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Simulation Based Study of the Effect of Competition on the Operations of Hyperconnected Crossdocking Hubs

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Abstract: *The current way that supply chains move, handle, store, realize and supply physical objects is unsustainable. To significantly improve supply chain sustainability worldwide, the Physical Internet was proposed as a paradigm breaking model for how supply chains should operate. This new system takes advantage of open flow consolidation across multiple parties in hyperconnected hubs to produce fuller truckloads, and more optimal routes with respect to social, economic and environmental objectives. As can be seen, hyperconnected hub networks are central to the Physical Internet. But, how will modular containers flow through them? How will each hub communicate with the other players in the system? How will demand be split between competing hubs? These are the types of questions that will need answers so that the hubs and the Physical Internet can become a reality on a large scale. In this paper, we exploit a previously developed hub design and create a simulation model in order to examine how different hubs would interact in a competitive environment.*

Keywords: *Physical Internet; Simulation; Hub; Crossdock; Facilities; Competition*

1 Introduction

The Physical Internet (PI) was proposed as a solution to the unsustainability caused by the inefficient, congested and segmented supply chains of today (Montreuil 2011 and Ballot et al. 2014). In the Physical Internet, physical objects are encapsulated in modular containers and then routed through a network of hyperconnected hubs until they reach their destination. Within this new system, the hubs leverage open flow consolidation across multiple parties resulting in fuller truckloads, and more optimal routes with respect to social, economic and environmental objectives. These hyperconnected hubs play a central role in the Physical Internet. In this paper, we examine the road-based crossdocking hubs that were first described by Montreuil et al. (2012).

The purpose of this paper is to explore how multiple hubs within the same region will interact with each other and with the other main players in the Physical Internet. Specifically, we focus on hubs in the peri-urban region of a city and examine how demand for hub services will be split between competitors. We also examine how the main players, such as shippers, truckers and hub operators, behave under this competitive hub landscape. We claim that understanding how these interactions take place is a very important step towards enabling hyperconnected hubs can become a reality on a large scale, a key to full Physical Internet implementation and adoption.

The paper is organized as follows. In section 2, we provide background information on the function of contemporary crossdocks, and highlight the differences with the hyperconnected crossdocking hubs envisioned by the Physical Internet. In section 3, we discuss the roles and motivations of the shippers, the truckers and the hub operators. In section 4, we present the different topologies under which we examine the interactions of the main players. We also explain the decision processes that each player will execute within our simulation. In section 5, we discuss our simulation-based investigation of the player's interactions under each topology. Finally, in section 6, we conclude our investigation and discuss future research avenues.

2 Hyperconnected Crossdocks

2.1 Crossdocks

To appreciate how hyperconnected road-based crossdocking hubs are utilized within the Physical Internet, it is important to first have a basic understanding of a crossdocking hub (also known as a crossdock). A crossdock is defined as a high-speed warehouse (Bartholdi et al. 2016). They are usually rectangular warehouses with truck docks along opposing walls. This allows for shipments to be carried from arriving trucks on one side, across the warehouse, to departing trucks on the opposite side. Crossdocks also have buffer areas in their center, so that when the departing truck has not arrived yet, the shipment may be stored for a short period of time. Figure 1 from Bartholdi (2016) shows a typical crossdocking hub layout.

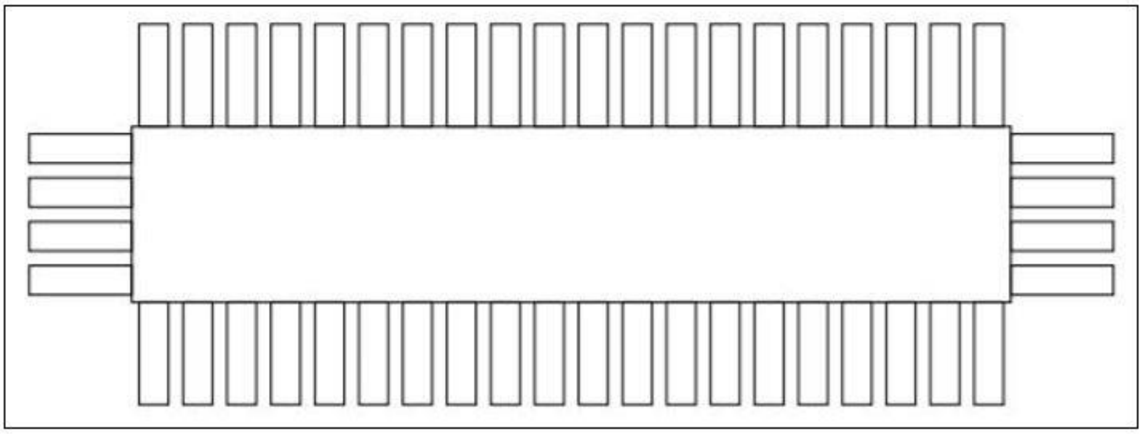

Figure 1: View from above of a typical high-volume crossdock. The large center rectangle is the crossdock and the outer rectangles are truck trailers. Source: Bartholdi (2016)

A core benefit of crossdocks is that they provide the ability to consolidate Less-Than-Truck-Load (LTL) shipments into Truck-Load (TL) shipments. For example, imagine a group of m suppliers, supplying n stores. Assume each supplier has a set of LTL shipments, one for each store, that combine to a TL shipment in total. Instead of paying to ship partially full trucks to each store, each supplier can send their total shipment amount as a TL shipment to a third party crossdock where the LTL shipments from all suppliers are consolidated into TL shipments and then shipped to each of the n stores. This not only decreases the rates that must be paid for shipping, but it also reduces the amount of truck trips needed from $m*n$ to $m+n$. This can be a considerable reduction in total trips, when m and n are large.

2.2 PI Hubs

In the road-based hyperconnected crossdocking hubs (PI Hub or hub) envisioned by the Physical Internet, the practice of consolidating shipments for cost and travel reduction is taken a step further. For instance, using the scenario from the previous example, the *m* suppliers would no longer just arrange for the third-party LTL company to transport their shipments to the third party crossdock where the shipments from the *m* suppliers would then be consolidated and sent to the *n* stores. In the Physical Internet, each supplier would transport their shipments to the closest PI Hub, where they would then be routed by contracted, PI verified truckers, from one independently operated hub to the next, until they reached their destination. These hubs would form a network where a shipment would never journey more than about 4 hours until reaching its next hub. At each leg of the journey, the shipments would be reconsolidated with other shipments going in their direction for that leg, maximizing transportation efficiencies and reducing costs. Also, each hub would only send shipments in a small number of directions, to the hubs in surrounding regions, resulting in better consolidation and space savings within the hub.

The inner workings of the proposed hyperconnected crossdocking hubs have been presented by Montreuil et al. (2014). Figure 2, sourced from Montreuil et al (2014), shows the consolidation process at a PI Hub.

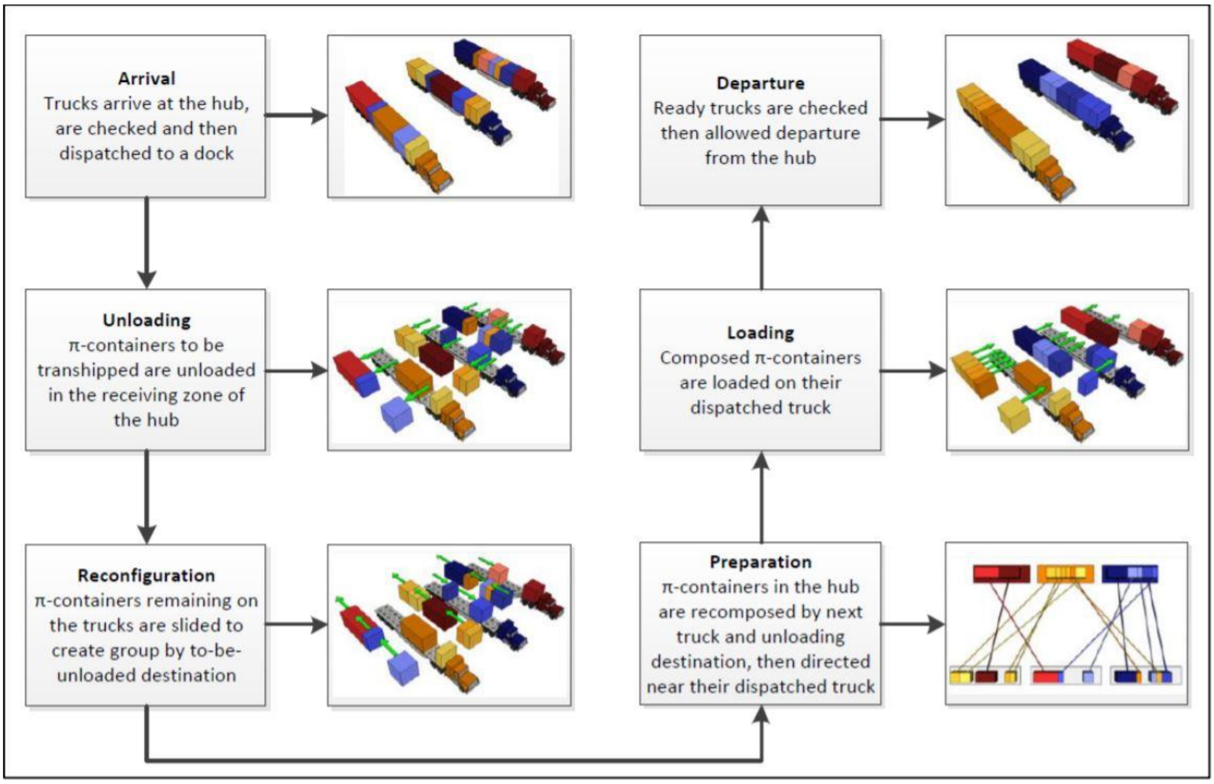

Figure 2: The crossdocking process and its key sub-processes
(Omitting the internal layout of the PI Hub) Source: Montreuil et al (2014)

Later in the paper we will go deeper into the decision processes, but the generalized process for how a shipment travels through the Physical Internet to its destination would be as follows:

1: Shipper contracts local trucker to transport shipment to nearest PI Hub.
2: Trucker delivers shipment to nearest PI Hub where it enters the Physical Internet Hub network.
3: Shipment is given preliminary route through hubs to its destination.

4: Hub management system consolidates its current shipments for efficiency and contracts trucker to take shipment to its next hub.
5: Contracted trucker delivers shipment to the next hub on its route.
6: Steps 4-5 are repeated until the shipment reaches its final hub.
7: Final hub contracts local trucker to deliver shipment on a milk run to its destination.

Here we can see that the shipping process using the hyperconnected crossdocking hubs involves three main players: the shippers, the truckers and the hub operators. In order to gain a perspective on how each player makes decisions, we will explore each of these players' roles and goals in the next section.

3 The Main Players

3.1 Shippers

In the hyperconnected goods transportation section of the Physical Internet, the shippers are a large source of demand for PI Hub services. They supply the shipments that need to travel through the network of PI Hubs. Once a mature Physical Internet is realized, the shippers will need to do nothing more than tell their shipments when and where to go and their budget, and the rest will be taken care of (Montreuil 2011). As described in Montreuil et al (2015), Physical Internet containers come in three varieties; packaging, handling and transport. Transport is the largest and resembles modern day shipping containers in functionality. They are able to withstand harsh environmental conditions and are stackable. Their cross-sections are 2.4m x 2.4m and their lengths are 12m, 6m, 4,8m, 3,6m, 2,4m or 1,2m. In this paper we deal only with transport containers. Another option gives the shippers more control, where they can preemptively plan their shipments routes through the network of PI Hubs, and make dynamic decisions as needed along the journey (Montreuil 2011). These decisions could be things such as choosing truckers who meet performance criteria and are going to the desired next hub, or choosing which hubs their shipments pass.

In this system, the shipper's objectives are to make sure their shipment is delivered and to make sure it is delivered on time. In this paper, we focus on these objectives as part of the shipper's decision making process.

3.2 Truckers

In the Physical Internet, the truckers drive the trucks that transport the encapsulated shipments from PI Hub to PI Hub (Montreuil et al 2012). In general, the player is the transport provider which ranges from a large scale company, such as Schneider, to an individual freelance trucker. In the simulations performed in this paper, we work with individual truckers for simplicity purposes so as to focus on the key concepts. They operate independently, similar to the drivers working for the ride-sharing companies of today. They must be PI certified and have their performance profile available to the Physical Internet community. In this way, PI Hubs and shippers could contract their services based on their past performance (Montreuil 2011). In addition to their performance profile, the trucker also makes their preferred final destination available so that they may be requested for shipping routes that bring them closer to that goal. In this paper, we will assume that their goal destination is their home location. If the trucker accepts the delivery request, they will pick up the load and move it to the next PI Hub in its journey.

In the Physical Internet, the trucker has multiple objectives. First, they want to make money by being hired for deliveries. This entails spending most of their time moving shipments and not waiting idly at hubs. Second, they want to maintain a certain quality of life. Part of this quality of life is to end up at their home location at the end of the day. For the purpose of this paper, we focus on these objectives and how they influence the trucker's decisions of which loads to take and which hubs to travel to.

3.3 Hub Operators

In the Physical Internet, the hub operators are the entities that control the flow of goods through the PI Hubs. Similar to the truckers, they are independent entities working within the Physical Internet. They must be PI certified and make public their KPI's so that truckers, and shippers could contract their services based on fact-based services (Montreuil 2011). These KPI's would be things like, trucker and container throughput time and percentage of trucks departing in preferred direction (Montreuil et al 2012). The hub operators manage the hub like managing a business. They make sure that the PI Hub and its facilities are working and able to service their clients, the truckers and the shippers, at the highest levels possible. At the same time, they want to make money.

The hub operators make their money by charging for allowing containers to pass through their facilities and so they would like to obtain as much demand for their facilities as possible. In this paper, we focus on this objective and how it affects the hub operator's decision process.

4 Peri-Urban Hyperconnected Hub Topologies

Now that the main players and processes of this paper have been described, we can begin to examine scenarios in which multiple hubs occupy a shared region around a city. Figure 3, from Crainic et al (2015), shows an imagined city in the Physical Internet, with hubs around the outside.

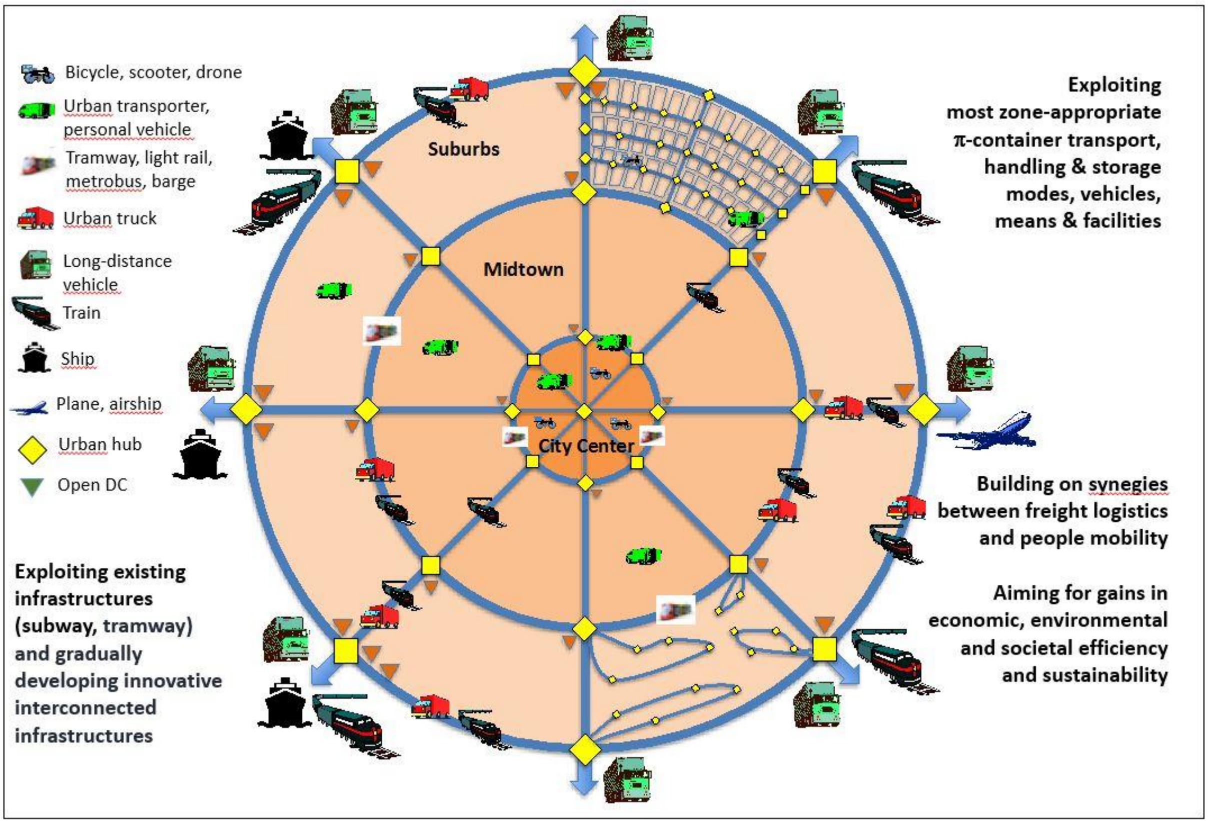

Figure 3: Hyperconnected City Logistics in the Physical Internet. Source: Crainic et al (2015)

For our simulation-based investigation, we assume that trucks are only able to travel around the outside of the city limits and do not travel through a city. For example, if a truck needed to get from a hub on the west perimeter of a city, they would need to travel around the perimeter to get to a hub on the east perimeter of the city. We also make the assumption that the hubs only locate on the North-South and East-West axes of the city. Under five different topologies, we will examine the decision processes of the three key players, specifically the decisions that must be made regarding their routes through the region. We also discuss the different influences affecting these decisions.

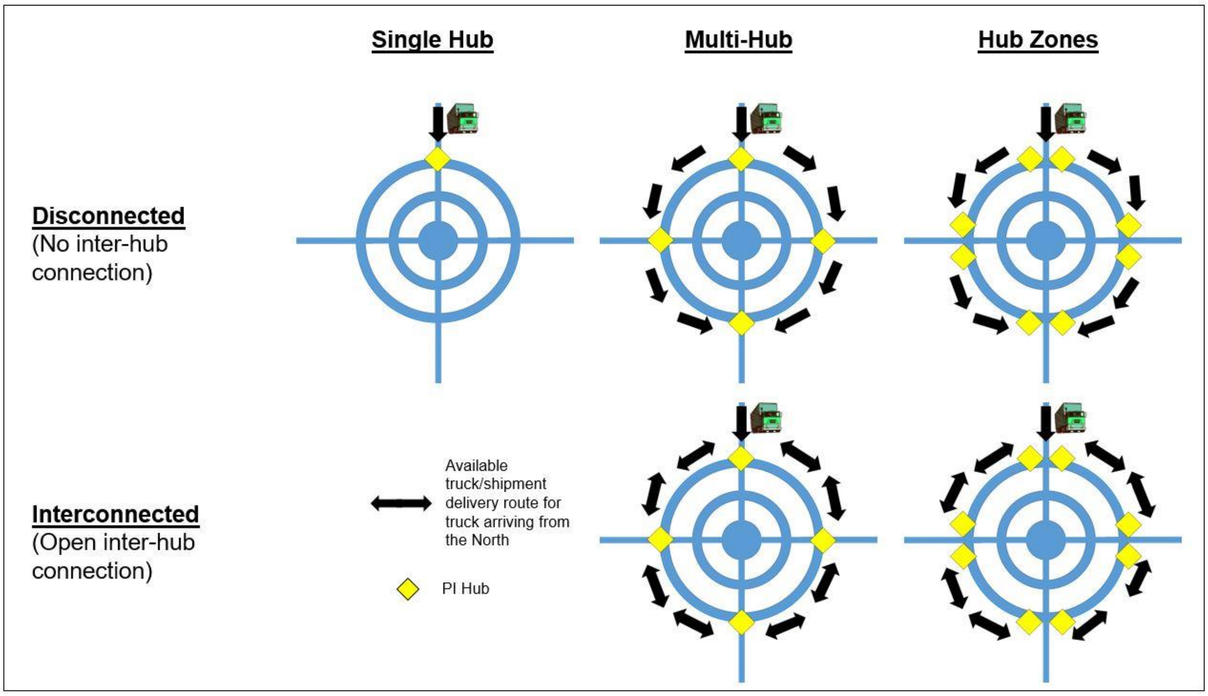

Figure 4: Five topologies for peri-urban hub-based routing, depicted assuming a north-origin truck

The topologies have been split between the disconnected scenario, in which there is no available shipping routes between the different hubs in the region, and the interconnected scenario, in which trucks and goods my flow between every hub in the region. We have also split them within the two scenarios into single-hub, multi-hub and hub-zones scenarios.

4.1 Single-Hub

In this topology, there is only one hub in the region around a city. It can be at any of the four axis points around the perimeter, but we will assume in our illustrations that it is located on the north side. In this design, there are no decisions to be made about which hub to travel to, as there is only one hub in the region. If a shipment is routed through this region, it will pass through the hub. If a trucker accepts a request to transfer shipments to this region, it will stop at the hub. The hub operator also does not need to make any decision with regards to gaining a larger share of demand passing through the region because they have a monopoly. This is the scenario implicitly modeled by Montreuil et al. (2014).

4.2 Disconnected Multi-Hub

In this topology, there are four hubs in the region around the city. One positioned at each major direction; North, East, South and West. There is no connection between the different hubs in the region. This means that if a truck or shipment passes through one hub in the region, they will not be able to pass through another in this region on their way to their next destination. Also, since we have multiple hub options for the truckers and shipments passing through the area, this is a scenario in which the truckers and the shippers must choose which hub to visit. However, because there is no connection between hubs, they must choose a single hub.

The decisions that must be made in this topology for the trucker are: which hub is the preferred hub, and whether to wait for a shipment travelling to its preferred hub or to just take a shipment because it is ready now.

The decisions that must be made for the shipper are: which hub is the preferred hub. In our investigation, because we do not deal with pricing, the hub operators are restricted to only take decisions on assigning containers to departing trucks.

4.3 Disconnected Hub-Zones

This topology is similar to the disconnected multi-hub case. There are hubs at each of the four major directions around the city and there is still no connection between the different hubs in the region. However, the difference is that in this topology, at each of the four major directions, there are now two hubs competing for demand, whose location we call a hub zone. The decision space is the same as described above, except that now the truckers and shippers have more hubs to choose from.

4.4 Interconnected Multi-Hub

This topology is set up in the same way as the disconnected multi-hub topology, with the difference being that now there is inter-hub connection. This means that truckers and shipments may visit one hub, e.g. the North hub, and then travel to another hub, e.g. the East hub, before they depart the region.

Because of this physical similarity to the disconnected multi-hub topology, the decisions from that section are still valid for each player. The difference is now there is full inter-hub connection that allows for trucks to make stops at multiple hubs within the region, consolidating inter-hub shipments. In our simulation, this allows for additional decisions that the truckers can make, but does not change the decision space for the shippers or the hub operators.

The additional decision that the trucker must make is: should they take each shipment to its preferred hub while travelling more and more empty along the way, or should they only deliver to one hub.

4.5 Interconnected Hub-Zones

This topology is similar to the disconnected hub zone topology, which allows for the decisions from that section to still be valid for each player. The key difference between the two topologies is the interconnectedness of the hubs. This interconnectedness allows for additional decisions that the truckers can make, but does not change the decision space for the shippers or the hub operators. Specifically, the new decision is: should they only deliver to one hub, or deliver to multiple hubs while travelling more and more empty along the way. This second option will bring more shipments to their preferred hubs.

5 Simulation Decision Processes

In this section, we discuss the decision processes that the players make in our simulation.

For the shipper, the decision process will be influenced by their objectives of making sure their shipments are delivered on time. For this reason, a hub with a fast average throughput time will be very desirable to a shipper. Also, to eliminate extra travel time and cost, a shipper will prefer a hub closer to their next destination. For example, if a shipment is travelling through the Atlanta region, and its next destination is to the East, then the value of passing through the East hub increases.

For the trucker, the decision process will be influenced by their objectives of making money and maintaining a quality of life. Their decision of preferred hub will be influenced by the hub's KPI's, such as average throughput time. Hub's with faster average throughputs will be preferred. This is because first and foremost, the trucker needs to make a living. They desire to spend their time on the road making money instead of sitting idly at a hub. For example, if the east hub has a shorter average throughput time than the west hub, the trucker might desire the east hub more. However, if their shipment is not willing to pass through their preferred hub, the trucker will choose to take their shipment to a hub that is the best compromise.

As we discussed in section 3, a hub operator is motivated by obtaining the most demand for its services, which in turn will generate it the most money. However, in our simulation, we assume all hubs have the same equipment and facilities, and so their KPI's, such as throughput times, that attract the shippers and truckers, are determined by how many shipments they have waiting. Thus, dynamic decision processes for the hub operators are limited to container assignment to outgoing trucks in the simulation. The hub operators make their decisions by deciding which topology to operate under.

6 Simulation Based Investigation

In order to evaluate the interactions between the three main players of the hubs, we designed a model for each topology listed in Section 4. Because this topic has not been studied before, these models are meant to provide an exploratory first look into the subject and so simplifying assumptions have been made. Our models each have four sources representing the four directions coming into a city; North, South, East and West. These sources generate trucks having a set of 5 transport containers, with each container's next destination chosen randomly from the remaining three directions. The truck and containers then follow the decision process outlined in Section 6 and choose a hub around the city to travel to. The hubs in these models are based on the structure of the model in Montreuil (2012). Once inside the hubs, the trucks drivers attempt to find a load going back to their home direction. If after a set time threshold, they cannot find a shipment heading in their preferred direction, they will take any available shipment heading in a different direction. Once the trucker accepts a shipment, they load the containers and start the journey to their next destination, effectively starting the process over again.

The assumptions made in the models are as follows. We assume that the hubs have infinite capacity for truckers and shipments, and are positioned around the four axis of a perimeter highway to a city. This highway is similar in size to I-285 around Atlanta. We assume the trucks are able to travel at about 60 miles per hour and that each quarter of the highway is about 15 miles long. Thus, travelling from one zone of hubs to the next will take a trucker about 15 minutes. We also assume that the distance between the perimeters of two cities is 250 miles. For our models, we also set the time waiting threshold for a trucker to 30 minutes, before they are willing to take a shipment heading in a different direction.

The KPI's that we observed for each topology focused on the truckers were, distance travelled, time in hub and percentage departing in non-preferred direction. The KPI that we observed for the shippers is the shipment time from hub. The KPI that we observed for the hub operators is the number of shipments in hub. This is defined as the number of shipments in the hub within the hub waiting to be picked up by a trucker and taken to their next destination. We ran each model ten times for a time period of one week, with a warmup period of 50 hours so that the hubs could become saturated with truckers and containers. We also ran each model under a low flow and high flow scenario with each source generating a truck according to an exponential random variable with a mean time of 15 minutes and 30 seconds respectively. This was done to get a sense of how extreme differences in flow volumes would affect the KPI's under the different topologies.

Tables 1 and 2 show the results of our simulation experiment, respectively for low and high flow scenarios.

Table 1: Results from low flow scenario

Topology	***Avg. Dist Travelled***	***Avg. # Shipments in Hub***	***Avg. Truck Time In Hub (mins)***	***Avg. % of Truckers Departing in Non-Preferred Direction***	***Avg. Shipment Time In Hub (hrs)***
Single Hub	*261*	*145*	*5.4*	*0.48%*	*1.85*
Disconnected Multi Hub	*270*	*99*	*28.2*	*63.08%*	*5.03*
Disconnected Hub Zones	*270*	*99*	*28.2*	*63.02%*	*4.95*
Interconnecte d Multi Hub	*280*	*98*	*30.6*	*73.71%*	*4.66*
Interconnecte d Hub Zones	*272*	*73*	*29.4*	*71.64%*	*7.93*

Table 2: Results from high flow scenario

Topology	***Avg. Dist Travelled***	***Avg. # Shipments in Hub***	***Avg. Truck Time In Hub (mins)***	***Avg. % of Truckers Departing in Non-Preferred Direction***	***Avg. Shipment Time In Hub (hrs)***
Single Hub	*261*	*2,705*	*4.8*	*0%*	*1.13*
Disconnected Multi Hub	*270*	*7,909*	*20.4*	*22%*	*13.54*
Disconnected Hub Zones	*270*	*8,473*	*19.2*	*18%*	*14.11*
Interconnecte d Multi Hub	*272*	*7,319*	*23.4*	*33%*	*13.14*
Interconnecte d Hub Zones	*271*	*4,175*	*21*	*26%*	*14.42*

We have also gathered the data into 6 charts for comparative purposes. Figures 5 to 7 show the results for each topology under low flow and high flow scenarios.

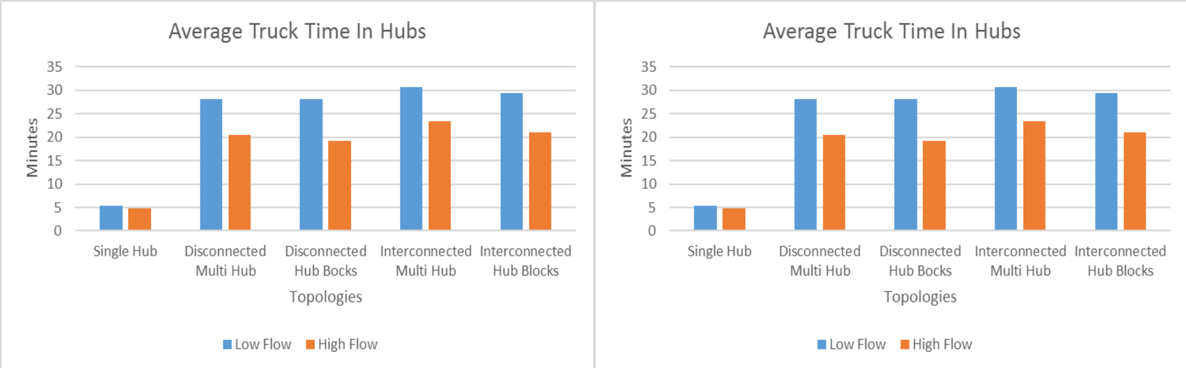

Figure 5: Average Driver Distance Travelled (Left) and Average Trucker Time in Hubs (Right)

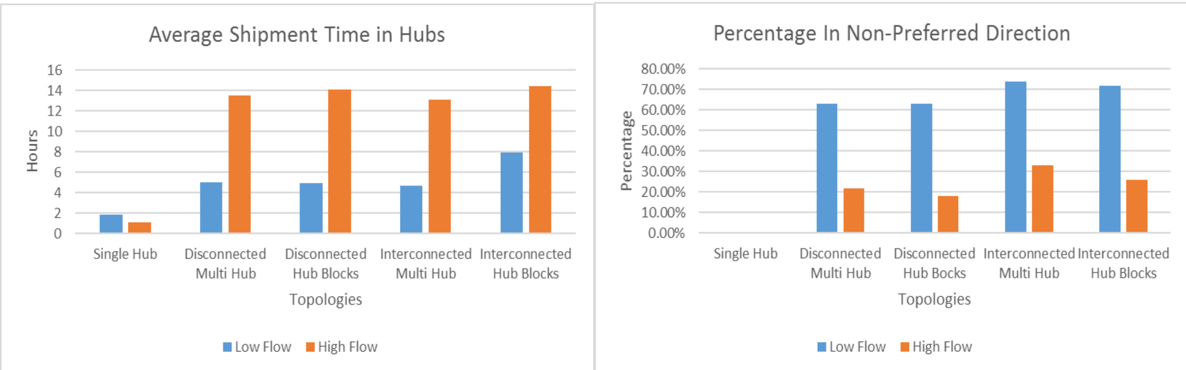

Figure 6: Average Shipment Time in Hubs (Left) and Average Percentage of Truckers Taking Loads in Non-Preferred Direction (Right)

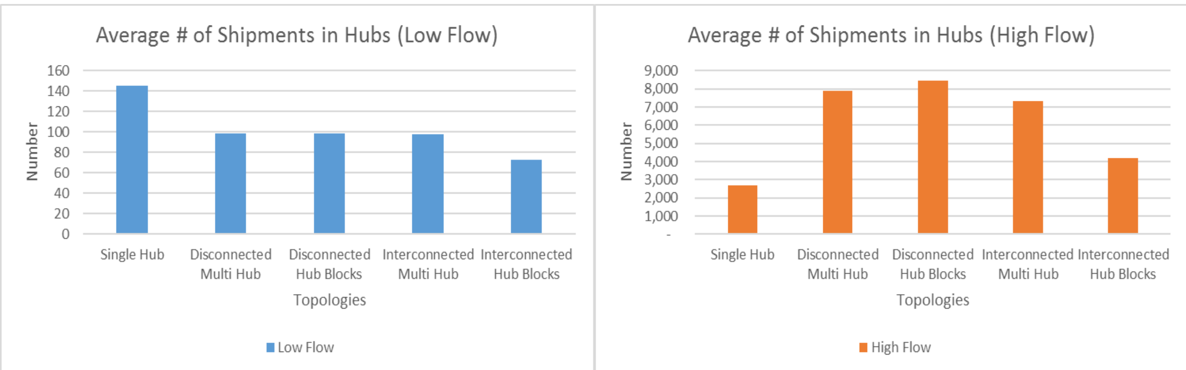

Figure 7: Average Number of Shipments in Hubs under Low Flow Scenario (Left) Average Number of Shipments in Hubs under High Flow Scenario (Right)

From our results, we can see that according to our simulation-based investigation, under the low flow scenario, the single hub topology would be preferred. This is because the average time in hub for both shippers and truckers is much shorter and almost no trucker ever departed in a non-preferred direction. This result makes sense, because under the same rate of flow, the multi-hub and hub-zone scenarios would spread the shipments out too thin acoss the hubs, and so at each hub it would take longer for shipments heading in the driver's preferred direction to appear. This is what caused the leap in average time in hubs and percentage departing in on-preferred direction between the single hub topology and the multi-hub and hub bock topologies.

However, when we examine the multi-hub and hub zone topologies under high-flow, as we would expect, the percentage of truckers departing in non-preferred directions and average truck time in hubs sharply decreases compared to the low flow scenario. This is because we now are starting to have enough flow through the hubs so that shipments heading in the driver's preferred direction appear more frequently.

What we see that at first seems counterintuitive, is that for the multi-hub and hub zones topologies, under the high flow scenario, the average number of shipments in hubs and the average shipment time in hubs greatly increases compared to the low flow. What is happening here is that because we do not have a capacity limit set for the hubs, the number of shipments can build up. We also do not have a time limit set on how long a shipment can wait until it is expedited, thus a shipment can wait for many hours before a trucker picks it up. Also, do not allow truckers to travel to a different hub to pick up their return load, which would help reduce this buildup of shipments.

Still under the high flow scenarios, the single hub topology has the shortest average time in hubs for truckers and shipments and no truckers departing in a non-preferred direction, but this makes sense, because there is so much demand for truckers that they can always find a shipment heading in their preferred direction. In a more realistic setting, however, one hub would challenged to be able to efficiently handle such a large flow of truckers and shipments and so a multi-hub or hub-zone topology would make more sense.

We also notice that in the interconnected multi-hub and hub -one topologies, the truckers in the low flow scenario were willing to travel farther and to more hubs than in the high flow scenario, so that they could find loads. This further supports our observation that in the low-flow scenario, single-hub topology would be preferrable because there is not enough flow to support mutiple hubs or hub zones.

Finally, we observe that in interconnected multi-hub and hub zones topologies, the truckers are allowed to travel to more hubs making deliveries which allows them to ideally deliver the shipments to hubs located closer to their next destination so the shipments spend less time in transit.

7 Conclusion

In conclusion, in order to further develop the Physical Internet and bring it to reality, we explored the interactions between PI hubs and other key Physical Internet players. Specifically, we examined how demand for hub services would be split over the competing hubs in the peri-urban region of a city. To do this, we described the main players of interest; the shippers, the truckers and the hub operators. Then we developed their objectives and decision processes, and examined these processes under five different hub topologies. As a further investigation, we ran a simulation of the topologies and discussed the results.

The topologies and scenarios presented in this paper have never before been explored. So far, the concepts of splitting demand between competing PI Hubs within the same region have not been studied. As such, our research is important as a basis to build upon, with the goal of creating a full description of the processes and operating models of PI Hubs. This in turn will further the progress towards a mature realization of the Physical Internet.

We believe the key learnings are that in a low flow scenario, it makes the most sense to operate under a single-hub topology. This is because when the flow of shipments is not large enough, a multi-hub topology will cause much greater hub waiting times and larger percentages of truckers to depart in non-preferred directions. However, in a high-flow scenario, when there are enough shipments to efficiently disperse them among multiple hubs, we believe that allowing truckers and shipments to visit multiple hubs, as in the interconnected topologies, will allow truckers to deliver shipments to hubs closer to their destination, thereby reducing travel time.

The key limitations of our research are that we did not place hub capacity limits on the number of truckers and shipments, nor capacity related efficiency and responsiveness correlations, and we did not allow for expediting of shipments if their waiting time exceeded a certain threshold. These limitations caused us to see very large average shipment times in hubs and number of shipments in hubs.

Given our key learnings and key limitations, the research in this paper provides good insight into the basic interactions between the players involved with PI Hub operations, and presents many future research avenues.

A first avenue to be explored is the case where capacity limits are in place on the number of trucks and shipments able to utilize a hub. This will give us a more accurate picture of the levels of flow at which it makes sense to transition from a single hub topology to a multi-hub topology, and will allow us to observe hub utilization.

Another avenue is to analyze the effect of pricing on the decisions of the shippers and truckers. In this scenario, truckers might charge more to go to less desirable PI Hubs, and shippers could arrange deals with hub operators to gain bulk discounts for large quantities of shipments sent through their hub. This is an interesting direction because it starts to explore business scenarios necessary for understanding how to operate a PI Hub, in the spirit of the conceptual work performed by Oktaei et al. (2015).

Lastly, another avenue of research is to examine the set of topologies where PI Hubs around a city collaborate. In this scenario, a truck coming in from the East, for example, would always go to the East Hub, then the shipments would travel on a smaller inter-hub truck to the PI Hub closest to its destination location. Then, from that PI Hub, it would depart the city on a truck towards its destination. We believe this to be a rich area for exploration because open consolidation and asset sharing are at the heart of the Physical Internet.

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