Outline

1. Introduction

2. Background
   - Hazardous Materials
   - HazMat Transportation
   - Risk Measurement
   - Routing in HazMat Transportation

3. Research Problem and Objectives
   - Research Problem
   - Objectives

4. Methodology
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1 Introduction
2 Background
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Figure: Hazardous Materials Transportation Incidents (Left: New Orleans 2014. Right: Bogotá 2012.)
Hazardous Materials in Logistics

Today not only efficient transportation is important, environmental and safety concerns have become significant drivers towards more efficient and responsible transportation.

Material transportation risks have become a new important logistics issue and today is an activity of significant economic importance.
Gasoline supply chain

![Gasoline supply chain overview](image-url)
HazMat Transportation Risks

Risks
- spills,
- fires and
- explosions
HazMat Transportation Consequences

Consequences

- severe illness (people),
- death (people),
- irreversible pollution (natural environment),
- money losses (infrastructure),
- traffic disruption (people and infrastructure)
Hazardous Materials

Definition

A hazardous materials (or dangerous goods) is a substance or material that is capable of posing an unreasonable risk to health, safety, and property when transported in commerce.
Hazardous Materials (HazMat)

Nine Classes of Hazardous Materials

Class 1: Explosives
Divisions: 1.1, 1.2, 1.3, 1.4, 1.5, 1.6

Class 2: Gases
Divisions: 2.1, 2.2, 2.3

Class 3: Flammable Liquid and Combustible Liquid

Class 4: Flammable Solid, Spontaneously Combustible, and Dangerous When Wet
Divisions 4.1, 4.2, 4.3

Class 5: Oxidizer and Organic Peroxide
Divisions 5.1, 5.2

Class 6: Poison (Toxic) and Poison Inhalation Hazard

Class 7: Radioactive

Class 8: Corrosive

Class 9: Miscellaneous

Dangerous

UN Recommendations on the Transport of Dangerous Goods - Model Regulations
Decree 1609 of 31 July 2002 “manejo y transporte terrestre automotor de mercancías peligrosas por carretera”

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Objective

The objective of the hazardous materials transportation problem is the transportation of the quantity from the origins to the destinations through the most economic and safest routes.
HazMat Transportation Problems

- Hazardous Materials
- HazMat Transportation
- Risk Measurement
- Routing in HazMat Transportation

(Risk assessment)

(combined facility location and routing)

(network design)

(routeing)

(Fluko et al., 2007)
Risk in HazMat Transportation

Definition

In the context of HazMat transport, risk is a measure of the probability and severity of harm to an exposed receptor due to potential undesired events involving a HazMat (Erkut et al., 2007).
Risk assessment in HazMat Transportation

- Transportation accident
  - Undesired event: spill, fire, explosion

Exposed receptor: people, the environment, properties

- Health effects
- Property loss
- Environmental effect
- Evacuations
- Traffic stoppage
An edge is a collection of $n$ unit road segments.
An origin-destination route $P$ for a HazMat shipment is a collection of edges.
Path Risks Axioms

There are three important axioms which can be used to assess the merits of the different models (Erkut and Verter, 1998) (Erkut et al., 2007):

- **Axiom 1**: (Monotonicity axiom for path evaluation models).
- **Axiom 2**: (Optimality principle for path selection models).
- **Axiom 3**: (Attribute monotonicity axiom)
Transportation Network Models

- Transportation Network Design
- Optimal Network Design Problem
- Transportation Problem
- Vehicle Routing Problem
- Shortest Path Problem
- Assignment Problem
- Assignment Problem
- Transhipment Problem
- Spanning Tree Problem
- Network Flow Problem

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Routing in HazMat Transportation Problem

**Approaches**

- Shortest path problems.
- Vehicle routing and schedule problems.
A network to be used for HazMat routing is usually different from a network to be used for other transport planning purposes.
Heterogeneous Fleet of Vehicles

Many companies that have to distribute fuel own a heterogeneous fleet, these vehicles have different capacities, fixed costs, and/or variable costs. A high percentage of these liquid combustibles are distributed by tank trucks and this distribution is based on Less Than Truckload (LTL) in urban areas,
Problem Definition

An urban road network \((N, L)\) is considered.

**Sets**

- The node set \(N = \{1, 2, \ldots, |N|\}\) includes the depot node, a set of customer nodes, \(C\), and a set of non-customer nodes, \(T\).
- The link set \(L = \{(i, j) | i, j \in N\}\) includes all available connections between nodes in \(N\).
- The set of trucks \(K = \{1, 2, \cdots, t\}\), an heterogeneous fleet of vehicles composed of \(t\) vehicles type.
- The sets of HazMat transportation risks \(R = \{1, \cdots, r\}\)
Problem Definition

Parameters

- \((nx_i, ny_i)\) : the coordinates of each node \(n_i \in N\).
- \(d_i\) : demand of customer node \(c_i \in N\) in gallons.
- \(l_{ij}\) : length of each each link \((i, j) \in L\).
- \(t_{ij}\) : average travel time of each each link \((i, j) \in L\).
- \(R_{ij} = \{r_{ij1}, \cdots, r_{ijr}\}\) a HazMat transportation risk vector associated to each each link \((i, j) \in L\).
Problem Definition

Parameters

- $Q_k$: capacity of each vehicle $k \in K$.
- $f_k$: a fixed cost for each vehicle $k \in K$.
- $v_k$: variable costs per distance unit for each vehicle $k \in K$.
- $a_k$: availability for each vehicle type $k \in K$.
- $md_k/mt_k$: the maximum travel distance/time of each vehicle $k \in K$. 
Problem Definition - Routing Constraints

**VRP problem**

A route or trip is a cycle performed by one vehicle, starting and ending at the depot node and visiting a subset of customer nodes. The vehicle capacity must not be exceeded. Each customer must be visited by one single trip, i.e., split deliveries are not allowed.
Problem Definition - Routing Constraints

Heterogeneous Fleet

- The number of a truck type have or not a limitation.
- Truck trip has limitation in the distance/time.
- The consequences of an incident depend on the quantity transported (vehicle load) at that moment.
Decision Variables

\( y_{ij} \) : flow of goods from node \( i \) to node \( j \).

\[ x_{ijk} : \begin{cases} 1 & \text{if a vehicle of type } k \text{ travels the link } (i, j) \\ 0 & \text{otherwise} \end{cases} \]

\( \delta_{ijk} \) : the load of the vehicle of type \( k \) when traversing link \( (i, j) \).
Objective Criteria

Routing costs
Minimize the total routing costs.

HazMat transportation risks
Minimize HazMat transportation total routing risks (aggregated and separated).
Multi-objective approach

Pareto front approximation.
Fleet Composition in Routing Problems

- Fleet Composition and Routing Problems
  - Vehicle Routing Problem (VRP)
    - Homogeneous Fleet Problems
      - Time Windows
    - Heterogeneous Fleet Problems
      - Multi Depot
        - The Fleet Size and Mix Vehicle Routing Problem
          - Time Windows
        - Heterogeneous Fixed Fleet Vehicle Routing Problems
          - Multi Depot
## Relevant Papers HVRP- Fleet Size and Mix

<table>
<thead>
<tr>
<th>Authors</th>
<th>Method</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Golden et al., 1984)</td>
<td>suggest several heuristics for the problem. The authors also developed a procedure to calculate a lower bound.</td>
<td>Heuristics</td>
</tr>
<tr>
<td>(Salhi and Rand, 1993)</td>
<td>Developed an heuristic based on route perturbation procedure to reduce the total cost of routing and acquisition.</td>
<td>Heuristics</td>
</tr>
<tr>
<td>(Salhi and Osman, 1996)</td>
<td>Proposed two heuristics: a constructive heuristic based on route perturbation procedure (Salhi and Rand, 1993) and tabu search metaheuristic.</td>
<td>Tabu Search</td>
</tr>
<tr>
<td>(Taillard, 1999)</td>
<td>Proposed a method that combines tabu search and linear programming to solve the problem.</td>
<td>Heuristics Column Generation</td>
</tr>
</tbody>
</table>
## Relevant Papers HVRP- Fleet Size and Mix

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>(Wassan and Osman, 2002)</td>
<td>Presented a reactive tabu search with several neighborhoods and special data structures for efficiency.</td>
<td>Tabu Search.</td>
</tr>
<tr>
<td>(Renaud and Doctor, 2002)</td>
<td>Described a sweep-based heuristic</td>
<td>Heuristics.</td>
</tr>
<tr>
<td>(Lima et al., 2004)</td>
<td>Described a memetic algorithm (MA), a hybrid of a genetic algorithm and a local search.</td>
<td>Memetic Algorithm.</td>
</tr>
</tbody>
</table>
### Relevant Papers HVRP - Fleet Size and Mix

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<thead>
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</thead>
<tbody>
<tr>
<td>(Yaman, 2006)</td>
<td>Proposed an exact approach deriving formulations and valid inequalities to compute lower bounds to the problem.</td>
<td>Lower Bounds.</td>
</tr>
<tr>
<td>(Choi and Tcha, 2007)</td>
<td>Proposed a better bound based on column generation and used in a branch-and-bound (B&amp;B) algorithm</td>
<td>Branch and Bound + CG</td>
</tr>
<tr>
<td>Authors</td>
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<td>Type</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>(Taillard, 1999)</td>
<td>Proposed a heuristic column generation method for the HVRP. This method combines tabu search and linear programming to solve the problem.</td>
<td>Heuristics Column Generation.</td>
</tr>
<tr>
<td>(Tarantilis et al., 2004)</td>
<td>Provided an improved version of the threshold accepting algorithm (TA)</td>
<td>Threshold Accepting.</td>
</tr>
<tr>
<td>(Li et al., 2007)</td>
<td>published a record-to-record (RTR) travel metaheuristics</td>
<td>Record to Record Algorithm</td>
</tr>
<tr>
<td>(Prins, 2009)</td>
<td>Presented two memetic algorithms based on chromosomes encoded as giant tours, without trip delimiters, and on an optimal evaluation procedure.</td>
<td>Memetic Algorithm.</td>
</tr>
</tbody>
</table>
### Relevant Papers HVRP - Heterogeneous Fixed Fleet

<table>
<thead>
<tr>
<th>Authors</th>
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</thead>
<tbody>
<tr>
<td>(Brandão, 2011)</td>
<td>tabu search algorithm</td>
<td>Tabu search.</td>
</tr>
<tr>
<td>(Penna et al., 2013)</td>
<td>Proposed an algorithm based on the Iterated Local Search (ILS) metaheuristic.</td>
<td>Iterative Local Search.</td>
</tr>
<tr>
<td>(Liu, 2013)</td>
<td>Proposed a hybrid population heuristic</td>
<td>Evolutionary Algorithm.</td>
</tr>
</tbody>
</table>
## Relevant Papers HazMat Transportation

<table>
<thead>
<tr>
<th>Authors</th>
<th>Approach</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>(List et al., 1991)</td>
<td>Presented a research survey.</td>
<td>Risk analysis, routing/scheduling and facility location.</td>
</tr>
<tr>
<td>(Erkut et al., 2007)</td>
<td>HazMat logistics research review</td>
<td>HazMat transportation models: risk assessment, routing, facility location and network design.</td>
</tr>
</tbody>
</table>
## Relevant Papers HazMat Transportation

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<tr>
<td>(Zografos and Androutsopoulos, 2008)</td>
<td>Decision support system. Determined alternative non-dominated hazardous materials distribution routes in terms of cost and risk minimization based on two integer programming models.</td>
<td>Bi-objective routing and scheduling</td>
</tr>
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<tbody>
<tr>
<td>(Lozano et al., 2011)</td>
<td>Identification of alternative paths and estimation of their population exposures in chlorine and gasoline transportation in Mexico City.</td>
<td>Risk assessment in Haz-Mat distribution in urban areas.</td>
</tr>
<tr>
<td>(Pradhananga et al., 2014)</td>
<td>Formulation and solution of a Pareto-based bi-objective optimization problem using MOACS.</td>
<td>Vehicle routing and scheduling problem in HazMat transportation.</td>
</tr>
</tbody>
</table>

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This work focuses on applications of operational research models to HazMat transportation, in this case transportation routing problems: effective methods for identifying routes that will give lowest costs and risks for HazMat transportation.
Research Questions: Risk in HazMat Transportation

How risk is incorporated into HazMat transportation problems is a main aspects in model formulation. This poses the following research questions.

- Which are the appropriate methods to be used for identifying and evaluating the different risk factors present in HazMat transportation?
- What are the risks to be included in the mathematical model? and, are the risks to be considered in a separate way or in an aggregate way?
Research Questions: Modelling and Solution of Routing Problem

- Which mathematical formulation approach is suitable for representing the heterogeneous vehicle routing problem in hazardous material transportation (HazMat-HVRP) in the mono-objective case and in the multi-objective case?
- What is the impact of using heterogeneous fleet of vehicles in the minimization of risks in single product HazMat transportation when these risks depend on the type of vehicle?
Research Questions: Modelling and Solution of Routing Problem

- Are the methods of solution used in minimizing costs equally efficient and effective in minimizing risks?
- Which is the most appropriate solution strategy for solving heterogeneous vehicle routing problems that incorporate risk minimization, both, independent and simultaneous?
General Objective

To develop optimization methods for problems concerning the transportation (collection / distribution) of hazardous materials (HazMat).
Specifics Objective

**S01.** To select/propose a mathematical model for numerical route risk assessment in hazardous material transportation using road networks.

**S02.** To propose a mathematical formulation for the heterogeneous vehicle routing problem (HVRP) that includes the risks that may arise in the transportation of hazardous materials.

**S03.** To design a new solution method for heterogeneous vehicle routing problem (HVRP) in the context of transport of hazardous materials and evaluate its performance.
## Route Risk Models

<table>
<thead>
<tr>
<th>Task Goal</th>
<th>Research Activities</th>
<th>Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Select a route risk model in HazMat transportation</td>
<td>- A literature review.</td>
<td>- A software implementation.</td>
</tr>
<tr>
<td></td>
<td>- Exploration of mathematical models.</td>
<td>- A technical report.</td>
</tr>
<tr>
<td></td>
<td>- Comparative study.</td>
<td></td>
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VRP in HazMat Transportation
### Task Goal

<table>
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<th>Research Activities</th>
<th>Deliverables</th>
</tr>
</thead>
</table>
| Present a mathematical formulation |  - A literature review.  
- Problem definition and formulation.  
- Propose test instances. |  - A technical report.  
- A set of test instances. |
## Solution Methods

<table>
<thead>
<tr>
<th>Task Goal</th>
<th>Research Activities</th>
<th>Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develop a new solution method</td>
<td>- A literature review.</td>
<td>- Software implementation.</td>
</tr>
<tr>
<td>for risk minimization.</td>
<td>- Exploration of selected methods</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Comparative study.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Propose a solution method.</td>
<td>- A paper.</td>
</tr>
</tbody>
</table>

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## Multi-Objective Optimization

<table>
<thead>
<tr>
<th>Task Goal</th>
<th>Research Activities</th>
<th>Deliverables</th>
</tr>
</thead>
</table>
| Proposed an algorithm for HazMat HVRP multi-objective problems. | • Definition of measures.  
• Exploration of selected algorithms.  
• To propose and validate an algorithm. | • Software implementation.  
• A paper. |


References II


References VII


