The Impact of Road Traffic Congestion on Supply Chains: Modelling and empirics

A/P Jay Sankaran
(with Amanda Gore, Baz Coldwell, Lincoln Wood, and Peter Li)
ISOM Department, U. of Auckland.

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Outline

- Background and motivation for the research.
- A long-term agenda of research.
  - First phase: case studies of the impact of congestion.
  - Second phase: exploration, through both mathematical modelling and simulation, of some key insights from the first phase.
  - Third phase (ongoing/skipped): a survey.
- First phase (Sankaran et al., *Int Jl of Log: Res & Applns*, 2005).
  - Summary findings from three manufacturers/distributors and their logistics/transport service providers.
- Second phase (Wood & Sankaran, *39th Ann Conf of ORSNZ*).
  - Brief review of the relevant literature on modelling.
  - Analytical results for two polar scenarios.
  - A simulation using real-world data.
  - Empirically testable hypotheses.

Background, Motivation

- Road traffic congestion is an important factor affecting cost and service in the UK (Fernie et al., 2000).
- Strands of literature that examine traffic congestion and freight transportation/ logistics.
  - Impact on logistical efficiency (McKinnon, 1998, 1999), JIT (Rao, Grenoble, & Young, 1991).
  - Trucking operators' perspective: perceptions of the impact of policies to reduce congestion (Regan & Golob, 1999; Golob & Regan, 2000); use of automated routing and scheduling systems to combat the effects of congestion (Golob & Regan, 2003).
  - Prescriptive studies that optimize logistical system configurations to alleviate traffic congestion: Taniguchi et al. (1999).

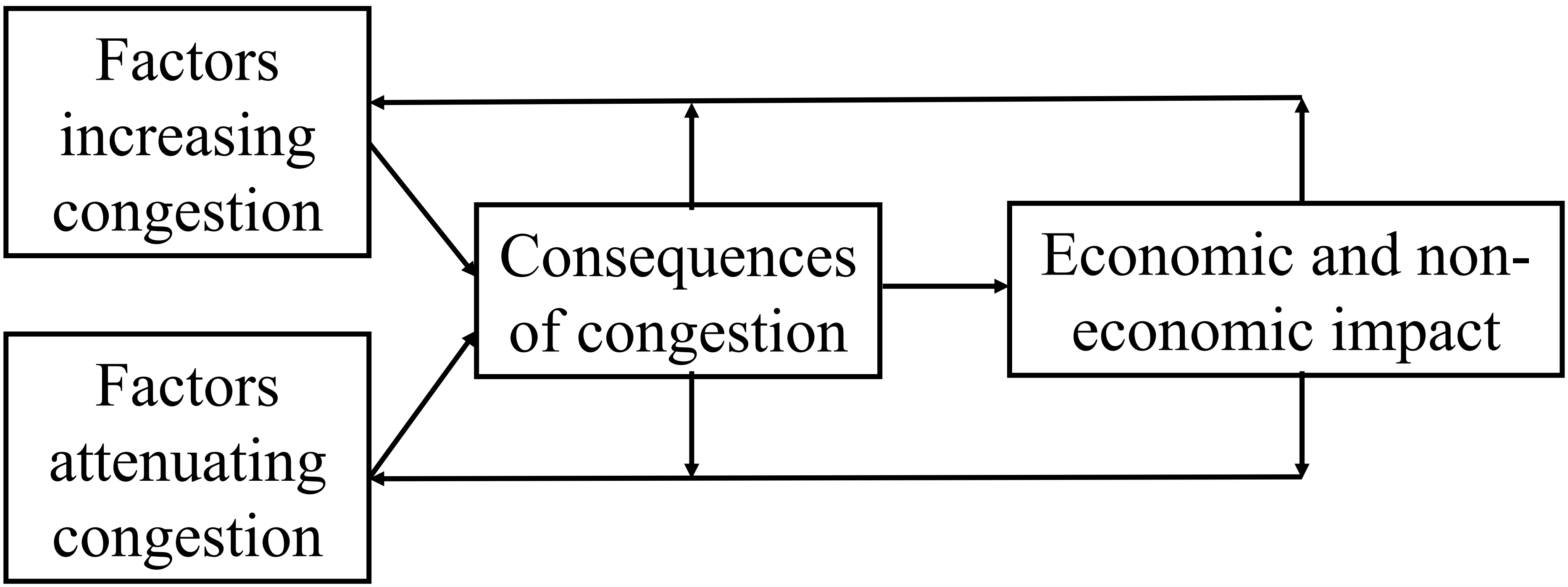
Background, Motivation, contd.

- Auckland's dominance in NZ is paralleled only by a handful of other instances: Buenos Aires in Argentina; Athens in Greece.
  - Thus, Auckland/NZ would furnish a fertile context.
- Impact of congestion on both shippers (e.g., manufacturers and traders) as well as logistics/transport service providers.
- The research was tabled by an academic-industry forum.

THE FIRST PHASE

Objectives/Aims

- With recourse to extant literature and participating organizations, understand how the supply chains of manufacturers and traders are affected by road traffic congestion and how they respond.
- Draw broader inferences from the participating organizations for manufacturing and trading enterprises in general, with regard to the impact of road traffic congestion as well as strategic planning for future projections of congestion.



Settings

- Underlined enterprises were members of the ESSCM forum.
  - Manufacturing/trading organizations.
    - ★OutdoorCom: a NZ subsidiary distributor of outdoor equipment.
    - ★BuildCom: a NZ manufacturer of building products.
    - ★NZCom: a NZ subsidiary manufacturer-cum-distributor of industrial, medical, and consumer products.
  - Logistics/transport service providers.
    - ★CourierCom: OutdoorCom's courier company.
    - ★FreightCom: OutdoorCom's international freight forwarder.
    - ★3PLCom: a 3PL service provider.
    - ★TruckCom: an affiliate of 3PLCom, which served several freight markets (line-haul, bulk, courier, etc.).
    - ★TransCom: another affiliate of 3PLCom, which was expanding into 3PL.

Three case studies of manufacturers/distributors

- OutdoorCom apparently least affected.
- BuildCom affected in both inbound and outbound logistics (for very different reasons).
- NZCom affected in outbound logistics for broadly similar reasons to BuildCom.
- Themes that emerged.
  - Company-specific factors *blunting* the impact on finished goods distribution.
  - Company-specific factors *aggravating* the impact on the business.
  - <u>Customer behaviours/expectations aggravating the impact of congestion.</u>
  - Extraneous influences compounding the impact of congestion.
  - Factors *attenuating* the impact of congestion on outbound logistics costs.
  - <u>Adverse impact of congestion on customer service and sales.</u>
  - Adverse impact of congestion on distribution costs and efficiency.
  - Adverse impact of congestion on inbound logistics.
  - Strategic importance attached to congestion management.
  - Strategies/tactics for mitigating the impact of congestion on inbound logistics.
  - <u>Shorter/longer-term means of combating the impact on distribution.</u>

Summary Findings

- Congestion affects various businesses in varied ways and degrees depending on nature of the market for the company's products (geographic distribution, customer expectations, etc.), the nature of raw materials and finished products, the location of the factory/ warehouse within the Auckland region, etc.
- Typically, service levels are the first casualties with the cost of congestion felt after a time lag.
  - Contractual terms; relative difficulty of some transport operators in negotiating higher rates, especially when the client is *increasing* volumes.
- Congestion is often an amplifier of delays and costs, which themselves burgeon for a variety of other reasons such as growth, increasing levels of service (both in terms of scope and intensity), urban sprawl in Auckland, bio-security regulation (MAF), etc.

Summary Findings, contd.

- Implications of the fact that congestion is only one cause of ineffectiveness/inefficiency.
  - Companies could seek to understand how they can negotiate some of the other challenges (e.g., congestion in the vehicle loading bays) that are unconnected to traffic congestion.
  - The isolation of the impact of congestion on logistics costs is not always easy; organizations are tempted to impute rising logistics costs to congestion more so than is justifiable.
  - Strategies (e.g., decentralized distribution) to efficiently satisfy JIT replenishment by customers also blunt the impact of congestion.
- Strategies for combating the flow-on consequences of congestion in the short-medium term are not confined to ‘hard’ investments in trucks, etc., but can also involve ‘soft’ investments, such as the inculcation of team-work between inbound and outbound logistics personnel in distribution centres.

Summary Findings, contd.

- Successful management of the impact of congestion by freight transport service providers will entail flexibility on the part of clients and their customers' receiving and dispatching processes, i.e., by having clients and their suppliers/resellers think in terms of the overall supply chain process.
  - Effective strategies for streamlining supply chain processes such as customer-order fulfilment, product replenishment (possibly through vendor-managed inventory), and procurement, exemplify such supply-chain thinking.
- Strategies that are aimed at shipment consolidation also blunt the impact of congestion. Such strategies might be client-induced, e.g., the rationalization of the base of freight carriers.
- For courier companies, the same strategies and tactics, such as the establishment of additional depots and the perpetual shrinkage of service areas of courier drivers, to respond to rapid business growth, also serve to blunt the impact of road traffic congestion.

THE SECOND PHASE

Background and Motivation

- Some salient findings (Sankaran et al., 2005).
  - Need to isolate the impact of congestion on costs vis-à-vis shrinking consignment sizes.
  - Fewer rounds/truck (e.g., from 4/day to 3/day).
  - Total vehicle tonnage increases out of proportion with business volume (e.g., 50% vs. 20%).
  - Shrinking consignment sizes (e.g., 10 tonne-loads down to 4.4), driven partly by more exacting service guarantees.

Problem Statement

- To develop models:
  - That capture the impact of congestion and shrinking consignments on logistics costs.
  - That are not data-hungry, given the survey envisaged in 2006.
- Need to inform the design of the survey instrument.
  - Hypotheses regarding distribution costs and their drivers.
  - Items to include in the questionnaire.
  - Integration of empirical research and mathematical modelling has been called for in operations management (Flynn et al., 1990).

Brief Review of Relevant Literature: congestion and JIT replenishment

- Adverse impact of JIT replenishment on distribution costs: e.g., within the Tokyo Metropolitan Area, trucks generated 94% of the total traffic volume (Shiomi et al., 1993).
  - In the Auckland region, cars account for about 85% of total traffic volume/trips; inadequate public transportation.
- Moinzadeh et al. (1997) assume that congestion is dependent on the lot sizes; hence, they study the impact of JIT replenishment *on* congestion as well as the impact of congestion on lead-times and inventories for *consignees*.
- Our research has a different focus: for a specific *shipper* (and associated transport service providers), isolate the impact of congestion vis-à-vis JIT replenishment on distribution costs; congestion levels are essentially **exogenous** in Auckland.

Brief Review of Relevant Literature: continuous approximation models

- Findings of Eilon et al. (1971).
  - The average value of the number of customers on any one route (C) critically affects the length of vehicle routes.
  - D_o (the total distance of the routes) has a very well-defined relationship with D_r (the sum of the radial distances between the depot and customers) and C.

$$D_0 \approx 1.1\sqrt{LD_r} + 1.8D_r / C$$

  - The relationship does not greatly depend on depot location.
- Chien (1992) presents somewhat improved approximations of the lengths of optimal TSP tours.
- Daganzo and Newell (1985).
  - Even if C is Poisson distributed, the approximations hold as long as is $\overline{C}$ is large (> 10).

Continuous approximation models: Daganzo (1984)

- Delivery zones should be elongated rectangles, oriented lengthwise towards the depot.
- The ratio of breadth to length, β, determines the shape of the (rectangular) delivery zones.
- For C < 7, β* is about 1 and sectors are squares holding C points each.
- For C ≥ 7, if β* ≅ 4(C/N), the delivery zone gets split into pie-shaped sectors that touch the depot; else if β* > 4(C/N), β := 6.7/C, and some sectors may not touch the depot.
- The total distance has 'line-haul' and 'local tour' portions, where δ is the point-density.

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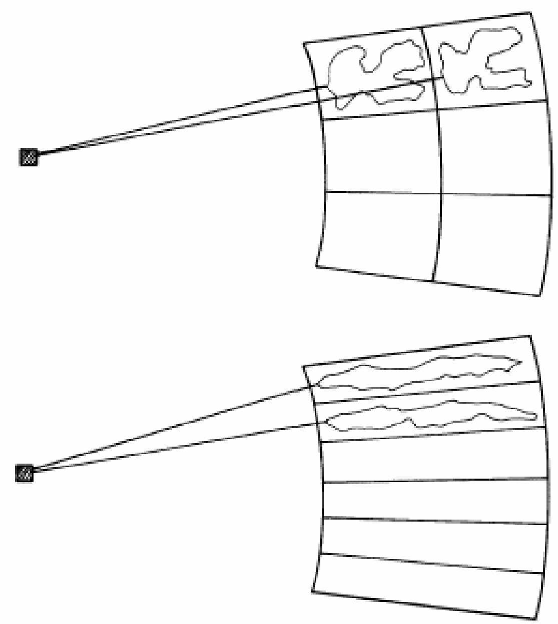


Fig. 1. Two possible partitions of a region into sectors.

$$D_0 \cong 2D_r / C + 0.57N / \sqrt{\delta}.$$

Preliminaries for Modelling: Assumptions

- Customers are uniformly distributed; precise locations are not known.
- Vehicles make multiple trips in a day of length T.
- Vehicle loading, unloading times are negligible.
- All vehicles are homogeneous.
- The unit travel-time, τ, is deterministic and constant across the service area but increases with congestion.
- No time-window restrictions for delivery.

Preliminaries for Modelling, contd.

- The key objective: develop an expression for the required number of vehicles as a function of both the number of consignments, N, and the unit travel-time, τ.
  - Number of vehicles is a the major determinant of distribution costs.
- Two cases.
  - All sectors are pie-shaped and touch the depot; this applies when C is large (≥ 7) and 4(C/N) **not** « 6.7/C (because otherwise, pie-shaped sectors will yield a much greater distance than optimal).
  - All sectors are square-shaped, several of which do not touch the depot; this applies when C is small.
- The two cases are treated separately because they are quite distinct from each other.

The Case of Pie-shaped Sectors

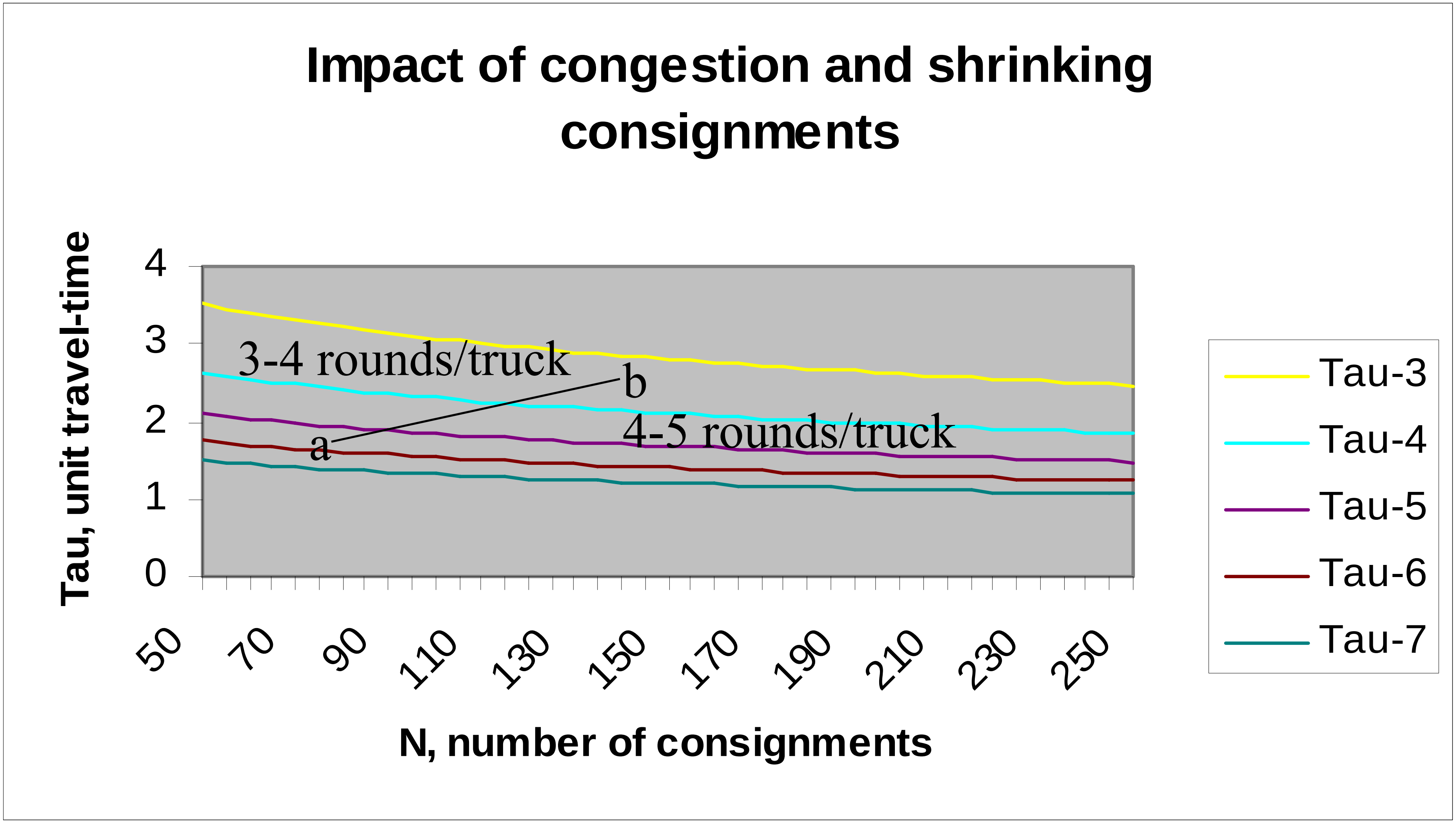
- All trips are roughly of the same length; all the ‘items’ (i.e., trips) to pack into ‘bins’ (i.e., vehicle-itineraries) of size T are homogenous.
- We assume C $\propto$ N.
  - This would overestimate the impact of congestion.
  - As N increases, since C $\propto$ N, 4(C/N) - 6.7/C increases with N (and C), thus increasing the validity of this case.
- The number of trips is $k \equiv \lceil N/C \rceil \cong N/C$ (presumed constant). Then, the average duration of a trip is:

$$\tau.\left(\frac{2\overline{\rho}(N/C) + 0.57.\left(N/\sqrt{\delta}\right)}{k}\right) == \tau.\left(2\overline{\rho} + \frac{0.57.\sqrt{A}.\sqrt{N}}{k}\right).$$

- For i ≥ 1, we define τ^i the cut-off unit travel-time, *exceeding* which a vehicle can make *fewer* than *i* rounds a day.

$$\tau^i = \frac{T.k}{i.\left(2k\overline{\rho} + 0.57.\sqrt{A}.\sqrt{N}\right)}.$$

The Case of Pie-shaped Sectors, contd.



Empirical Testing

- Operational measure of the *relative* impact of congestion: the percentage change in the fleet size resulting from a unit change in the travel-time per kilometre; call it θ.
- If KPV is the average kilometres per vehicle and T the length of the workday, a crude estimate of θ is (100*KPV/T).
  - If V is the total number of vehicles, then V.KPV is the total kilometers traveled in a day.
  - If τ drops by T/(V.KPV), the total elapsed time reduces by one workday and thus the number of vehicles 'lowers' by 1 (percentage reduction of 100/V).

Empirical Testing, contd.

- For $i \geq 1$, percentage reduction in the fleet size when τ decreases from τ^{i+1} to τ^{i} is 100/(i+1). The measure is then

$$\frac{(100/(i+1))}{(\tau^{i}-\tau^{i+1})} = \frac{200\bar{\rho}}{T}.\left(\frac{k}{V}\right) + \frac{57\sqrt{A}}{T}.\left(\frac{\sqrt{N}}{V}\right), \text{ and}$$

$$\theta = f\left(\uparrow A, \uparrow \frac{\sqrt{N}}{V}, \uparrow \frac{k}{V}, \downarrow T\right).$$

- Hypotheses.

  H1. Greater the market-area (A), greater the impact of congestion on the total fleet size (θ). (The average distance to a consignee also increases with the market-area.)

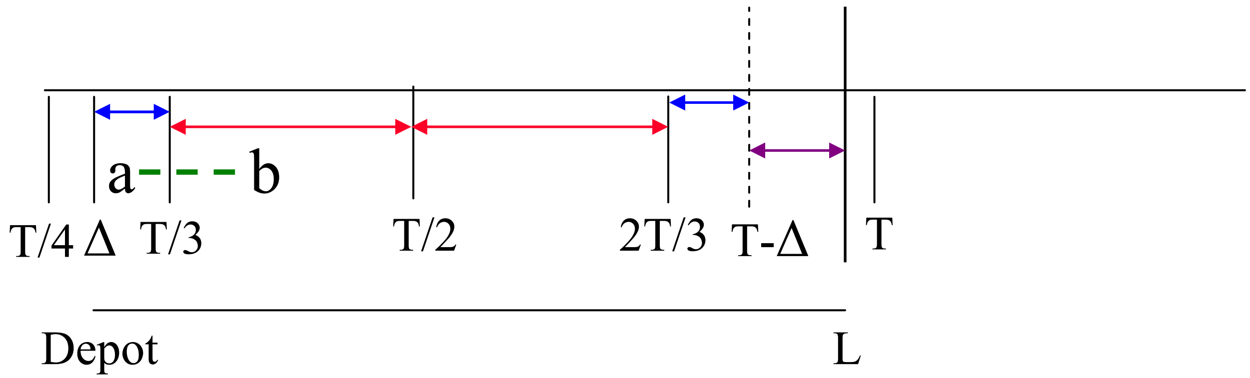
  H2. Greater the ratio of the square-root of the number of daily consignments (N) to the number of vehicles (V), greater θ.

  H3. Greater the average number of rounds/day/vehicle (k/V), greater θ.

  H4. Greater the length of a workday (T), *lesser* θ.

  ★Reinforces the need for customers to open longer hours.

The Case of C = 1 and a Linear Market Region



- Assume a linear market-region of length L km; N consignments.
- Loading/unloading times imply each trip ≥ Δ days (assume Δ > T/4).
  - A vehicle can make at most three rounds in a day.
- Reasonable first approximation for some situations in Auckland.
- We estimate the min # of vehicles vide Hochbaum & Shmoys (1986).
- Depending on the time taken to service the farthest customer, five cases arise; two cases defy a closed-form expression for the number of vehicles, owing to a recursion on intervals of the kind (a- - - b).
- In the case shown above,
  - Consignments (trips) shown in red can be paired with each other.
  - Consignments (trips) shown in blue can be paired with each other.
  - Consignments (trips) shown in purple cannot be combined with others.

The Case of C = 1 and a Linear Market Region, contd.

- In the case shown,

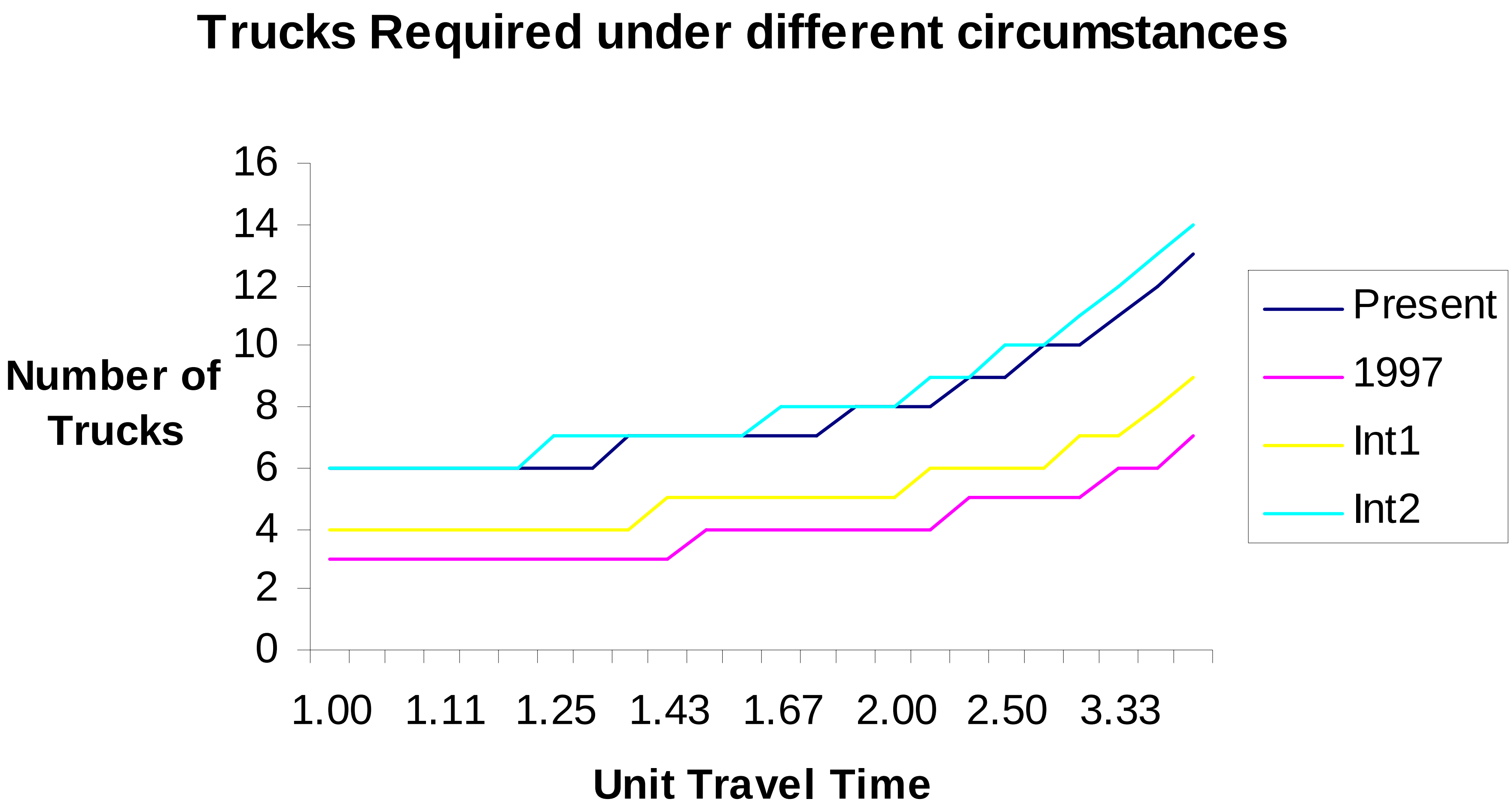
$$V = N.\left(1-\left(\frac{T/2-\Delta}{2\tau L}\right)\right), \quad \frac{dV}{d\tau} = \left(\frac{N}{L}\right).\left(\frac{T/2-\Delta}{2\tau^2}\right).$$

- The (negative) impact of τ on distribution costs *increases* as T increases.
  - A longer day increases the prospects of, e.g., packing the smaller trips into triples and reducing the number of vehicles - but an increase in τ negates this.
  - Trips are very heterogeneous in duration in contrast with the preceding case.

Real-world Simulation

- Distributes building products in NZ, including house-lot distribution in the Auckland region.
- Shorter order turnaround times (24 hours in lieu of 48) tend to shrink consignment sizes.
- Scenario.
  - ◆Most deliveries (66%) have one order on the truck (C=1) with a maximum of C=3.
  - ◆Deliveries are restricted by industry: daylight hours, fine weather etc., lead to longer days in summer.
  - ◆Delivery zones are of varying sizes, roughly rectangular.
  - ◆Auckland is approximated as a rectangle of 30x50km.

Results

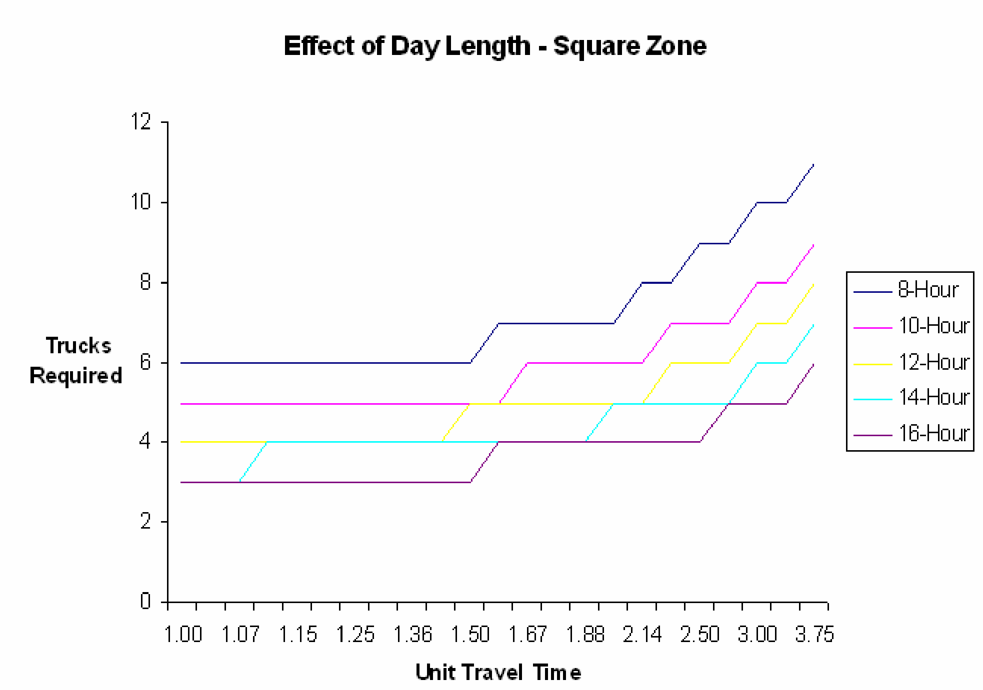

Trucks Required under different circumstances
Number of Trucks
16
14
12
10
8
6
4
2
0
1.00
1.11
1.25
1.43
1.67
2.00
2.50
3.33
Unit Travel Time
Present
1997
Int1
Int2

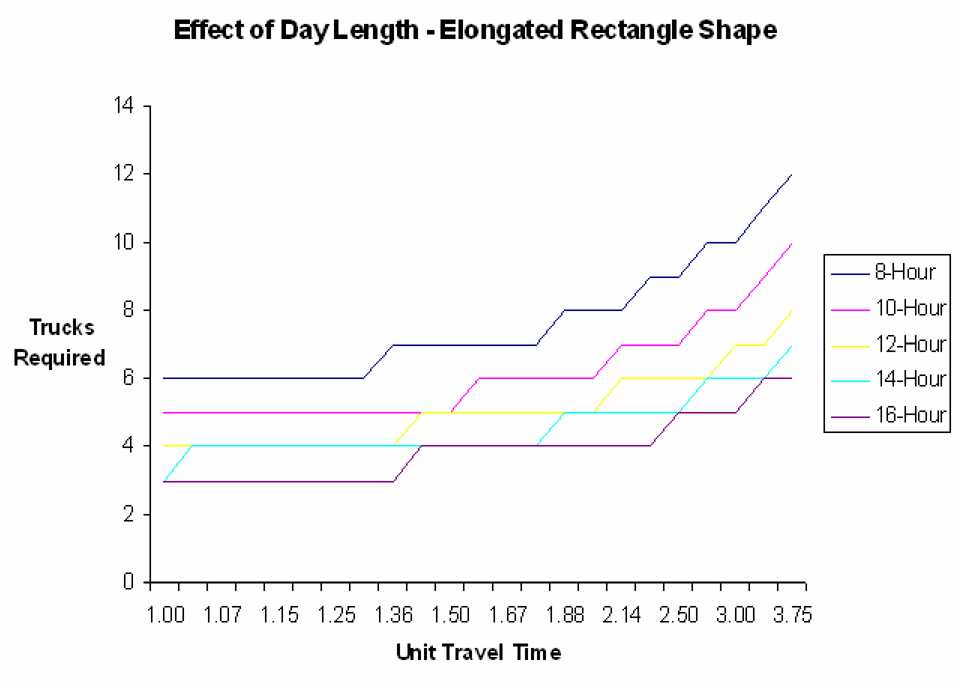
Observations

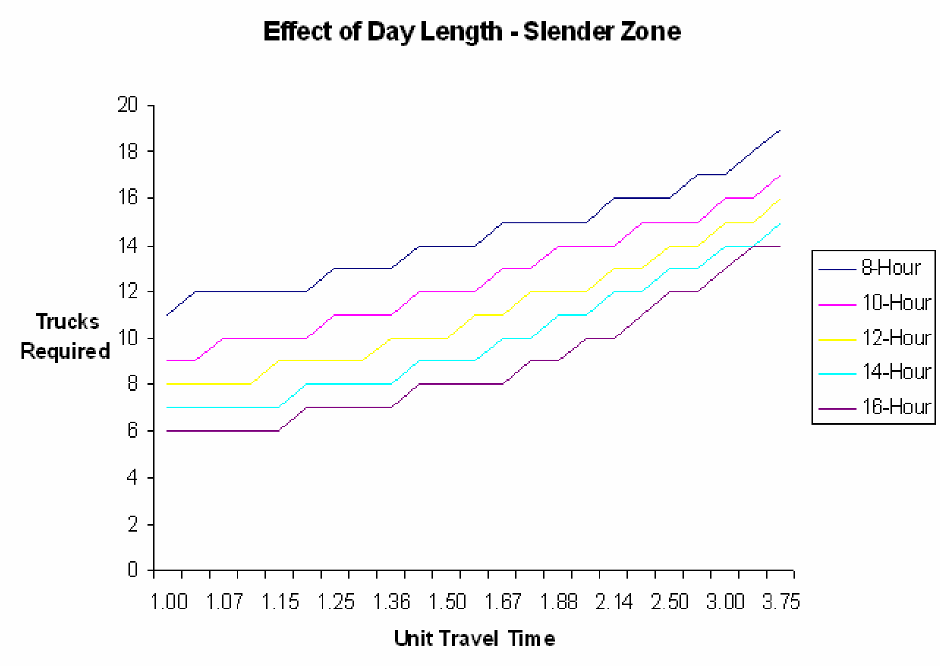
- The marginal impact of τ on the required number of vehicles increases as consignment sizes shrink.
- Accords with the results of pie-shaped sectors (Case 1).
  - As N increases, either *the total out-and-back distance across all trips* and/or *the total within-sector distance across all trips* increases.
  - Hence, the total distance across all trips increases, thus increasing the marginal impact of congestion (τ) on V.

Comparison of the number of trucks requirements for zones of different shapes.

Note divergence of requirements for square shaped zone c.f. convergence for slender zone.







Summary and Conclusion

- Addressed the impact of both congestion and shrinking consignment sizes on distribution costs.
  - Two cases: homogenous trips (pie-shaped route sectors) and heterogenous trips.
  - The former case is easier to analyse; deduction of hypotheses.
  - The length of the workday, T, influences the impact of congestion in opposite ways in the two models.
    - ★Might need to qualify H4 in terms of the mediating impact of C since trips are increasingly heterogeneous as C decreases.
- Further research.
  - Include the impact of time-windows and investigate the case of stochastic τ.

CUSTOMER BEHAVIOUR/EXPECTATIONS AGGRAVATING THE IMPACT OF CONGESTION

Theme	OutdoorCom	BuildCom	NZCom
Customer behaviour/ expectations that aggravate the impact of congestion.			
		JIT procurement by resellers/end-users (and reduced truck capacity utilization) because merchants are pushing back inventory to BuildCom.	Increased tendency of customers to order on a JIT basis: “Many years ago a customer would just give us an order for a week. That doesn’t happen any more. Some customers are actually giving us orders … even 3 or 4 times a day;” customer expectations of continually shrinking cycle times (“There is much more of a courier expectation for JIT”).
		Delivery during daylight hours: “We are restricted for delivery to daylight hours.”	Customers’ not working longer days: Some delays are “probably [because the carrier] tried to go there the first day and didn’t quite make it because of congestion and the customer had shut.”
			Increasingly tight, customer-specified, time-windows for delivery: “Some of our major customers are saying to us, ‘You are going to deliver those on Tuesday afternoon between 2 & 3pm.’”
			Non-repetitiveness in customer order patterns: “Each day [the transport service provider] doesn’t know what he has to deliver.”
			Customers’ buying through the credit cycle: “At the beginning of the month [missed deliveries owing to congestion] rises as the trucks are fully loaded up.”
			Limited ability to drop-ship containers directly to customers: “What we are trying to … do is to encourage customers to take our product direct bypassing our distribution process.”

ADVERSE IMPACT OF CONGESTION ON CUSTOMER SERVICE AND SALES

Theme	OutdoorCom	BuildCom	NZCom
Adverse (direct or indirect) impact of congestion on customer service and sales.	The courier company occasionally misses late pickups, partly because the original driver cannot return due to congestion.	Need to constantly update customers on delivery times: “Often we will have to ring a customer during the day and give them an update on the delivery times because we have a delivery window and the previous job for the driver has run late.”	Undermining NZCom’s competitive advantage: “Our business is at risk of becoming non-competitive as a consequence [of congestion].”
	Consignments exiting OutdoorCom may not go overnight for next-day delivery to customers.		Delays in getting product out of Auckland down country by not getting product in time to the on-forwarding depot in S Auckland.
			Bringing forward the order closeout time for both Auckland and non-Auckland orders.
			Possible lost sales owing to product substitution by distributor.
			Non-delivery of goods in the Auckland area.
			Needing to maintain a ‘negative’ KPI “which is undelivered orders that have not been delivered in the promised time because of congestion.”
			Need for a special process that “kicks in, in the event of service failures.”
			Congestion’s putting paid to customers’ trading electronically with NZCom.

SHORTER- AND LONGER-TERM MEANS OF COMBATING THE IMPACT OF CONGESTION ON DISTRIBUTION

Theme	OutdoorCom	BuildCom	NZCom
Shorter-term means of combating the impact of congestion (directly or indirectly) on finished goods distribution.		Deploying vehicle routing technologies to increase vehicle utilization.	Increasing the number of zones from the current figure of five.
			Putting a greater variety of SKU's at the south Auckland DC.
			Seeking process improvements to cut down on other elements of delivery time: "We will do process change to compensate."
			Seeking to deliver after-hours to those customers that are a 24/7 organisation.
Longer-term means of combating the impact of congestion (directly or indirectly) on finished goods distribution.		Satellite DC's, which "would be replacing the inventory sitting in [merchants'] stores."	Positioning additional DC's in the city.
		[In conjunction with satellite DC's,] use of smaller vehicles to increase utilization of the truck fleet.	Greater number of vehicles of smaller sizes, and associated rezoning.
		Attenuating other sources of delay in truck turnaround through segregation of distribution volume across multiple distribution sites.	Possibly delivering into several hubs for the Auckland region.
		Consolidate freight with suppliers of complementary product.	Managing customer inventories, which would be "one of the best ways [of combating congestion]."
			Seeking to "encourage customers to take our product direct [in container-loads] bypassing our distribution process."

STRATEGIES FOR COMBATING CONGESTION

Theme	CourierCom	FreightCom	3PLCom and affiliates
Strategies for combating congestion	Secondary hubs: "We are setting it up so at the same time one [courier vehicle] leaves North Harbour, one leaves the West base. So they cross over in suburb X, drop freight off for the crossover and keep going; West will end up over on the Shore and vice versa."	Depot relocation strategies, "getting more centralized, getting more central to the motorway."	Multiple hubs and dedicated inter-hub shuttle services for the courier service: "We run a dedicated shuttle vehicle out to the couriers who work in each region; we run that out three times a day [to] stop couriers running backwards and forwards."
	Spatial balancing (avoiding hubs altogether for some freight): "We are putting on more shuttle vehicles, e.g., an extra couple in the system for North Harbour and West. They are going to run the freight directly between those depots. Also between two other depots in S. Auckland."		Possibility of a hub-spoke system for the general transport market not just the courier segment.
	Diversification of routes: "If there is a problem with the traffic for the North Harbour [courier,] he can get across the back out west, so it is giving us more options for when things do go wrong which is quite often."		Shipment consolidation by avoiding delivering to the clients' smaller customers: "A large [client] might have, say, a hundred customers that may have three or four that are huge volumes for us. We are trying to find ways to zoom in on the good work and avoid some of the not-so-good work."
			Shipment consolidation by seeking clients who are synergetic with the base of existing clients: "We will plot where stuff is arriving from and where it actually ends up – and then again try to minimise/remove our competitors away from the people. We want to do business with [prospective clients] by saying, 'Use us because we are already going there,' etc. We are [asking,] 'How we can market products to deliver more to the same sites as presently?'"
			Suggesting means by which clients can "take all the handling out, just getting it from A to B quicker."

TACTICS FOR COMBATING CONGESTION

Theme	CourierCom	FreightCom	3PLCom and affiliates
Tactics for combating congestion	Introduction of additional vehicles/drivers: "We just have to increase our contractor numbers. It will always be ongoing [since existing drivers] will run out of time in their areas."	Additional manpower.	Traversing congested transport links (e.g., the Auckland Harbour bridge) early in the morning and stationing trucks in delivery zones.
	Reduction of service areas for existing drivers: "If [drivers] get to the point where they can no longer fit all of their freight in their vehicle for the amount of customers that they deal with, … if they are running short of time because of traffic or because of the volumes then that is when we step in and have to look at the areas they are servicing … and maybe cut it down a bit."	Driver rezoning.	Parking trucks overnight outside customers' premises: "We do actually do … have trucks parked at customer sites to overcome [delays]. The driver will park his truck there overnight and start from there in the morning so he doesn't have to get the truck from the depot to the customer [for pickups]."
	Extended workdays: "It has gone from where couriers used to start at 7-8 in the morning back to the couriers starting at 5:30am so they can get loaded and get out there in time to meet the service standards that are set. In the last year–18 months, it has increased majorly in the mornings in all directions."		Exploiting opportunities to deliver first to customers who open early and then to other customers: "Our couriers and drivers have worked out which of their customers are open early and which don't. They generally set their time up accordingly to get the best utilisation of their hours behind the wheel."
	Drivers' working smarter: "[Couriers] have to think smarter. If you are in an area where there is a major route through your area and you know it is built up in the mornings, it [means] that you are going to service one side of the road and come back down the other rather than criss-crossing that eats into your time. It does save you a heap of time if you can just go next door to next-door and cut down on your side streets."		Importation and distribution of mixed container-loads that are destined for Wellington, Christchurch, etc., and bypass the port of Auckland.
			Efficient cross-docking to minimize handling delays.
			Streamlining the customer order fulfilment process through, for instance, direct delivery to residences of retail customers to reduce freight movement.
			Hauling containers after-hours: "The productivity between 6pm – 6am or probably 7pm – 7am … is 3 – 4 times that during normal working hours."