Modelling Short-Haul Rail as a Demand-Shifting Solution for Metropolitan Container Transportation

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1. Context

Although accounting for a small share of the transport distance, pre- and end-haulage of shipping containers through metropolitan areas is responsible for the largest contribution to the cost of international container transportation. This is due in no small part to the fact that metropolitan container transport networks in the import-export (IMEX) market are dominated by road transportation. This is particularly true in the Australian context, which features sparsely located but densely populated metropolitan areas with ports located close to the city center. Although pervasive, road transportation is problematic from environmental, service-quality, congestion, and cost perspectives.

2. Port-shuttles as a vehicle for demand-shifting

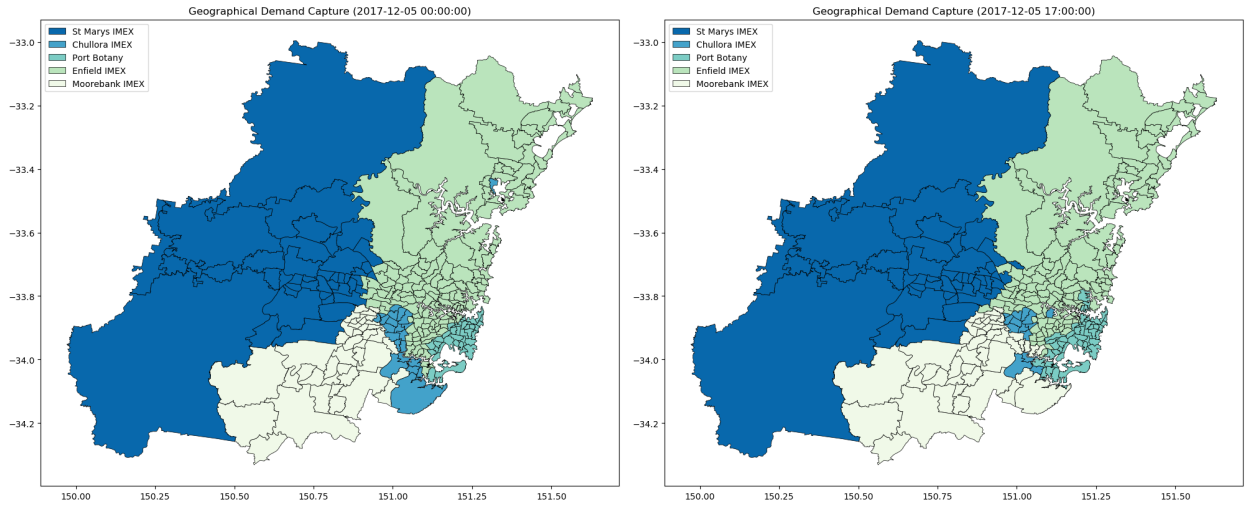
An emerging alternative to road transportation in metropolitan areas are short-haul rail, or *port-shuttle*, services which combine a rail leg from the port and an associated road leg from the suburban rail head to complete the inland container transportation task (for imports, the reverse for exports). Adoption of these services in metropolitan areas has the ability to reduce road congestion, noise, and pollution (Bureau of Infrastructure, Transport and Regional Economics 2016)—the particularly troublesome societal impacts of a road-only transportation model. Given the trend of increasing urbanisation and the growth in demand for consumer goods globally, investigation into the viability of port-shuttles for high-throughput container ports and their conditional adoption naturally emerges as a high priority for government and private industry alike.

When looked at in isolation, the economic argument for transporting IMEX containers by rail over what is a very short linehaul distance does not often appear to stack up, with conventional

wisdom placing the 'sweet-spot' of rail efficiency at a linehaul distance of between 320 and 1500 km (Bureau of Infrastructure, Transport and Regional Economics 2016). Nevertheless, this reductionist analysis of port-shuttles on their per TEU cost alone is not likely to be a faithful assessment of their viability. In practice port-shuttles and the inland terminals they supply do not exist nor function in isolation, with metropolitan container transportation networks that feature port-shuttle modalities and inland container terminals operating qualitatively differently to road-only networks. Indeed it is in this structurally different approach to transportation that many of economic benefits (as distinct from the aforementioned societal benefits) of port-shuttles lie, and also why they are easily overlooked in cursory analyses. In particular, benefits such as *demand shifting* (where container flows may be shifted from high- to low-congestion corridors and times) can only be properly estimated by accounting for the structural differences in network dynamics during modelling. Port-shuttles as a vehicle for demand-shifting become even more appealing when flow-based modelling is layered with additional real-world considerations from metropolitan container transportation:

- Given regulatory shift-length constraints for drivers and practical refueling / recharging considerations, there is a hard limit to the amount of time that a single truck may be on the road: thus introducing a shift-packing problem. Demand-shifting via port-shuttles leads to road transportation tasks with shorter durations, thus facilitating more efficient truck shifts.
- In addition to reducing the duration of road tasks, port-shuttles shift the road element of these container movements to road links less prone to unexpected disruptions (than the often highly congested links incident with the port). This thereby increases the expected service level and permits a shift from day-of-operation style scheduling to a more robust route-selection mode of operation.
- Although container ports accept vessel arrivals continuously, small to medium sized customers will not accept deliveries nor facilitate pickups at all times. In the case of Sydney's Port Botany, this leads to trucks that visit the port late in the day (outside of these windows) to stage containers at their depot ready for transportation the next day—introducing largely unnecessary additional transportation tasks. In this setting port-shuttles provide both a transportation and potential staging solution for road operations, one that also boasts round-the-clock access.

As such, for a faithful assessment of the viability of port-shuttles as a solution to (at least some of) the woes of metropolitan container transportation in the IMEX market, we must take a whole-of-system approach to modelling. This theoretical motivation is backed up preliminary results (see Figure 1), showing that least-cost demand capture by metropolitan transport modalities may vary considerably by time of day.



(a) Midnight (b) Afternoon peak

Figure 1 Preliminary results: geographical demand captured by IMEX terminals under least-cost allocation.

3. Relevant literature

A number of authors have recently considered similar modelling contexts and approaches. However, a distinct gap remains for research incorporating both road and rail modalities for the transportation of IMEX containers within metropolitan areas that also considers demand-shifting at a fine enough level of detail. In this vein,Teye, Bell, and Bliemer (2017) consider a location problem for the intermodal terminals that serve as the rail heads for port-shuttle services within the Sydney metropolitan area. The authors employ an entropy maximisation objective and consider static, highly aggregated flows without temporal demand-shifting considerations. Additionally, Li, Negenborn, and De Schutter (2015) model intermodal transportation for containers passing through the Port of Rotterdam. In their flow-based model the authors consider road, rail, and barge transportation in addition to demand-shifting via storage at terminals. Their proposed model however uses terminals as the smallest network element (instead of individual IMEX customers or customer regions) and spans a vast geographical region—making the modelling inappropriate for the context at hand.

Our previous work (Perrykkad, Ernst, and Krishnamoorthy 2020) considers the single time period version of this problem; developing new methodology to efficiently solve problems of the size required for a whole-of-network inquiry. In the current piece we extend this previous work to consider network dynamics over time and include modelling of important terminal operations.

4. Approach

Accordingly, in this work we propose a new model of metropolitan container transportation, that determines the least-cost freight transportation strategy for the entire metropolitan area. In our model we break each day in the cyclic time horizon (one cyclic week) into a number of time

periods to closely match congestion patterns. For each time period, decision variables track modality choices, container movements, storage, and service network design decisions. Constraints ensure the realistic and rational functioning of the system, whilst facilitating:

1. Both road-only and road-rail (port-shuttle) modalities for container transportation,
2. Spatial demand shifting via port-shuttle services and temporal demand-shifting via paid short-term storage at intermodal terminals (the rail heads of port-shuttle services),
3. Time-dependent road travel durations and transportation costs (based on an original bottom-up microeconomic model and predictive traffic software),
4. Haulage capacity, track interaction (between separate rail heads), and time-of-day restrictions on port-shuttle services,
5. Terminal operations considerations including throughput limits, modal-switches, and storage restrictions, and
6. Time-based IMEX customer, terminal, and port access rules.

This model is subsequently formulated as a mixed-integer program (MIP) amenable to the decomposition techniques of Perrykkad, Ernst, and Krishnamoorthy (2020).

Whilst the primary contribution of this work is the proposed modelling approach and the surrounding discussion, the conference presentation will be framed around a real-world case-study for Port Botany—one of Australia's largest containers port in Sydney, New South Wales. We will additionally elaborate on how this modelling approach can be used to gain powerful managerial insight into the viability of port-shuttle services that is of interest to logistics operators, terminal developers, and governments alike.

Acknowledgments

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