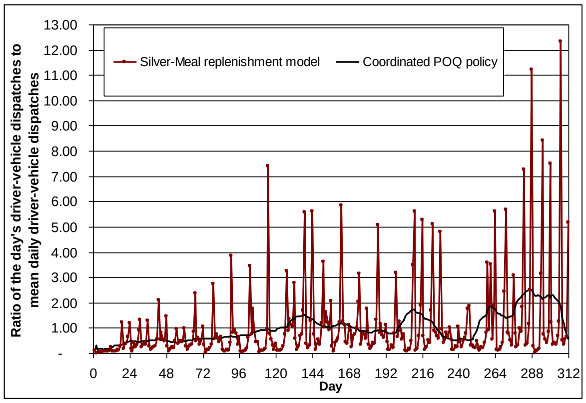
FIGURE 2: The Influence of Capacity Flexibility



<ins>Fluctuations in the Carrier's Activity Levels</ins>

Figure 3 extends the earlier discussion of findings on the non-cost BWE measure of day-to-day fluctuations in driver-vehicle dispatches. It depicts a 312-day time series of daily driver-vehicle dispatches (as a ratio of the per-day mean number of dispatches) for the two studied replenishment policies. The features of these two plots reinforce that the coordinated POQ policy yields a relatively smooth pattern in the carrier's day-to-day activity levels. Notably, the observed coefficient of variation in driver-vehicle dispatches over the year (0.57) is not materially above the 0.433 for the coefficient of variation in end-customer demand. In contrast, when retailers use the Silver-Meal replenishment model, the distortion of end-customer demand activity is much more pronounced as the coefficient of variation is 1.62 (nearly quadrupling the statistic at the end-customer level). Though this study was unable to put a monetary value on this result, it is clear that such erratic changes in day-to-day activity levels for a service operation such as trucking, especially one that is labour intensive (regardless of whether capacity is owned or procured at short notice) are likely to increase the carrier's cost.

FIGURE 3: Driver/Vehicle Dispatch Activity

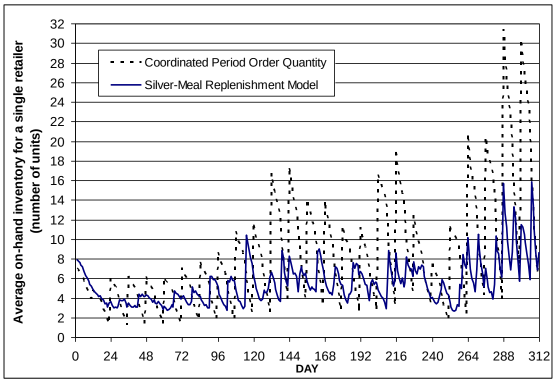


<u>BWE Mitigation Implications for Retailers</u>

While it is clear from the second and fourth column of numerical results in Table 1 that if retailers are on board with the coordinated POQ replenishment policy, the network cost (aggregate network cost of transportation and inventory) is also mimimized. However, the Silver-Meal method yields lower inventory cost for the retailers so their use of the coordinated POQ results in higher inventory cost. On average, the total cost increase in per-day inventory cost across all retailers was between $1263 (a 13.44% increase). These inventory cost increases are very small in relation to the resulting gains from reduced transportation cost. The managerial implication of this is clear: instead of making internally optimal inventory decisions, the retailers, in concert with wholesalers, should coordinate replenishment decisions with the carrier with a view to producing *and sharing* the immense network cost savings that are achievable.

Notwithstanding the clear advantage of logistics/supply chain network coordination that the data in Table 1 depict, two managerially significant caveats are in order. First, if the goods involved are perishables with tight "best before" dates, then costs associated with steep mark-downs and disposals at zero salvage value, it might be difficult to convince some retailers to adopt the rigid replenishment cycle a coordinated POQ policy requires. Second, the additional inventory storage requirements associated with POQ would have to be within the physical space limitations at the retailers’ facilities. As Figure 4 shows for a typical retailer, average daily inventory holdings are invariably greater for the coordinated POQ policy (dotted line plot). More importantly, they are much greater around the seasonal peaks (e.g., towards the end of the year between day 288 to day 312). So although on the basis of average daily inventory cost discussed above, it would appear that a retailer switching from Silver-Meal to coordinated POQ would be making only a minor sacrifice, the time series plot in Figure 4 suggests that with consideration of seasonal peaks, the real sacrifice is non-trivial if retail storage space is scarce.

FIGURE 7: Retailer Inventories



## 6. Conclusions

This paper's primary contribution to the study of BWE-producing distortions of end-customer demands is treatment of issues concerning the one supply chain member that cannot use inventory to counter the effects: the carrier. Being a service provider and thus constrained by inability to use inventory, the carrier must use surplus capacity to handle the distorted fluctuations in requests for deliveries from wholesalers to retailers. Under the scenarios considered, the study indicates that for carriers without flexibility to quickly adjust capacity, the extra costs to provide surplus capacity can be as high as four to five times the capacity costs that would apply in the absence of distortions. Carriers with greater flexibility are more resilient to the bullwhip effect and incur considerably lower costs. Analysis of those costs helped to highlight that efforts to manage the distortions (via changes in the retailers' replenishment practices) may be far more beneficial for the carrier than efforts to improve forecasting accuracy at the end-customer demand level. The study shows that changed replenishment practices (which involve moving from the myopically optimal Silver-Meal model to the coordinated POQ approach) can materially reduce overall supply chain costs by reducing the carrier's transportation capacity costs. The study showed that the changed order release practices to achieve the aforementioned reductions in supply chain costs can create some potentially serious inventory storage implications for retailers, implications that should not be overlooked. Working to address these concerns through collaborative efforts that explicitly include carrier input is worthwhile effort because the supply chain benefits appear far too rewarding to forgo.

## References

Anderson, E.G. and D. J. Morrice. 2000. A simulation game for teaching service-oriented supply chain management: Does information sharing help managers with service capacity decisions? *Production and Operations Management* **9**(1) 40-55.
Anderson, E.G., D. J. Morrice, and G. Lundeen. 2005. The "physics" of capacity and backlog management in service and custom manufacturing supply chains. *System Dynamics Review* **21**(3) 217-247.
Anderson, E.G., D. J. Morrice, and G. Lundeen. 2006. Stochastic optimal control for staffing and backlog policies in a two-stage customeized service supply chain. *Production and Operations Management* **15**(2) 262-278.
Akkermans, H. and B. Vos. 2003. Amplification in service supply chains: An exploratory case study from the telecom industry. *Production and Operations Management* **12**(2) 204-222.
Baganha, M. and M. Cohen. 1998. The stabilizing effect of inventory in supply chains. *Operations Research* **46** S72-S83.
Chopra, S. and P. Meindl. 2007. *Supply Chain Management: Strategy, Planning, and Operation* (*Third Edition*). Upper Saddle River, New Jersey: Pearson Prentice Hall.
Croson, R. and K. Donohue. 2003. Impact of POS data sharing on supply chain management: An experimental study. *Production and Operations Management* **12**(1) 1-11.
Garrod, P., and W. Miklius. 1984. Owner-operators, demand fluctuations and the choice of technology. *Journal of Transportation Economics and Policy* **18**(3) 293-302.
Kao, E. P. C., and G. Tung. 1981. Bed allocation in a public health care delivery system. *Management Science* **27**(5) 507-520.
Kilcarr, S. 2005. Sizing up the driver shortage. *Fleet Owner* September 1: accessed at http://fleetowner.com/management/feature/fleet_sizing_driver_shortage/.
Metters, R. 1997. Quantifying the Bullwhip effect in supply chains. *Journal of Operations Management* **15**(2) 89-100.

Silver, E. A. 1978. Inventory control under a probabilistic, time-varying, demand pattern. *AIIE Transactions*. **10(4)**, 371-379.
Silver, E. A., D. F. Pyke, and R. Peterson. 1998. *Inventory management and production planning and scheduling* (*Third Edition*). New York: John Wiley & Sons.
Sterman, John, D. 1989. Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment. *Management Science* **35**(3) 321-339.
Stiles, P.M. 2005. Navigating Transportation's Perfect Storm. *Council of Supply Chain Management Professionals (CSCMP): Supply Chain Comment* **39** 4-5.
Transport Canada and Trimac Logistics Ltd. Consulting Services (2000), "Operating Costs of Trucks in Canada", accessed at http://www.tc.gc.ca/pol/en/Report/OperatingCost2000