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Integrated fleet mix and routing decision for hazmat transportation: A developing country perspective

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ABSTRACT

In developing countries, truck purchase cost is the dominant criteria for fleet acquisition-related decisions. However, we contend that other cost factors such as loss due to the number of en route truck stoppages based on a truck type and recovery cost associated with a route choice decision, should also be considered for deciding the fleet mix and minimizing the overall costs for long-haul shipments. The resulting non-linear model, with integer variables for the number and type of trucks, and the route choices, is solved via genetic algorithm. Using real data from a bulk liquid hazmat transporter, the trade-offs between the cost of travel, loss due to number of truck stoppages, and the long-term recovery cost associated with the risk of exposure due to a hazmat carrier accident are discussed. The numerical experiments show that when factors related to public safety and truck stoppages are taken into account for transportation, the lowest total cost and optimal route choice do not align with the cheapest truck type option; rather, the optimal solution corresponds to another truck type and route with total costs significantly less than the total costs associated with the cheapest truck type. Our model challenges the current truck purchasing strategy adopted in developing countries using the cheapest truck criteria.

1. Introduction

"Over 3 billion tons of hazardous materials (HAZMAT) are transported by commercial carriers in the United States each year. Such hazmat shipments can be highly risky and highly sensitive and if improperly handled, labeled, or packaged could result in the loss of life, property damage, and harm to national security interests," (United States Government Accountability Office, 2014). The most common hazardous materials (hazmats) for transportation include cooking gas, fuel oil, and chemicals such as ethyl alcohol, and gasoline (Kara & Verter, 2004). Due to flammable, corrosive, explosive, poisonous or radioactive nature of dangerous goods, the carriers of hazmats, when involved in a road accident, may lead to disastrous consequences such as fire, explosion, spillage, and leakage, resulting in a large number of fatalities and injuries besides property loss and environmental pollution (Yang et al., 2010).

Road network, the most used transportation network in developed countries, is highly regulated in terms of hazmat movement. The regulatory body controls the maximum amount of long-haul drive time (without stoppages), limit choice of routes, and capacity of truck for hazmat movement (Toumazis & Kwon, 2013). Such regulations include US Department of Transportation, HOS (Hours of Service) Regulations for long-haul and regional operations of transporters. It mandates a driver carrying any shipment to drive not more than 11 hours after 10 consecutive hours of off-duty. Further, drivers must take a mandatory 30 minutes break by their eighth hour of coming on duty. The 14-hour duty period may not be extended with off-duty time for breaks, meal and fuel stops. Limitation on the choice of routes also exists in the real world scenario. For example, Canadian city of Brandon in Manitoba province can serve as an illustration where a website gives a map of the city which shows the roads that can be used by the trucks carrying dangerous goods (http://www.brandon.ca). However, developing countries such as India, are yet to develop a holistic regulatory regime of hazmat transportation while facing issues of either lack of regulation or lax implementation of existing regulations.

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Hence, there is a potential threat to public safety in developing countries where lax regulations on movement of hazardous goods may allow transport companies to choose minimal distance routes, while completely ignoring vulnerable zones of high density areas leading to high transport risk. Transport risk, which is defined as a measure of expected number of people, who would suffer the consequence of a possible hazmat accident, receives minimal consideration during route choice decisions. Chakrabarti and Parikh (2013b) confirms that about 90% of hazmat incidents in India occur on highways and majority of them occur in close vicinity to rural areas. Factoring in the potential threats posed by transportation of hazards, the paper attempts to bring about an optimal balance between minimizing cost of transport and cost of recovery (remedies) associated with hazmat transportation.

Among the more recent transporter challenges, driver-related issues have gained little attention (Zhou & Chen, 2015). Major challenges faced by the drivers (especially in developing countries) are: poor vehicle operating conditions, nonstandard working hours, no standard resting places between origin and destination points, and delays due to policy and regulatory needs (border/custom delays). To improve the vehicle operating condition, commercial vehicle manufacturers are designing trucks with ergonomic chairs and seats that have been found to increase productivity and comfort for the drivers (De Looze, Van Rhijn, Schoenmaker, Van der Grinten, & Van Deursen, 1993; Eikhout, Vink, & der Grinten, 2005; Hedge & Sakr, 2005; Rosecrance, Dpuphrate, & Cross, 1993; Vink, 2005). In concurrence with research on ergonomic design, we contend that the choice of truck (brand) has an effect on the comfort of the driver's seat, resting seat, and the number of truck stoppages per kilometer of travel (beyond the necessary stoppages such as mandatory rest-breaks). In long-haul transport, there could be potential cost advantages with trucks that include an ergonomic seat with an air-conditioned driver cabin against a cheaper truck with a non-ergonomic seat, and without an air-conditioned truck cabin. In such a scenario, the combined effect of cost advantages with less number of stops per kilometer (km) may out-weigh the difference in acquisition cost between the cheaper and the expensive truck types for long distance shipments. Hence, the decision with respect to the fleet mix (number and type of trucks) is affected by the relative position of the origin and destination nodes in the network.

Several studies in literature determine the optimal fleet mix by integrating it with the vehicle routing problem (Desrochers & Verhoo, 1991; Golden, Assad, Levy, & Gheysens, 1984; Salhi & Rand, 1993). However, existing models that are mostly developed from a developed country perspective do not capture the nuances with respect to long-haul transport in developing countries. The differences are:

1. *Large variety of the truck types (make and capacity)*: As discussed earlier, the transporters can select from a variety of truck brands (with different make, driver-cabin comfort, and capacity). All truck types in developed countries have a good basic operating condition for the drivers (such as air blower or air conditioner in the cabin). From a developing country's perspective, this criteria becomes special because the basic amenities may be absent in low cost truck types. Hence, different amount of driver discomfort may cause the number of truck stoppages between two places to vary from one truck to another.

2. *Population-based risk*: In developing countries, the road network may have limited route choices for hazmat transport and the transporter is often compelled to use a road that passes through a dense neighborhood, which carries a high population risk. Further, the restriction over transportation of hazardous materials over highly populated road network is minimal or absent. Hence, population-based risk should be assessed for fleet mix and the route choice decision (Chakrabarti & Parikh, 2013a; 2013b).

3. *Criteria for fleet acquisition*: Truck purchase cost is the dominant factor considered during fleet acquisition. The authors also surveyed 50 fleet owners in India and asked them to identify the most important factor for a new truck purchase. The factors included after-sales service, fuel efficiency, total cost of ownership, spares availability, brand image, ongoing relation with brand, modern and new brand, durability and reliability, strong dealer support, purchase price, finance arrangement by brand, relation with truck supplier, driver recommendation and mechanic recommendation. Out of 50 fleet owners, 24 responded that purchase price is the most important factor for truck purchase decision.

These issues have been studied separately in the prevailing literature. One of the primary contributions of this paper is to incorporate all three nuances in an integrated model. In addition, our approach in capturing the truck type-dependent stoppages and representing the population risk faced by the people residing along the highway segments as well as the population centers, is quite novel. Hence, the model built in this paper is more relevant and compelling from a developing country perspective.

Trucking companies expect their hired drivers to ensure a minimum daily travel distance irrespective of the truck make. Since a poor truck make may lead to excess number of truck stoppages, the driver may lag behind his schedule. To make up the lost time, the driver takes shorter routes associated with higher risks (in a unrestricted road network). Hence, the three factors: truck type, truck's load capacity and number of trucks used in a shipment, together referred to as 'fleet mix' decides the optimal route choice. We argue that studies that have ignored the losses suffered due to truck stoppage in deciding the 'fleet mix' may not be optimal and accounting for such losses presents a much more realistic scenario compared to the existing studies. In this research, we study the trade-offs between the truck purchase finance loan costs (trucks type in the shipment) and the costs associated with the routing decisions (i.e., the costs of transportation, loss due to truck stoppages, and costs associated with accident recovery). We also develop a population-based measure of risk to quantify recovery cost in the event of an accident. The hazmat transportation risk is incorporated in the objective function of the model as the expected accident recovery costs. The proposed risk measure not only captures the population at risk at the source and destination nodes, but also includes the ones along the travel route. Using this definition of risk, we attempt to answer the following research questions:

(*a*) *If the transport carrier intends to purchase a fleet of trucks with different make (truck type), capacities, and load type, what should be the fleet size and type for every shipment?*

(*b*) *For a particular shipment, how should the transporter select the optimal route among a set of available routes between origin and destination nodes?*

The decision variables are the appropriate fleet of vehicles serving a particular shipment and the route index. The objective of this problem is to minimize the sum of travel cost of shipment over the network, the cost of transport risk, and the loss due to truck stoppages. We specifically examine the problem that involves the transportation of multiple types of dangerous goods (chemical goods) to be shipped over multiple origin-destination pairs. The resulting mathematical formulation is a non-linear optimization model with integer decision variables.

The remainder of the paper is organized as follows. Section 2 reviews literature on modeling hazmat transportation problems. Section 3 describes model specification with discussion on the transportation network design problem and the model formulation to determine the optimal fleet mix. Section 4 discusses the solution methodology adopted to solve the non-linear optimization formulation. Section 5 first presents an illustrative example to demonstrate the main trade offs in the problem, and