NEW DIRECTIONS IN OPTIMIZING HAZARDOUS MATERIALS TRANSPORTATION DECISIONS

BY

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INTRODUCTION (1/6)

➢ HAZARDOUS MATERIALS DEFINITION

“HAZARDOUS MATERIAL: A SUBSTANCE OR MATERIAL […] BEING CAPABLE OF POSING AN UNREASONABLE RISK TO HEALTH, SAFETY, OR PROPERTY WHEN TRANSPORTED IN COMMERCE […]”

➢ HAZARDOUS MATERIALS TRANSPORTATION IS AN ACTIVITY OF SIGNIFICANT ECONOMIC IMPORTANCE (2.23 x 10^9 TONS OR 18% OF TOTAL GOODS TRANSPORTED)

➢ HIGH RISK IS ASSOCIATED WITH THEIR ACCIDENTAL RELEASE WHILE TRANSPORTED

INTRODUCTION (2/6)

- U.S. Code of Federal Regulations, 49CFR ("Transportation"), 105
INTRODUCTION (3/6)

- **Date**: May 24, 2004
- **Location**: 50 km northeast of Bucharest, Romania
- **Type of Accident**: truck overturn, explosion
- **Material**: more than 22t of “nitrous fertilizers”
- **Consequences**: 20 killed (including 7 military firefighters, 2 journalists, 3 local people watching the fire, and 5 people who stopped their cars to watch the fire)

INTRODUCTION (4/6)

- **Date**: April 22, 2004
- **Location**: Ryongchon, North Korea
- **Type of Accident**: two train wagons came into contact during shunting operations at the city railway station, massive explosion
- **Material**: each wagon containing 44t of AN (ammonium nitrate)
- **Consequences**: 54 killed, appr. 1,300 injured, town severely damaged (leveling everything in a 500-m radius)


http://gmfranci.wordpress.com/category/railroads-2/
INTRODUCTION (5/6)

✓ RISK = ACCIDENT PROBABILITY x CONSEQUENCE

✓ TRUCK ROUTING IS CONSIDERED A MAJOR PROACTIVE RISK MITIGATION MEASURE
  ▪ REDUCE ACCIDENT PROBABILITY
  ▪ REDUCE ACCIDENT CONSEQUENCE
INTRODUCTION (6/6)

➢ CONSIDERABLE RESEARCH EFFORT


- 7 books. ¹

- Appr. 10 journal papers per annum on average.

➢ NOT ALL REAL WORLD ASPECTS OF THE PROBLEM HAVE BEEN INCORPORATED IN EXISTING MODELS

PRESENTATION OBJECTIVES

➢ TO PRESENT THE EVOLUTION AND CHARACTERISTICS OF HAZARDOUS MATERIALS TRANSPORTATION AND DISTRIBUTION MODELS

➢ TO FORMULATE AND SOLVE A NEW MODEL FOR HAZARDOUS MATERIALS DISTRIBUTION

➢ TO PROVIDE RECOMMENDATIONS FOR FUTURE RESEARCH
### Classification and Evolution of Hazmat Models (1/3)

| O-D Predefined | - Yes  
<table>
<thead>
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| Type of Transportation | - FTL  
|                | - LTL   |
| Time Restrictions | - No  
|                | - Yes  
| Intermediate Stops | - No  
|                | - Yes  
| Number of Objectives | - Single  
|                | - Multiple |
| Type of Objectives | - Time  
|                | - Accident Probabilities  
|                | - Exposure - Different Measures  
|                | - Risk  
|                | - Equitable Distribution of Risk  
| Link Attributes | - Dynamic  
|                | - Static  
|                | - Deterministic  
|                | - Stochastic  
|                | - Capacity Constraints  

---

**Classifications and Evolution of Hazmat Models**

- **O-D Predefined**: Indicates whether the origin and destination are predefined or not.
- **Type of Transportation**: Differentiates between Full Truck Load (FTL) and Less Than Truck Load (LTL).
- **Time Restrictions**: Specifies if time windows, curfews, or delivery waiting times are applicable.
- **Intermediate Stops**: Determines if intermediate stops are allowed.
- **Number of Objectives**: Specifies whether a single or multiple objectives are considered.
- **Type of Objectives**: Determines the type of objectives, including time, accident probabilities, risk, equitable distribution of risk, dynamic, static, deterministic, stochastic, and capacity constraints.
- **Link Attributes**: Identifies link attributes such as deterministic, stochastic, static, and dynamic.
CLASSIFICATION AND EVOLUTION OF HAZMAT MODELS (2/3)

MAJOR CATEGORIES OF PROBLEMS

- LOCATION – ROUTING
- ROUTING – FTL
- ROUTING AND SCHEDULING FTL
- ROUTING AND SCHEDULING LTL-VRP
- NETWORK DESIGN
CLASSIFICATION AND EVOLUTION OF HAZMAT MODELS (3/3)

MAJOR CATEGORIES OF PROBLEMS

- CAPACITATED
- STOCHASTIC
- TIME-DEPENDENT
- DETERMINISTIC
- STATIC

OBJECTIVES
- SINGLE
- MULTIPLE

LINK ATTRIBUTES
- ROUTING - FTL
- ROUTING AND SCHEDULING - FTL
- ROUTING AND SCHEDULING - LTL-VRP
- NETWORK DESIGN

TYPE OF PROBLEM
PROBLEM DEFINITION (1/5)

Top 10 Commodities 2005-09 ranked by Weighted High-Impact Casualties

- Gasoline: 33.56%
- Chlorine: 24.56%
- Diesel fuel: 15.69%
- Propylene: 4.94%
- Fireworks: 4.19%
- Liquefied Petroleum Gas (LPG): 4.00%
- Carbon dioxide, refrigerated liquid: 3.56%
- Sulfuric acid: 3.31%
- Propane: 3.00%
- Argon, refrigerated liquid: 3.00%

- U.S. Department of Transportation, 2011
PROBLEM DEFINITION (2/5)

- A HIGH PERCENTAGE OF THESE COMMODITIES ARE DISTRIBUTED BY TRUCK
- DISTRIBUTION OF SUCH COMMODITIES IS BASED ON LTTL
- URBAN ENVIRONMENT

- U.S. Department of Transportation, 2011
PROBLEM DEFINITION (3/5)

- **CRITERIA**: TRAVEL TIME AND TRANSPORTATION RISK
- **LINK PROPERTIES**: ROADWAY NETWORK WITH TIME-DEPENDENT TRAVEL TIME AND RISK
- **DEMAND**: KNOWN IN ADVANCE
- **FLEET COMPOSITION**: NON-HOMOGENEOUS
- **GOAL**: IDENTIFY EFFICIENT ROUTES (TRAVEL TIME, RISK) FOR SERVICING A SET OF SPECIFIED ORDERS OF HAZARDOUS MATERIALS
- **SERVICE CONSTRAINTS**: TIME WINDOWS FOR CUSTOMERS AND DEPOT
PROBLEM DEFINITION (4/5)

MAJOR CATEGORIES OF PROBLEMS

- NETWORK DESIGN
- ROUTING - FTL
- ROUTING AND SCHEDULING - FTL
- ROUTING AND SCHEDULING - LTL-VRP
- Type of Problem
  - Single
  - Multiple
  - Static
  - Deterministic
  - Time-dependent
  - Stochastic
  - Capacitated
- Link Attributes
PROBLEM DEFINITION (5/5)

- BI-OBJECTIVE TIME DEPENDENT
- LOAD DEPENDENT RISK
TRAVEL TIME MODEL (1/5)

- CENTRAL ISSUE TRAVEL TIME MODELING:
  - ACCURACY, WHICH AFFECTS THE FEASIBILITY AND OPTIMALITY OF THE ROUTES
  - COMPUTATIONALLY EFFICIENT CALCULATION
TRAVEL TIME MODEL (2/5)

- Travel Time (i-j)
  - Non-FIFO

- Time of day
  - Instant change of travel speed

- Departure Time
  - Smooth travel speed
    - Horn, M (2000)

- Travel Speed
  - Converts the Non-FIFO piecewise constant travel time to piecewise linear function satisfying the FIFO conditions
TRAVEL TIME MODEL (3/5)

- THE TRAVEL TIME MODEL (WITH TRAVEL SPEED EXPRESSED THROUGH A PIECEWISE LINEAR FUNCTION OF THE TIME OF THE DAY) IS SELECTED:
  - IT IS MORE ACCURATE SINCE IT TAKES INTO ACCOUNT TRAVEL SPEED VARIATIONS.
  - THE ESTIMATION OF TRAVEL TIME IS MORE COMPUTATIONALLY INTENSIVE.

- A NEW EFFICIENT COMPUTATIONAL PROCEDURE IS PROPOSED.
**TRAVEL TIME MODEL (4/5)**

Departure Time (min) | Arrival Time (min)
---|---
0 | 0
5 | 5.8
10 | 10.2
15 | 15

\[
0 \leq Dd \leq 4.75 \rightarrow D\alpha
\]

\[
S = \left( \frac{1}{2} \right) (0.6)(\frac{5}{60})^2
\]

Since \( s < L \) then set \( L = 2 - 1.668 = 0.332 \)

Calculate distance \( s \) traveled from 0→5 min, i.e., \( s = 1.668 \) km through formula \( S = (\frac{1}{2})(0.6)(\frac{5}{60})^2 \)

Calculate distance \( s \) traveled from 5→10 min, i.e., \( s = 1.916 \) km. Since \( s > L \) then: calculate how much time is needed in order to travel 0.332 km in period 5-10 min. The result is: 0.8 min.
TRAVEL TIME MODEL (5/5)

Knowing the arrival time for a single departure time \( (\tau_d) \), a closed form solution has been derived that can estimate arrival time \( (\tau_a) \) at next node for any other departure time.

\[
A(\tau_d + \Delta d) = \tau_a + \left( \frac{1}{g_{ij}(\tau_{k+m})} \right) \left\{ -\left[ g^{k+m}_{ij} [\tau_a - \tau_{k+m}] + \nu^{k+m}_{ij} \right] + \left\{ g^{k+m}_{ij} [\tau_a - \tau_{k+m}] + \nu^{k+m}_{ij} \right\}^2 + 2 g^{k+m}_{ij} \left[ \frac{1}{2} g^k_{ij} \Delta d^2 + \left\{ g^k_{ij} [\tau_d - \tau_k] + \nu^k_{ij} \right\} \Delta d \right] \right\}^{1/2} \]

\[
A(\tau_d + \Delta d) = \tau_a + \frac{1}{\nu_{ij}(\tau_{k+m})} \left\{ \frac{1}{2} g_{ij}(\tau_k) \Delta d^2 + \left\{ g_{ij}(\tau_k)[\tau_d - \tau_k] + \nu_{ij}(\tau_k) \right\} \Delta d \right\}
\]
TRANSPORTATION RISK (1/5)

- Zografos and Davis (1989)
TRANSPORTATION RISK (2/5)

- **Probability of a Hazardous Materials Accident** is affected by **Traffic Flow Intensity**, **Prevailing Meteorological Conditions**, and **Roadway Network Characteristics**.

- **The consequences of an accident** are estimated based on:
  - **The area of impact**: It depends on the prevailing meteorological conditions and the intensity of the accident (explosion, fire, or contamination).
  - **The population density** of the areas exposed to transportation risk which also varies during different parts of the day.
TRANSPORTATION RISK (3/5)

http://www.truckaccidents360.com/
TRANSPORTATION RISK (4/5)

- **The intensity of the accident depends (among others) on the quantity transported at the time of the accident.**

- **The sequence of the stops affects the total transportation risk.**

- **Time-dependent**

- **FIFO assumption does not hold**
TRANSPORTATION RISK (5/5)

➢ HAZMAT ACCIDENT PROBABILITY MODEL

\[ \pi_{ij} := P[A_{ij}]P[R_m | A_{ij}]P[I_m | R_m] \]

- Probability of a truck accident.
- Probability of release given a truck accident.
- Probability of incident (e.g., fire, explosion) given a release.

➢ TRANSPORTATION RISK ON ANY ARC (i-j)

\[ R_{ij}^\tau (q) = \pi_{ij}^\tau P op_{ij}^\tau (q) \tau \in T, q \in [m_k, m_{k+1}] \]

q: THE QUANTITY TRANSPORTED THROUGH LINK (i,j)
MATHEMATICAL FORMULATION (1/6)

- Any route is expressed as a scheduled path (route-path) which connects an origin with a destination (depot) and passes through a series of stops.

- More than one route path may pass from any node hosting a customer.
MATHEMATICAL FORMULATION (2/6)

- A DUMMY NODE IS CREATED AND LINKED TO THE ORIGINAL NETWORK FOR EVERY NODE THAT HOSTS A STOP

- THE CUSTOMER IS ASSUMED TO BE HOSTED IN THE DUMMY NODE
MATHEMATICAL FORMULATION (3/6)

$S$  SET OF STOPS (CUSTOMERS)

$N$  SET OF NODES OF THE NETWORK

$A$  SET OF ARCS OF THE NETWORK

$d_j$ DEMAND AT NODE $j$

$x_{ijv}^\tau \in \{0,1\}$ IT TAKES VALUE 1 IF VEHICLE $v$ ENTERS LINK $(i,j)$ AT TIME $\tau$

$t^s(s_k)$ SERVICE TIME FOR STOP $s_k$

$[\alpha_{s_k}^e, \alpha_{s_k}^l]$ SERVICE TIME WINDOW FOR STOP $s_k$

$\Gamma^{-1}(s) := \{i \in N : (i,s) \in A\}$

$D_i(s_k) := \{\tau : \alpha_{s_k}^e \leq \tau + c_{(i,s_k)}^l(\tau) \leq \alpha_{s_k}^l\}$

$\Gamma^{+1}(s) := \{i \in N : (s,i) \in A\}$

$A_j(s_k) := \{\tau : \tau - t_{s_k}^s \leq \alpha_{s_k}^l\}$
**MATHEMATICAL FORMULATION (4/6)**

\[ \text{Min}(Z_1, Z_2) \]

\[ Z_1 := \sum_{\tau \in T} \sum_{i \in \Gamma^{-1}(s_{n+1})} \sum_{v \in V} (\tau x_{i,s_{n+1},v}^\tau) - \sum_{\tau \in T} \sum_{j \in \Gamma^+1(s_0)} \sum_{v \in V} (\tau x_{s_0,j,v}^\tau) \]

\[ Z_2 := \sum_{\tau \in T} \sum_{(i,j) \in A} \sum_{v \in V} (R_{ij}^\tau (\varphi_{ij,v}^\tau)) \]

\[ \text{Subject to:} \]

\[ \sum_{\tau \in T} \sum_{i \in N} \sum_{v \in V} x_{i,s,v}^\tau = 1 \quad s \in S \]

\[ \sum_{\tau \in T} \sum_{j \in N} x_{i,j,v}^\tau - \sum_{\tau \in T} \sum_{j \in N} x_{j,i,v}^\tau = 0 \quad v \in V \quad i \in N\backslash\{s_0, s_{n+1}\} \]

\[ \sum_{\tau \in T} \sum_{j \in N} x_{s_0,j,v}^\tau = 1 \quad v \in V \]

- **Total travel time**
- **Total Risk**
- **Each stop is serviced only once**
- **If a vehicle enters a node, it should also leave the node**
- **Each truck v leaves the origin s_o**
MATHEMATICAL FORMULATION (5/6)

\[
\sum_{\tau \in T} \sum_{j \in N} x_{s0jv}^\tau - \sum_{\tau \in T} \sum_{j \in N} x_{sn+1jv}^\tau = 0 \quad v \in V
\]

Any vehicle leaving the origin should arrive at a destination.

\[
\sum_{i \in I_j^{-1}} \sum_{\tau' \in \{l : l + c_{i,j}(l) = \tau - t_j^s\}} x_{ijv}^{\tau'} - \sum_{k \in I_j^+} x_{kvj}^{\tau} = 0 \quad \tau \in T, j \in N \quad \text{where} \quad I_j^+ := \{i \in N : (j, i) \in A\}
\]

If a truck leaves a node at time \(\tau\) then it should arrive at that node at a time \(\tau\) minus the service time at that node.

\[
\sum_{\tau \in D_i(s)} \sum_{v \in V} \sum_{i \in I_s^{-1}} x_{isv}^\tau = 1 \quad s \in S
\]

Any stop \(s\) is visited by a truck no later than the corresponding latest service start time \(\alpha^l_s\).

\[
\sum_{\tau \in A_j(s)} \sum_{v \in V} \sum_{j \in I_s^{-1}} x_{sjv}^\tau = 1 \quad s \in S
\]

The truck can depart between an earliest and a latest departure time (defined by the earliest and latest service start time of the visited customer).
MATHEMATICAL FORMULATION (6/6)

\[ \omega_{iv}^{\tau} - \omega_{jv}^{\tau'} + (1 - x_{ijv}^{\tau})M \geq d_j \quad (i,j) \in A, i \neq s_n, v \in V, \quad \tau' = \tau + c_{(i,j)}^{1}(\tau) + t_j^{s} \]

\[ \varphi_{ijv}^{\tau} + (1 - x_{ijv}^{\tau})M \geq \omega_{iv}^{\tau} \]

If a truck uses link \((i,j)\) then the change of the load when leaving node \(i\) from the load when leaving node \(j\) is \(d_j\) (demand in node \(j\)) at least.

Definition of the load of the truck \((v)\) when traversing link \((i,j)\) at time \(\tau\)

\[ \omega_{s0v}^{\tau} \leq K_v \]

The total demand covered by each truck \(v\) should not exceed its capacity \(K_v\)

\[ \omega_{sn+1v}^{\tau} = 0 \]

Every truck must arrive empty at the destination

\[ x_{ijv}^{\tau} \in \{0,1\} \quad \omega_{iv}^{\tau} \geq 0, \quad \varphi_{ijv}^{\tau} \geq 0 \]
SOLUTION ALGORITHM (1/9)

- THE PROBLEM UNDER STUDY CAN BE EXPRESSED BY A BI-CRITERION TIME DEPENDENT VEHICLE ROUTING PROBLEM WITH TIME WINDOWS

- THE WEIGHTING METHOD IS APPLIED WHICH LEADS TO A SERIES OF SINGLE OBJECTIVE (TIME-DEPENDENT) VRP WITH TIME WINDOWS AIMING TO OPTIMIZE THE WEIGHTED SUM OF TRAVEL TIME AND RISK

\[ C(R; \bar{w}) = \sum_{j=1}^{2} w_j c_j(R) \]

where \( w_j \in [0,1] \)

and \( \sum_{j=1}^{2} w_j = 1 \)

- Ehrgott, 2005.
SOLUTION ALGORITHM (2/9)

- The classic single-criterion VRP (time-dependent or not) is defined on a complete graph where each link denotes an a priori selected path.

- This convention does not work for the VRPTW problems arising from the application of the weighting method:
  - Different combination of weights in the objective function may lead to different shortest paths between any pair of stops for different departure times.
  - For any pair of stops, it is burdensome to calculate in advance the list of shortest paths for any possible combination of weights and departure times.
SOLUTION ALGORITHM (3/9)

- THEREFORE WE SHOULD DEAL SIMULTANEOUSLY WITH TWO PROBLEMS
  - SPECIFY SEQUENCE OF STOPS (ROUTE)
  - FIND PATH BETWEEN ANY TWO CONSECUTIVE STOPS

- SEQUENTIAL ROUTE CONSTRUCTION HEURISTIC WHERE EACH NEW CUSTOMER IS INSERTED AT THE BEGINNING OF THE ROUTE (1ST CANDIDATE POSITION)
SOLUTION ALGORITHM (4/9)

1. FOR EACH CANDIDATE CUSTOMER (LOAD FEASIBLE), WE CALCULATE TDSP FOR ALL POSSIBLE DEPARTURE TIMES

   ▪ ASSOCIATED TRAVEL TIMES ARE CALCULATED USING THE IMPROVED QUADRATIC TRAVEL MODEL
Required Path Finding Calculations for \((s_0, s_{\text{new}}, s_1)\)
- Find shortest paths from \(s_{\text{new}} \rightarrow s_{n+1}\) through 
\(\{s_1, s_2, s_3, s_4, s_5, s_6\}\), by applying the label setting algorithm 
from \(s_{\text{new}}\) to \(s_1\)

- Find shortest paths from \(s_0 \rightarrow s_{n+1}\) through 
\(\{s_{\text{new}}, s_1, s_2, s_3, s_4, s_5, s_6\}\), by applying the label setting 
algorithm from \(s_0\) to \(s_{\text{new}}\)

Required Path Finding Calculations for \((s_2, s_{\text{new}}, s_3)\)
- Find shortest paths from \(s_{\text{new}} \rightarrow s_{n+1}\) through 
\(\{s_3, s_4, s_5, s_6\}\), by applying the label setting algorithm from \(s_{\text{new}}\) to \(s_3\)

- Find shortest paths from \(s_2 \rightarrow s_{n+1}\) through 
\(\{s_{\text{new}}, s_3, s_4, s_5, s_6\}\), by applying the label setting algorithm from \(s_2\) to \(s_{\text{new}}\)

- Find shortest paths from \(s_1 \rightarrow s_{n+1}\) through 
\(\{s_2, s_{\text{new}}, s_3, s_4, s_5, s_6\}\), by applying the label setting algorithm from \(s_1\) to \(s_2\)

- Find shortest paths from \(s_0 \rightarrow s_{n+1}\) through 
\(\{s_1, s_2, s_{\text{new}}, s_3, s_4, s_5, s_6\}\), by applying the label setting algorithm from \(s_0\) to \(s_1\)
SOLUTION ALGORITHM (6/9)

2. INSERT A CUSTOMER AND ESTIMATE

\[ \eta(s_0, s_i, s_1; \bar{w}) = \left( \sum_{\tau=\tau^e}^{\tau^l} \theta_r(s_i; w_1, w_2) \right) \cdot \frac{a^l_{s_{n+1}} - a^l_{s_i}}{a^e_{s_1} - \tau^e} \]

3. INSERT CUSTOMER WITH THE LOWER INSERTION COST
SOLUTION ALGORITHM (7/9)

4. IF VEHICLE CAPACITY IS VIOLATED OR NO NEW CUSTOMER CAN BE INSERTED, CLOSE CURRENT ROUTE


6. IF ALL CUSTOMERS ARE ROUTED, TERMINATE. OTHERWISE START A NEW ROUTE AND REPEAT
SOLUTION ALGORITHM (8/9)
SOLUTION
ALGORITHM (9/9)
COMPUTATIONAL PERFORMANCE (1/5)

TESTING ACCURACY

- SMALL TEST PROBLEMS
- COMPLY WITH STRUCTURE OF A REAL-LIFE PROBLEM
- SOLVABLE BY A MIXED INTEGER PROGRAMMING (MIP) SOLVER
- TIME-DEPENDENT LOAD-INVARIANT RISK VALUES
- 49 NODES
- GRID-LIKE NETWORK
- FIVE CUSTOMERS
COMPUTATIONAL PERFORMANCE (2/5)

- DEMAND RANDOMLY SPECIFIED / RANGE: 2-4 TONS
- TRUCK CAPACITY: 10 TONS
- DIFFERENT ORIGIN / DESTINATION
- EARLIEST DEPARTURE – LATEST ARRIVAL: 60 min.
- TIME WINDOW: 10 min.
- 168 LINKS
- RANDOM LINK LENGTH 600-900m
COMPUTATIONAL PERFORMANCE (3/5)

ES: Exact Solution
HS: Heuristics Solution

Risk

Travel Time

ES-1
ES-2
ES-3
ES-4
COMPUTATIONAL PERFORMANCE (4/5)

- Heuristic solutions were compared to exact (using the exact solution with the minimum Euclidean distance) solutions by calculating the percentage difference of travel time and risk.

- Travel time difference: 11.1%
- Risk difference: 14.6%
- Worst heuristic travel time: 36.4%
- Worst heuristic risk: 48.3%

- Substantial differences in computational time (15 sec. Vs. 5,000 sec)
COMPUTATIONAL PERFORMANCE (5/5)

- COMPUTATIONAL TIME INCREASES WITH TIME WINDOW WIDTH AND NUMBER OF CUSTOMERS

<table>
<thead>
<tr>
<th>Test Problem</th>
<th>Number of customers</th>
<th>Depot Time window (min)</th>
<th>Average Number of Problems Solved</th>
<th>Average number of solutions</th>
<th>Average Computational Time (in sec)</th>
<th>Average Comp. Time per problem solved (sec)</th>
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CONCLUDING REMARKS

- BI-OBJECTIVE TIME-DEPENDENT VRP WITH TIME WINDOWS
- SIMULTANEOUS PATH FINDING AND SCHEDULING
- USE OF PIECE-WISE LINEAR TRAVEL SPEED ENHANCED RELIABILITY IN SATISFYING SERVICE TIME WINDOWS
- RISK MODEL
  - TIME-DEPENDENT ACCIDENT PROBABILITIES
  - LOAD-DEPENDENT POPULATION EXPOSURE
FUTURE RESEARCH DIRECTIONS

- SIMILAR MODEL AND SOLUTION ALGORITHM CAN BE USED FOR THE TIME DEPENDENT AND LOAD DEPENDENT POLLUTION-ROUTING PROBLEM
  - TRAVEL TIME
  - CO\textsubscript{2} EMISSIONS

- METAHEURISTICS (ANT COLONY SYSTEM) CAN BE USED TO IMPROVE SOLUTION QUALITY

- DEVELOP METHODOLOGIES FOR ESTIMATING TIME AND LOAD DEPENDENT RISK VALUES
ACKNOWLEDGMENTS

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REFERENCES (1/2)


REFERENCES (2/2)


