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 […]"

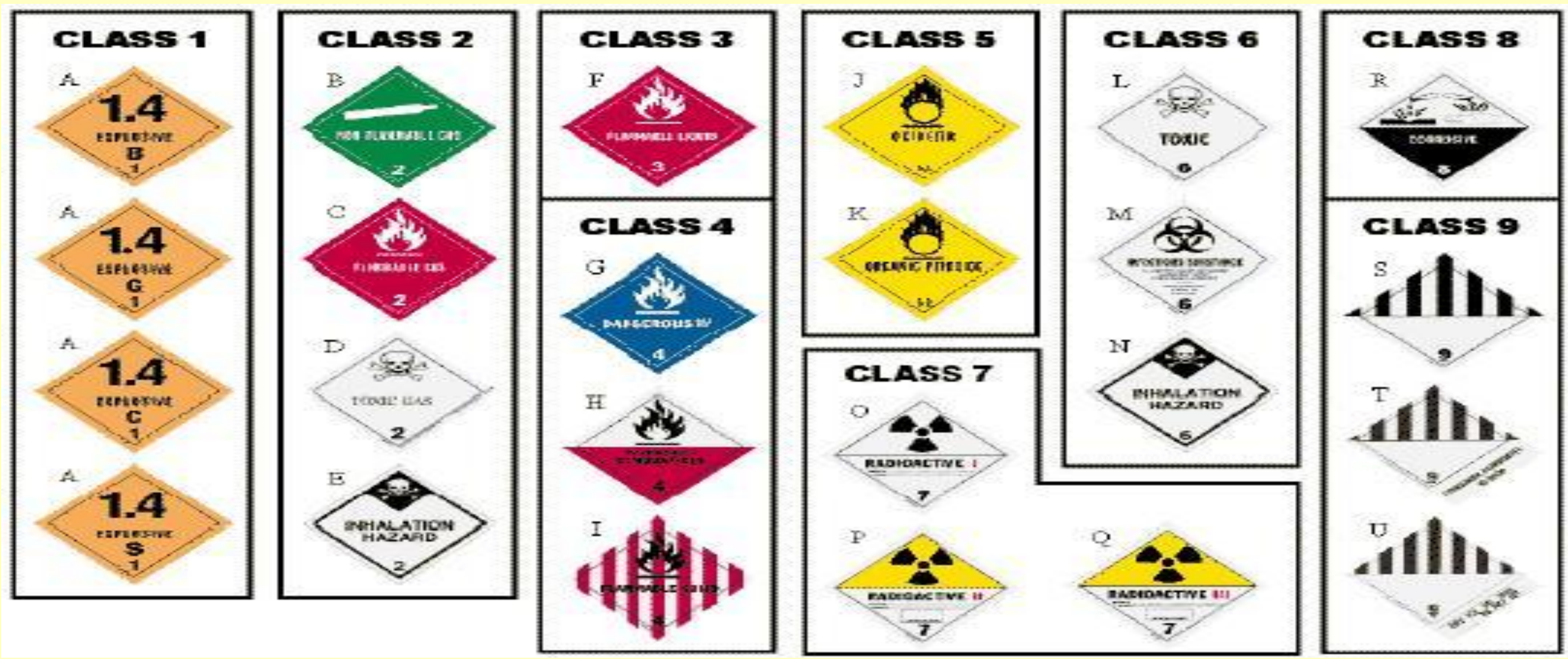
- HAZARDOUS MATERIALS TRANSPORTATION IS AN ACTIVITY OF SIGNIFICANT ECONOMIC IMPORTANCE (2.23×10^9 TONS OR 18% OF TOTAL GOODS TRANSPORTED)

- HIGH RISK IS ASSOCIATED WITH THEIR ACCIDENTAL RELEASE WHILE TRANSPORTED

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

INTRODUCTION (2/6)

EXPLOSIVES | COMPRESSED GASES | FLAMMABLE LIQUIDS & SOLIDS | OXIDIZERS | POISONS | CORROSIVE LIQUIDS



RADIOACTIVE MATERIALS | MISCELLANEOUS

- 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)

Mainiero, R.J., J.H. Rowland III, "A Review of Recent Accidents Involving Explosives Transport", Journal of Explosives Engineering, 26(2), pp.6-12, 2009.

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)

Mainiero, R.J., J.H. Rowland III, "A Review of Recent Accidents Involving Explosives Transport", Journal of Explosives Engineering, 26(2), pp.6-12, 2009.

http://www.internet-law-firm.com/articles/Train%20derailment%20in%20Baltimore/Train%20derailment%20reveals%20fragile%20Net.htm
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

- 8 special issues of journals [**Transportation Science** (2 issues), **Journal of Transportation Engineering**, INFOR (double-issue), Location Science, Studies in Locational Analysis, **Computers & Operations Research**, International Journal of Heavy Vehicle Systems], [1]
- 1 Chapter (by E. Erkut, S.A. Tjandra, and V. Verter) in the "**Handbook in OR & MS**", edited by C. Barnhart and G. Laporte, Vol. 14, Elsevier, 2007. [1]
- 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

[1]Erkut, E., S.A. Tjandra, and V. Verter, "Hazardous Materials Transportation", Chapter in "Handbook in OR & MS", Edited by C. Barnhart and G. Laporte, Vol. 14, 2007.

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
  - NO
- **TYPE OF TRANSPORTATION** →
  - FTL
  - LTL
- **TIME RESTRICTIONS** →
  - NO
  - YES → TIME WINDOWS, CURFEWS
- **INTERMEDIATE STOPS** →
  - NO
  - YES → DELIVERY, WAITING
- **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

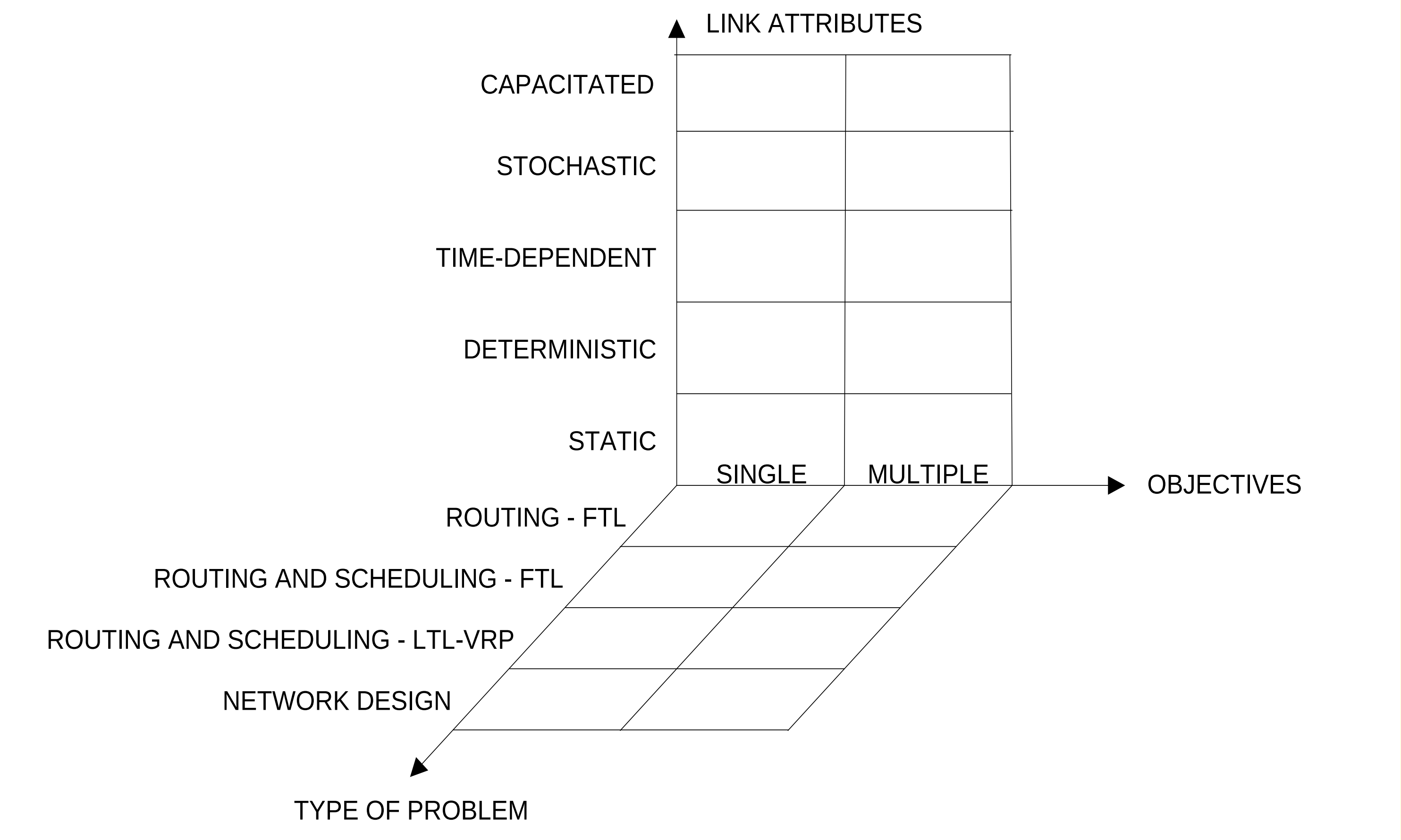
CLASSIFICATION AND EVOLUTION OF HAZMAT MODELS (2/3)

MAJOR CATEGORIES OF PROBLEMS

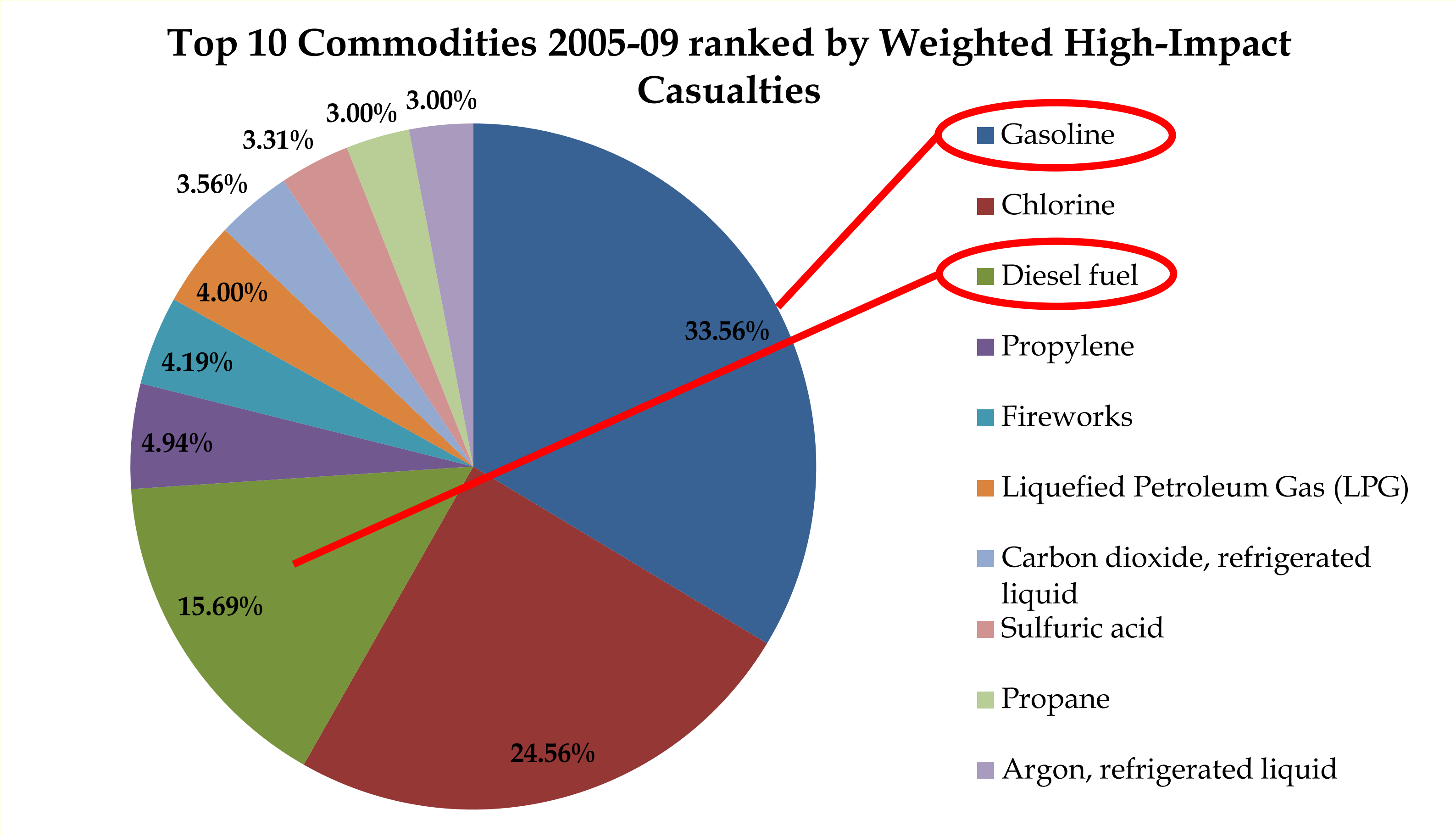
- LOCATION – ROUTING
- ROUTING – FTL
- ROUTING AND SCHEDULING FTL
- ROUTING AND SCHEDULING LTL-VRP
- NETWORK DESIGN

CLASSIFICATION AND EVOLUTION OF HAZMAT MODELS (3/3)

MAJOR CATEGORIES OF PROBLEMS



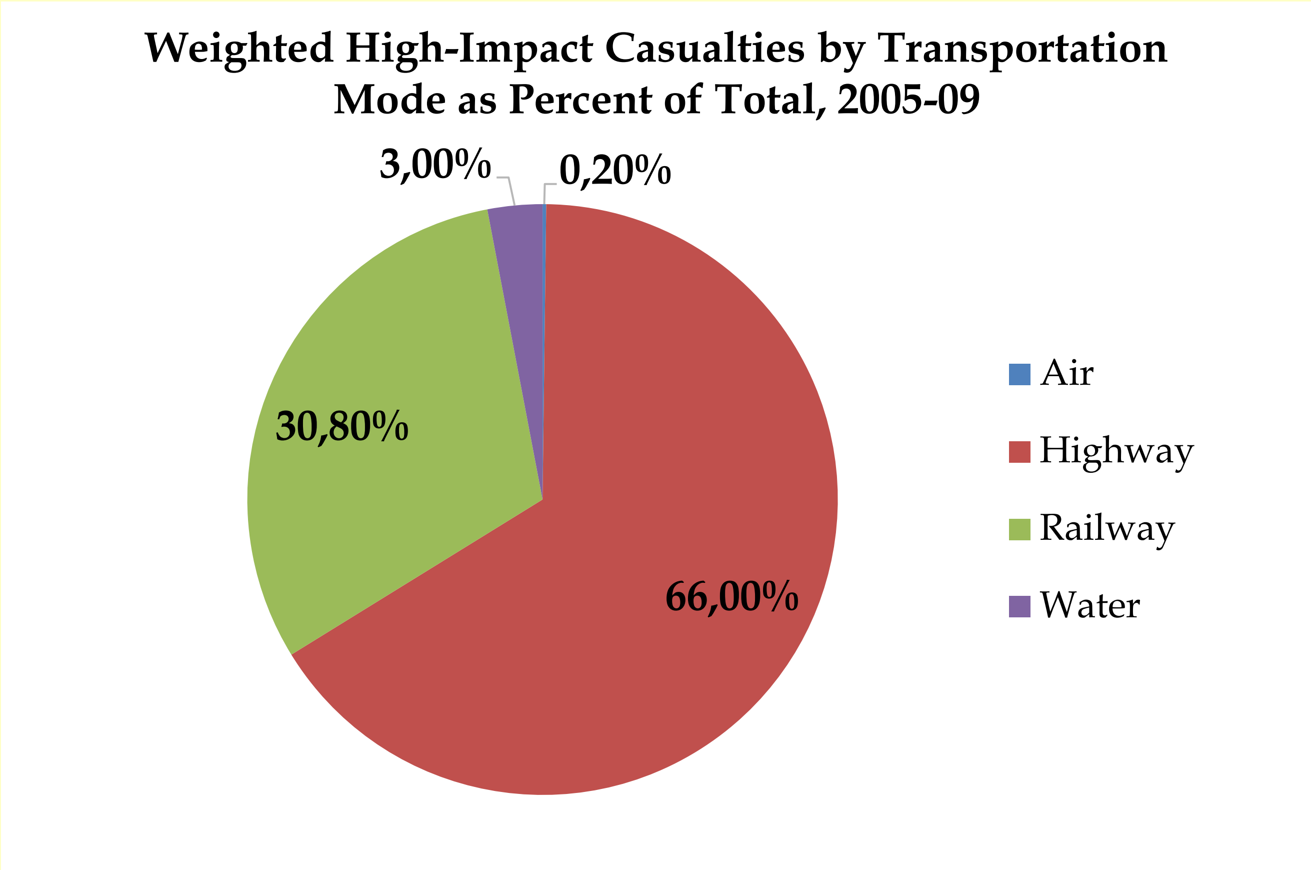
PROBLEM DEFINITION (1/5)



- 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



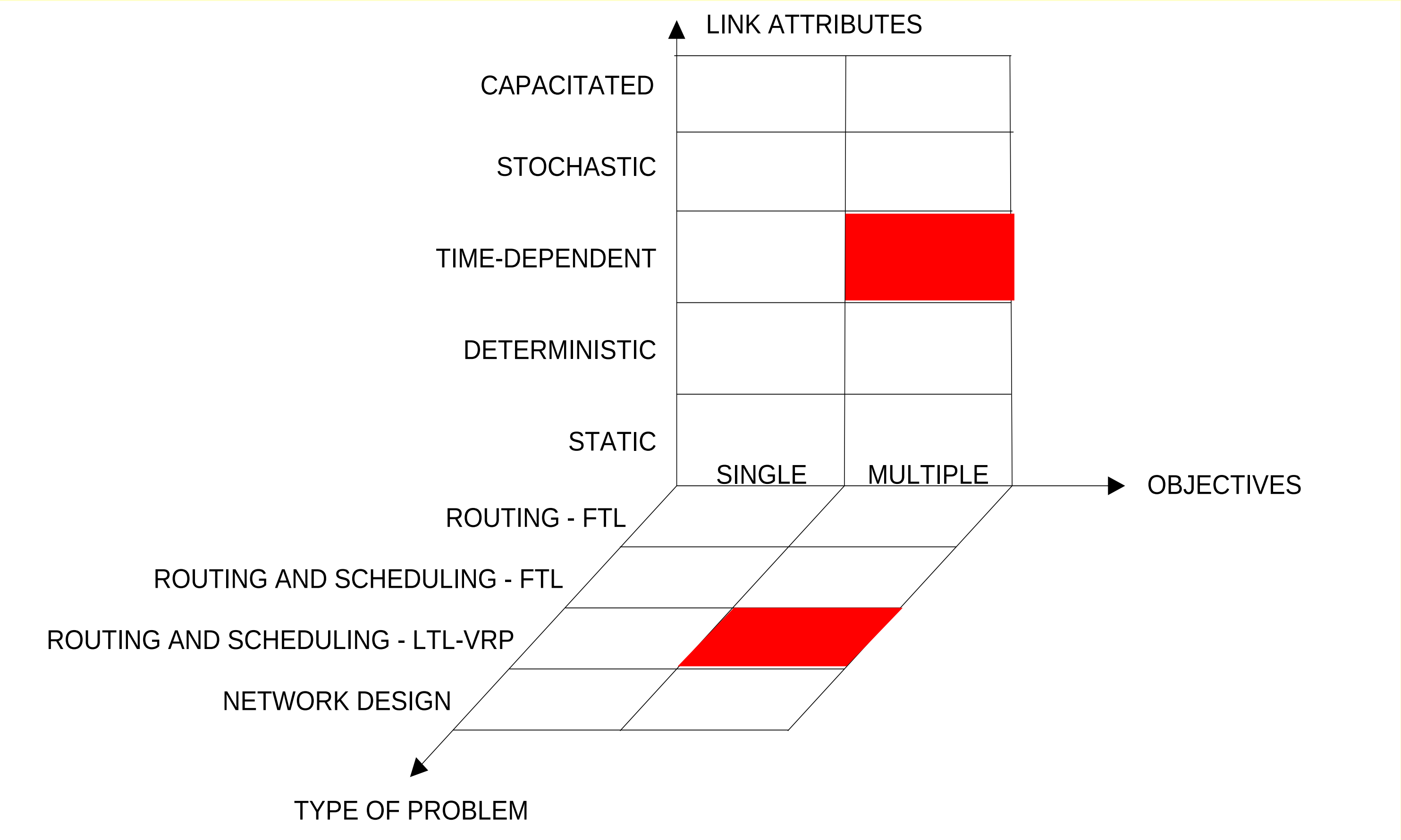
- U.S. Department of Transportation, 2011

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



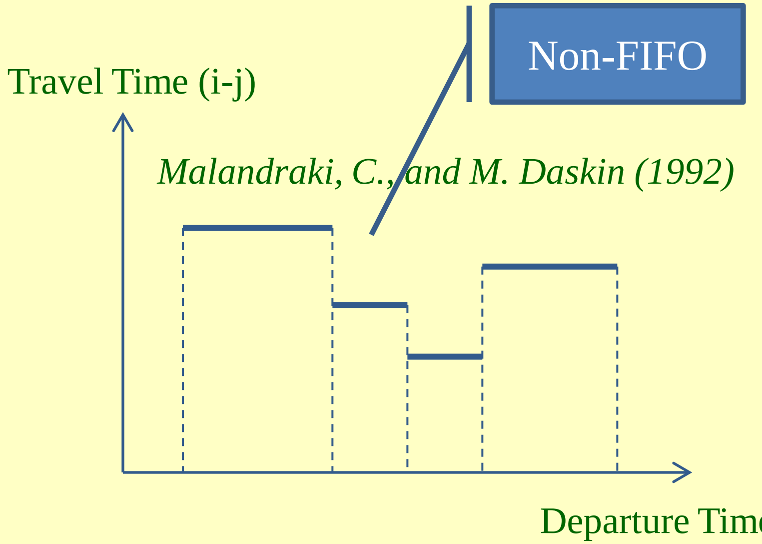
PROBLEM DEFINITION (5/5)

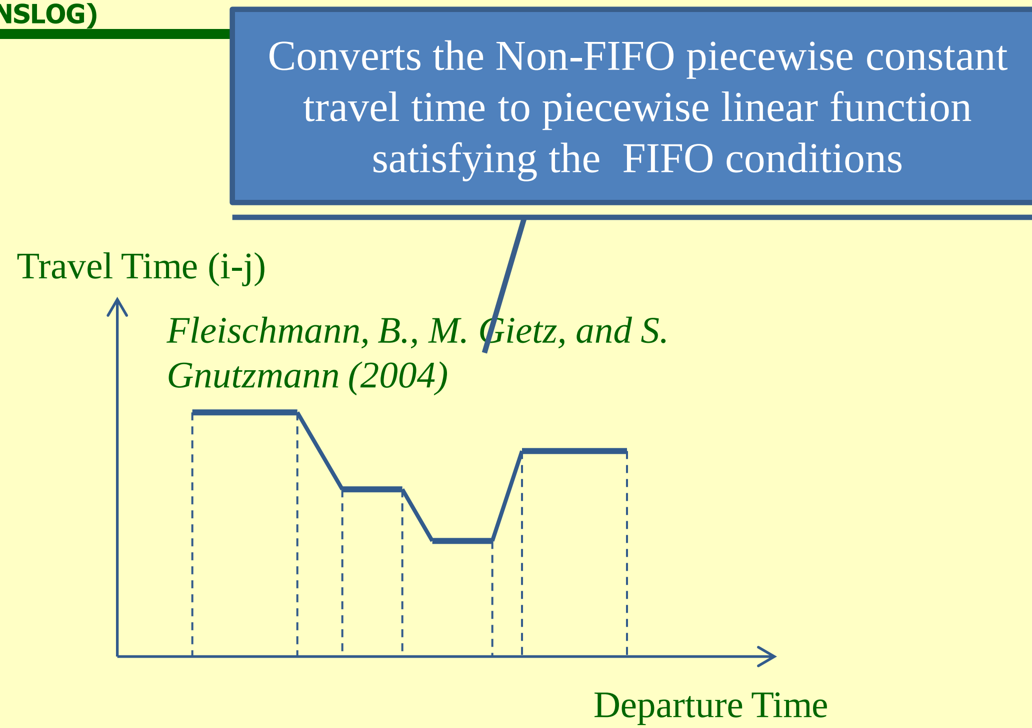
- BI-OBJECTIVE TIME DEPENDENT
- LOAD DEPENDENT RISK

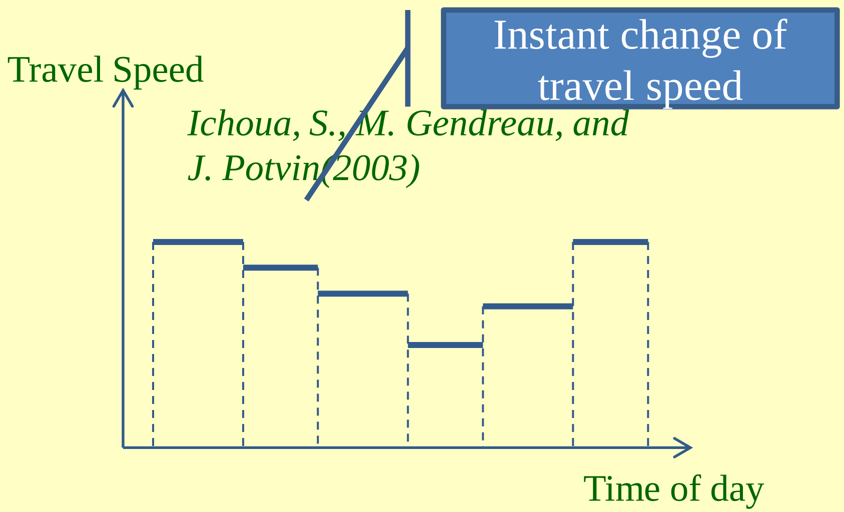
TRAVEL TIME MODEL (1/5)

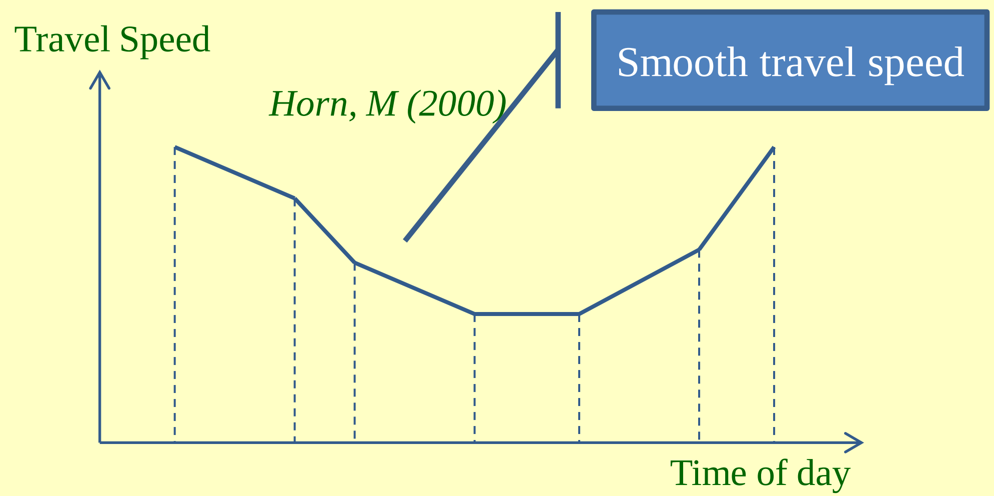
- CENTRAL ISSUE TRAVEL TIME MODELING:
  - ACCURACY, WHICH AFFECTS THE FEASIBILITY AND OPTIMALITY OF THE ROUTES
  - COMPUTATIONALLY EFFICIENT CALCULATION

TRAVEL TIME MODEL (2/5)





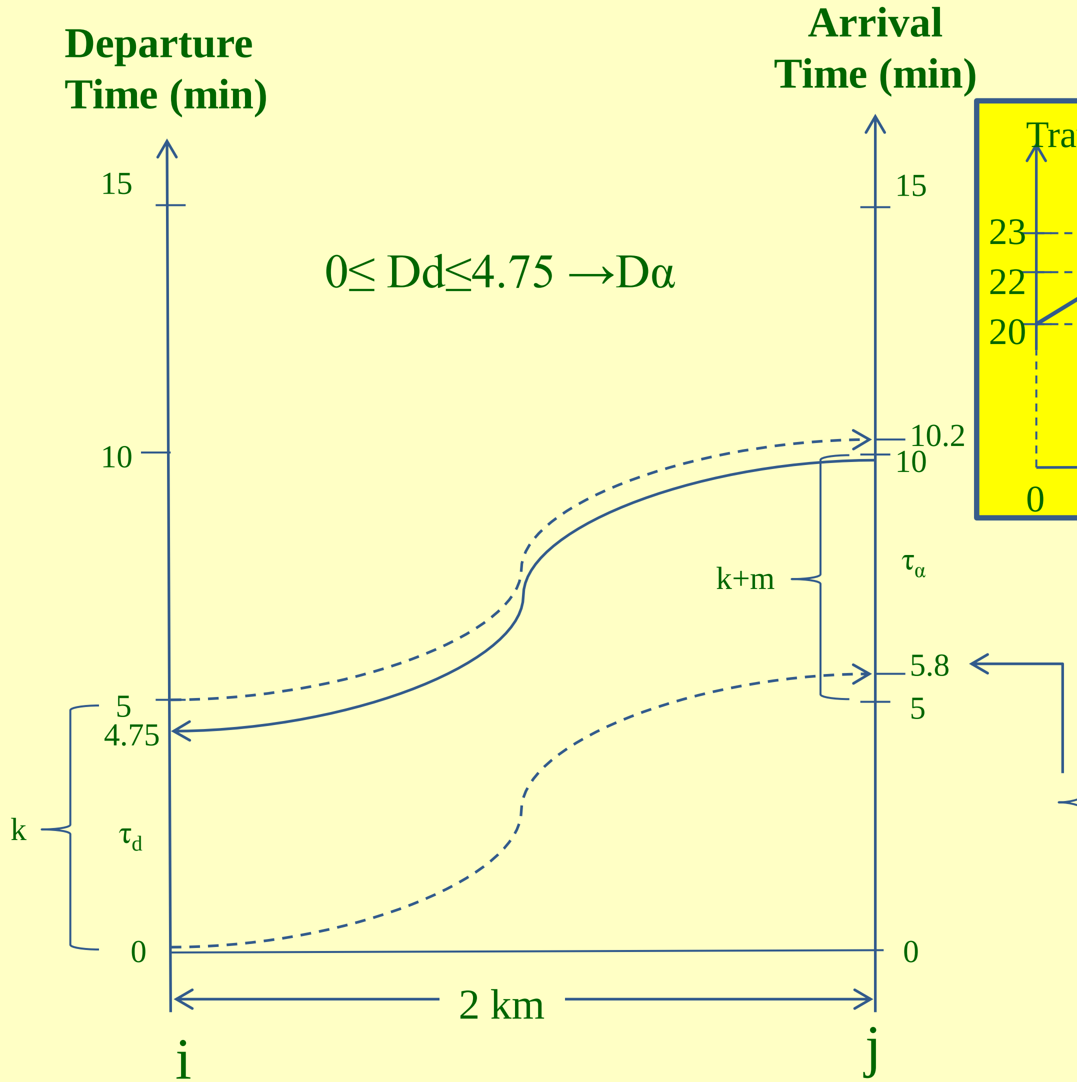


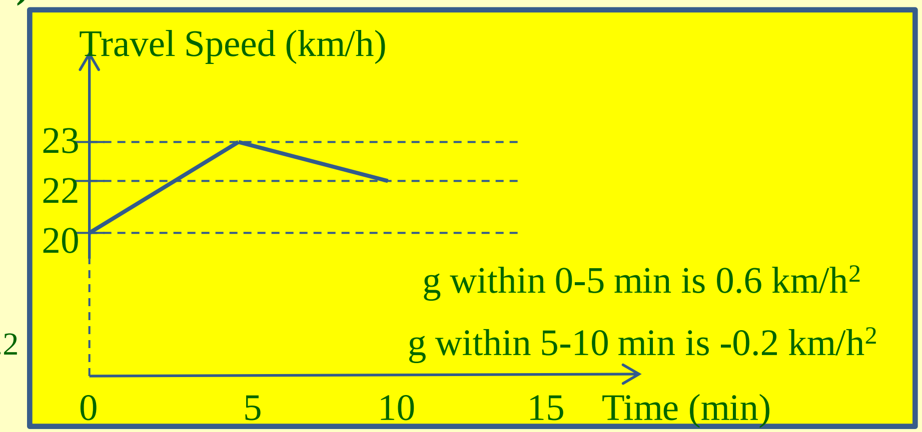


TRAVEL TIME MODEL (3/5)

- 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 is 0 min. Set L=2 km.

Calculate distance (s) traveled from 0→5 min, i.e., s=1.668 km through formula $\mathbf{S=(\frac{1}{2})(0.6)(\frac{5}{60})^2}$ Since s<L then set L=2-1.668=0.332

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 (τ_d), A CLOSED FORM SOLUTION HAS BEEN DERIVED THAT CAN ESTIMATE ARRIVAL TIME (τ_α) AT NEXT NODE FOR ANY OTHER DEPARTURE TIME

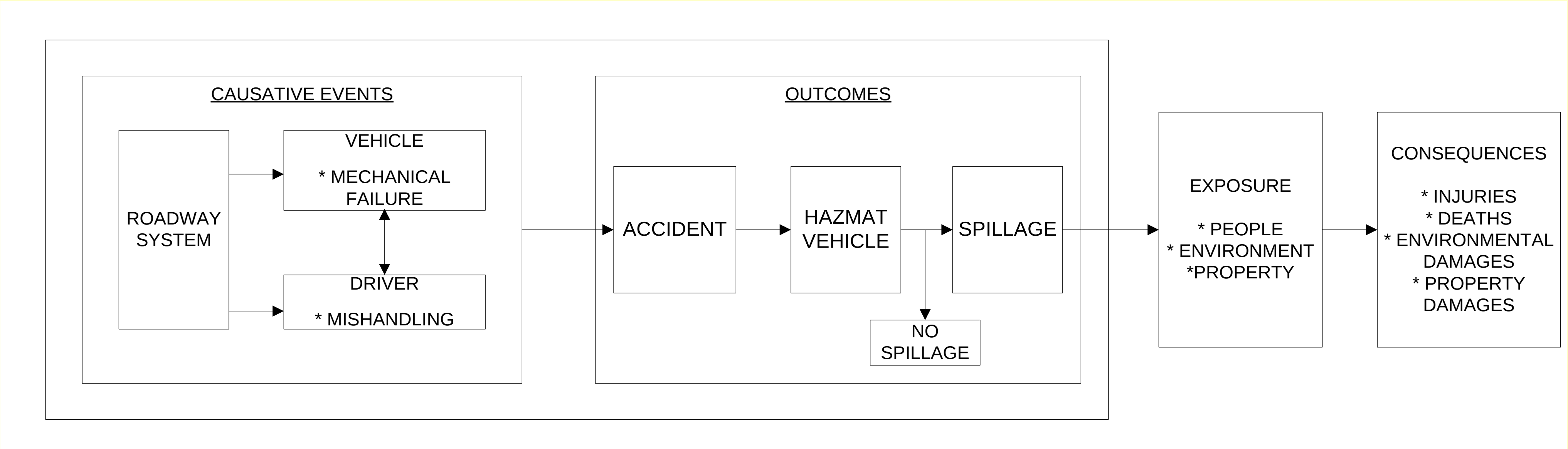
$g_{ij}(\tau_{k+m}) \neq 0$

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

$g_{ij}(\tau_{k+m}) = 0$

$$A(\tau_d + \Delta d) = \tau_a + \frac{1}{v_{ij}(\tau_{k+m})}\left\{\frac{1}{2}g_{ij}(\tau_k)\boldsymbol{\Delta d^2} + \left\{g_{ij}(\tau_k)[\tau_d - \tau_k] + v_{ij}(\tau_k)\right\}\Delta d\right\}$$

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/

http://www.internet-law-firm.com/articles/Train%20derailment%20in%20Baltimore/Train%20derailment%20reveals%20fragile%20Net.htm

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

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

- $P[A_{ij}]$: Probability of a truck accident.
- $P[R_m|A_{ij}]$: Probability of release given a truck accident.
- $P[I_m|R_m]$: Probability of incident (e.g., fire, explosion) given a release.

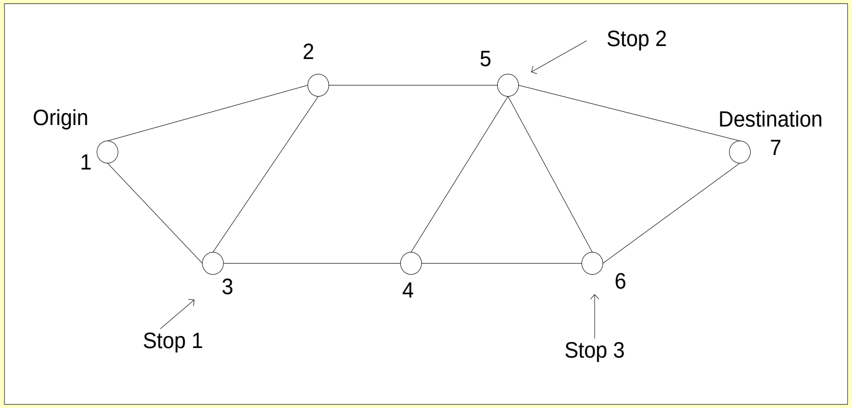
- TRANSPORTATION RISK ON ANY ARC (i-j)

$$R_{ij}^{\tau}(q) = \pi_{ij}^{\tau} Pop_{ij}^{\tau}(q) \quad \tau \epsilon T, q \epsilon [m_k, m_{k+1}]$$

q: THE QUANTITY TRANSPORTED THROUGH LINK (i,j)

MATHEMATICAL FORMULATION (1/6)

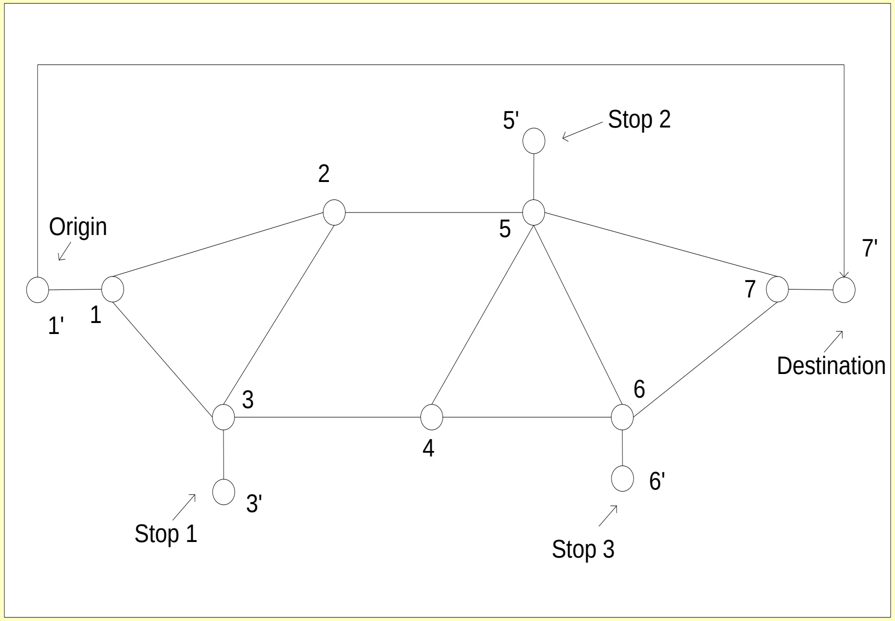
- ANY ROUTE IS EXPRESSED AS A SCHEDULED PATH (ROUTE-PATH) WHICH CONNECTS AN ORIGIN WITH A DESTINATION (DEPOT) AND PASSES THROUGH A SERIES OF STOPS



- 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 τ
$t^s(s_k)$	SERVICE TIME FOR STOP s_k
$[a_{s_k}^e, a_{s_k}^l]$	SERVICE TIME WINDOW FOR STOP s_k

$$\Gamma^{-1}(s) := \{i \in N : (i,s) \in A\} \qquad D_i(s_k) := \{\tau : \alpha_{s_k}^e \le \tau + c_{(i,s_k)}^1(\tau) \le \alpha_{s_k}^l\}$$

$$\Gamma^{+1}(s) := \{i \in N : (s,i) \in A\} \qquad A_j(s_k) := \{\tau : \tau - t_{s_k}^s \le \alpha_{s_k}^l\}$$

MATHEMATICAL FORMULATION (4/6)

$$Min(Z_1, Z_2)$$

$$Z_1 := \sum_{\tau \epsilon T} \sum_{i \epsilon \Gamma^{-1}(s_{n+1})} \sum_{v \epsilon V} (\tau\, x^{\tau}_{i s_{n+1} v}) - \sum_{\tau \epsilon T} \sum_{j \epsilon \Gamma^{+1}(s_0)} \sum_{v \epsilon V} (\tau\, x^{\tau}_{s_0 j v})$$

Total travel time

$$Z_2 := \sum_{\tau \epsilon T} \sum_{(i,j) \epsilon A} \sum_{v \epsilon V} (R^{\tau}_{ij} (\varphi^{\tau}_{ijv}))$$

Total Risk

Subject to:

$$\sum_{\tau \in T} \sum_{i \in N} \sum_{v \in V} x^{\tau}_{isv} = 1 \quad s \in S$$

Each stop is serviced only once

$$\sum_{\tau \in T} \sum_{j \in N} x^{\tau}_{ijv} - \sum_{\tau \in T} \sum_{j \in N} x^{\tau}_{jiv} = 0 \quad v \in V \quad i \in N \backslash \{s_0, s_{n+1}\}$$

If a vehicle enters a node, it should also leave the node

$$\sum_{\tau \in T} \sum_{j \in N} x^{\tau}_{s_0 j v} = 1 \quad v \in V$$

Each truck v leaves the origin s_o

MATHEMATICAL FORMULATION (5/6)

$$\sum_{\tau \in T} \sum_{j \in N} x^{\tau}_{s_0 j v} - \sum_{\tau \in T} \sum_{j \in N} x^{\tau}_{j s_{n+1} v} = 0 \quad \boldsymbol{v \in V}$$

Any vehicle leaving the origin should arrive at a destination

If a truck leaves a node at time τ then it should arrive at that node at a time τ minus the service time at that node.

$$\sum_{i \epsilon \Gamma_j^{-1}} \sum_{\tau' \epsilon \{l : l + c^1_{(i,j)}(l) = \tau - t^s_j\}} x^{\tau'}_{ijv} - \sum_{k \epsilon \Gamma_j^{+1}} x^{\tau}_{kjv} = 0 \qquad \tau \in T, j \in N$$

where $\Gamma_j^{+1} := \{i \in N : (j,i) \in A\}$

$$\sum_{\tau \in D_i(s)} \sum_{v \in V} \sum_{i \in \Gamma_s^{-1}} x^{\tau}_{isv} = 1 \qquad s \in S$$

Any stop *s* is visited by a truck no later than the corresponding latest service start time α^l_s

$$\sum_{\tau \in A_j(s)} \sum_{v \in V} \sum_{j \in \Gamma_s^{-1}} x^{\tau}_{sjv} = 1 \qquad s \in S$$

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)

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

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

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

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

$$\omega_{s_0 v}^{\tau} \leq K_v$$

The total demand covered by each truck *v* should not exceed its capacity K_v

$$\omega_{s_{n+1} v}^{\tau} = 0$$

Every truck must arrive empty at the destination

$$x_{ijv}^{\tau} \epsilon \{0,1\} \qquad \omega_{iv}^{\tau} \geq 0, \qquad \varphi_{ijv}^{\tau} \geq 0$$

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

$$C(R;\overline{w}) = \sum_{j=1}^{2} w_j c_j(R)$$

where $w_j \epsilon [0,1]$

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

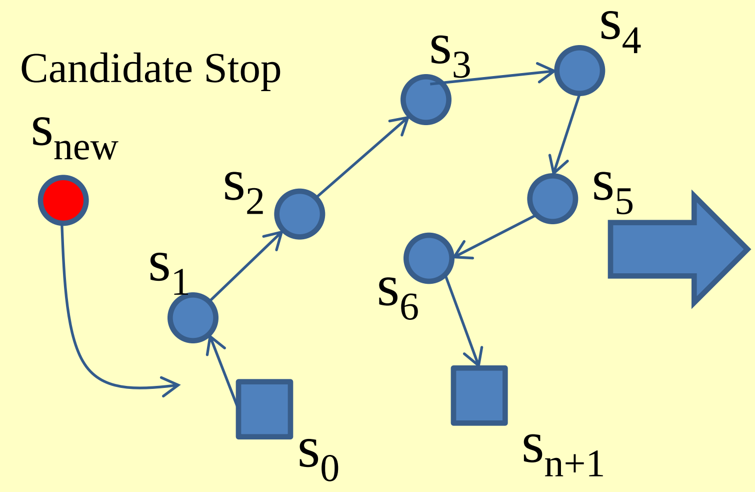
- SEQUENTIAL ROUTE CONSTRUCTION HEURISTIC WHERE EACH NEW CUSTOMER IS INSERTED AT THE BEGINNING OF THE ROUTE (1^{ST} CANDIDATE POSITION)

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

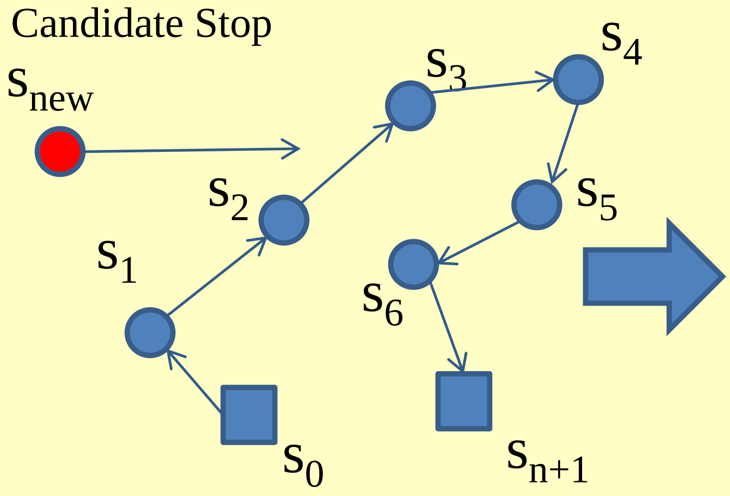
SOLUTION ALGORITHM (5/9)



Required Path Finding Calculations for (s_0,s_{new},s_1)

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

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



Required Path Finding Calculations for (s_2,s_{new},s_3)

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

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

- Find shortest paths from $s_1 \rightarrow s_{n+1}$ through {s_2, s_{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_{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

$$\eta(s_0, s_i, s_1; \overline{w}) = \left(\frac{\sum_{\tau=\tau^e}^{\tau^l} \theta_r^{\tau}(s_i; w_1, w_2)}{\tau^l - \tau^e} \right) \cdot \left(\frac{a_{s_{n+1}}^l - a_{s_i}^l}{a_{s_1}^e - \tau^e} \right)$$

Cost of shortest route path after inserting s_i

Average cost value for each candidate stop

Latest feasible departure time from the origin.

Earliest feasible departure time from the origin.

Latest arrival time at destination

Latest arrival time at stop i.

Lateness of the service time window of any candidate stop

3. INSERT CUSTOMER WITH THE LOWER INSERTION COST

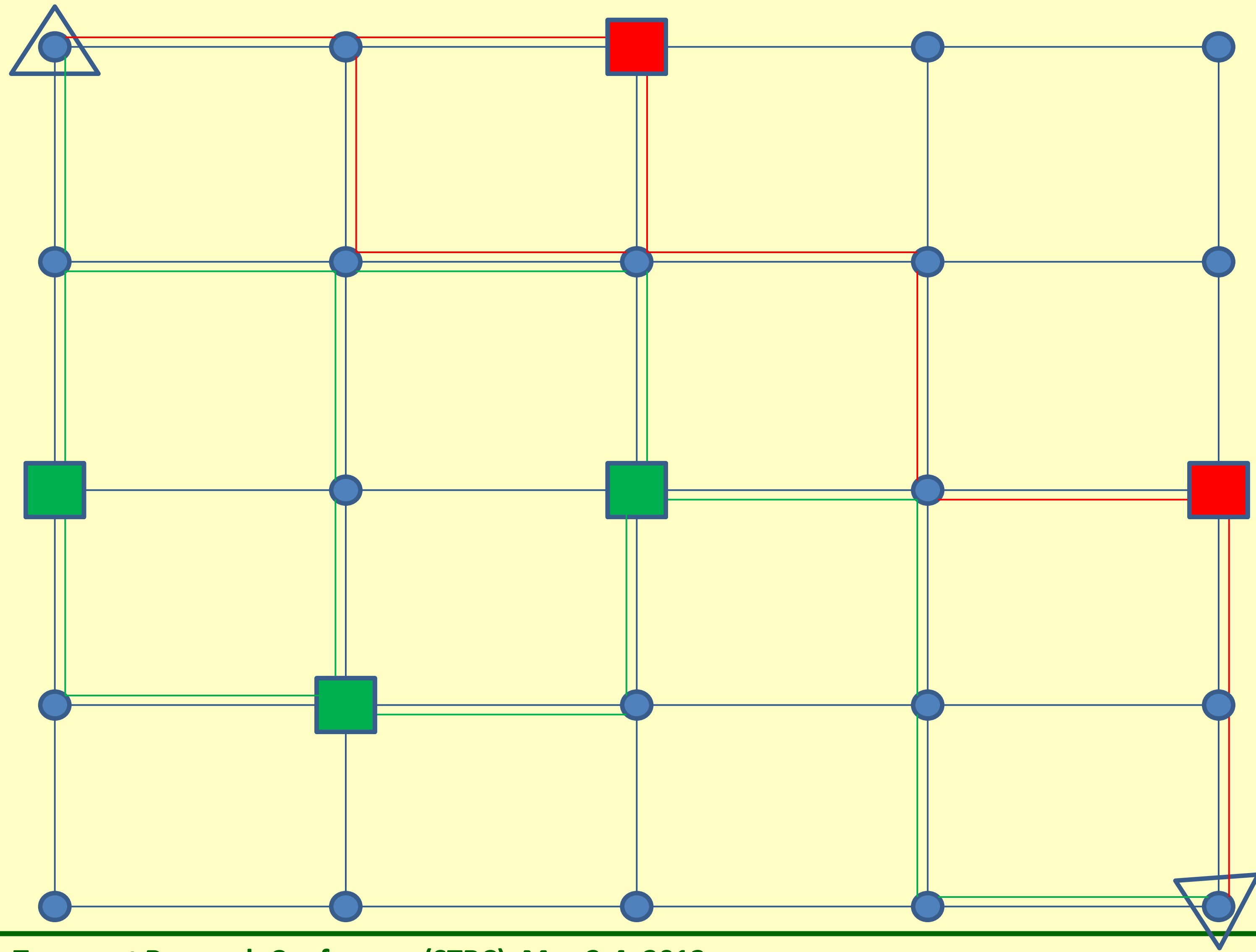
SOLUTION ALGORITHM (7/9)

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

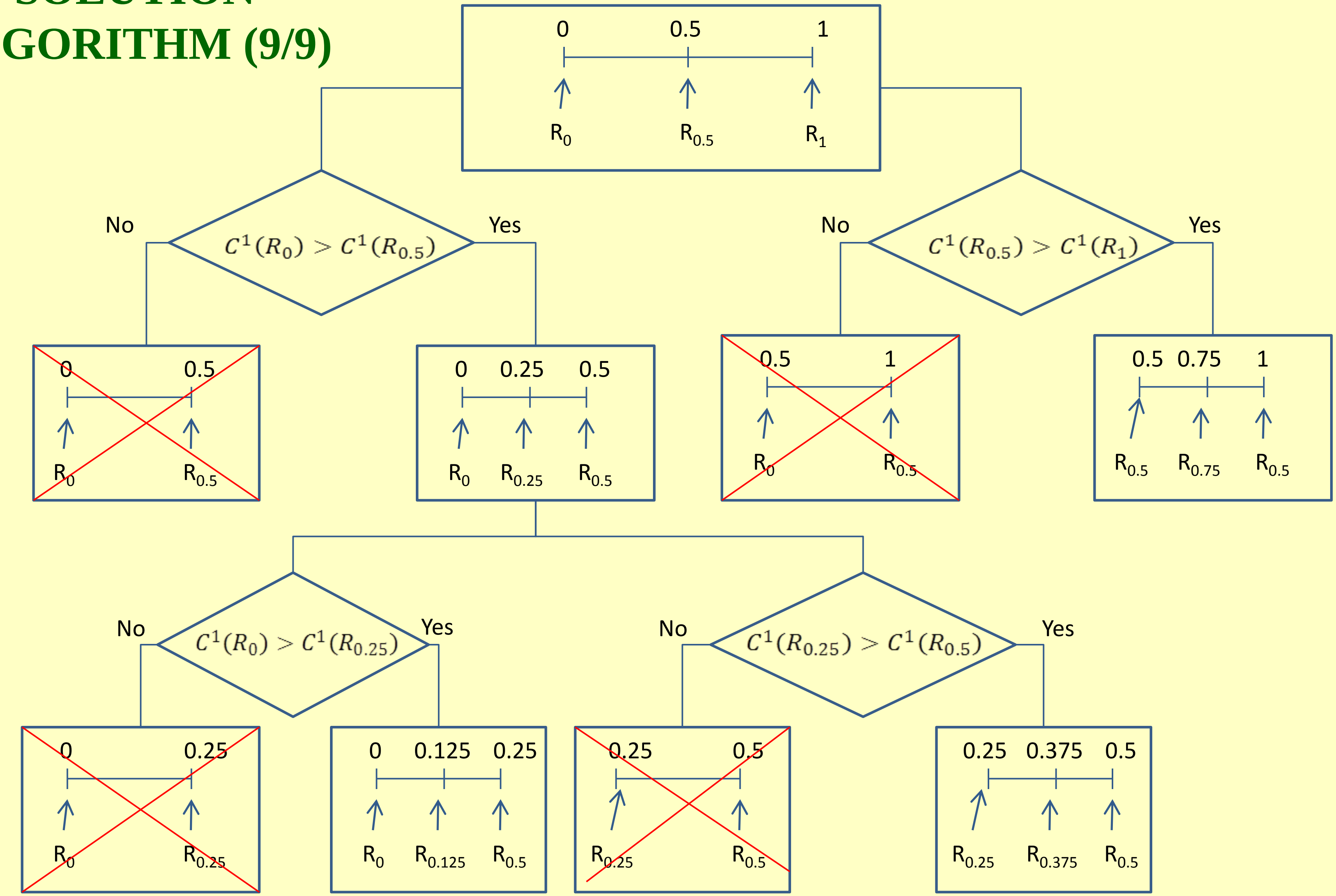
5. UPON THE CLOSURE OF A ROUTE, ONE SCHEDULED PATH HAS BEEN DETERMINED FOR EACH POSSIBLE DEPARTURE TIME FROM THE ORIGIN. AMONG THE LIST OF SCHEDULED PATHS FROM THE ORIGIN, **RETAIN** THE ONE WITH THE **MINIMUM COST VALUE** – EXCLUDE THE REST

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

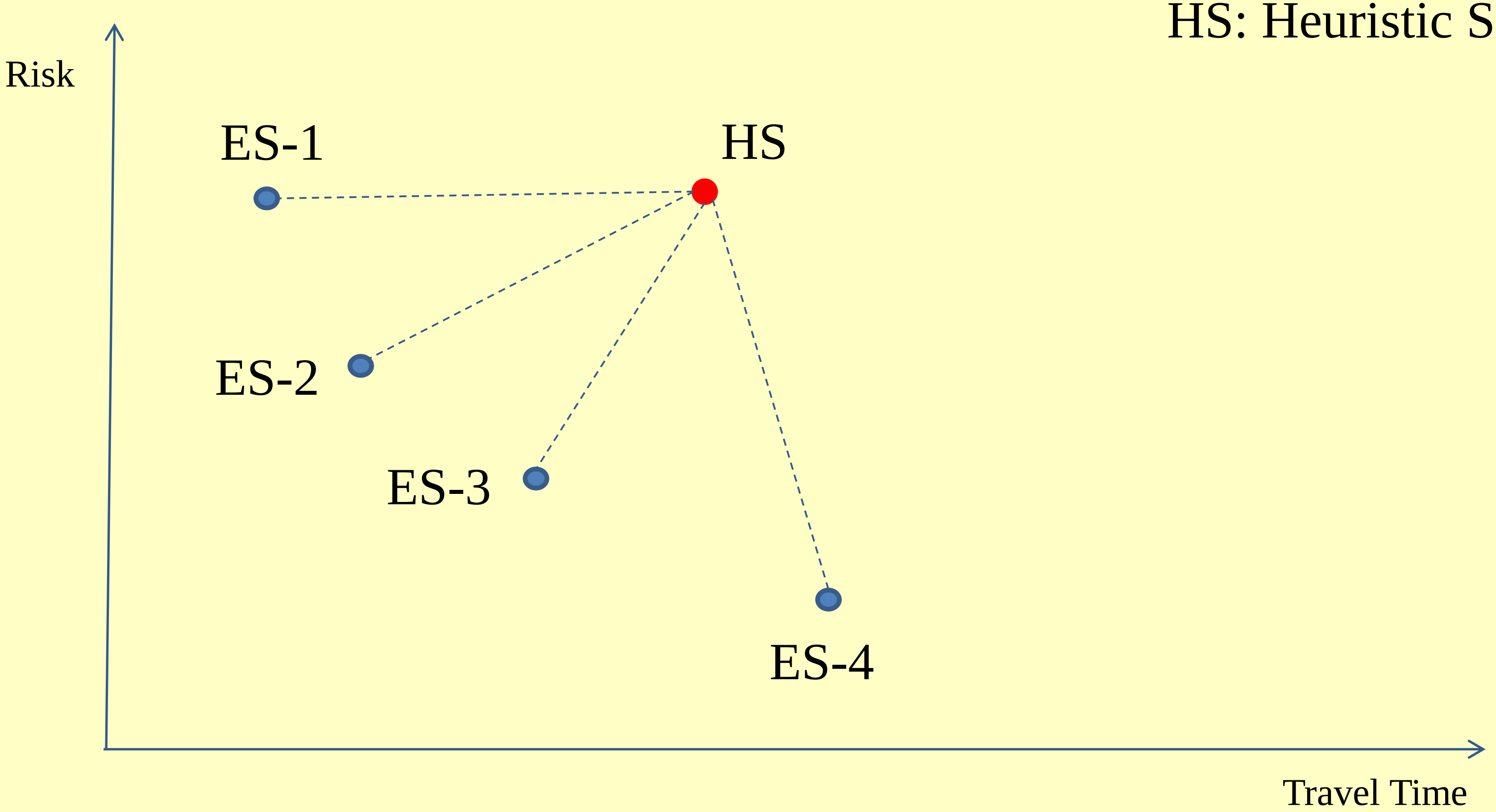
- SMALL TEST PROBLEMS
- COMPLY WITH STRUCTURE OF A REAL-LIFE PROBLEM
- SOLVABLE BY A MIXED INTEGER PROGRAMMING (MIP) SOLVER
- TIME-DEPENDENT LOAD-INVARIANT RISK VALUES
- 49 NODES
- GRID-LIKE NETWORK
- FIVE CUSTOMERS

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: Heuristic Solution



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

Test Problem	Number of customers	Depot Time window (min)	Average Number of Problems Solved	Average number of solutions	Average Computational Time (in sec)	Average Comp. Time per problem solved (sec)
1	10	120	17	7	104.5	5.9
2	10	180	18	7	233.8	12.8
3	20	120	20	5	281.4	13.9
4	20	180	20	8	512.75	25.2

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_2 EMISSIONS

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

- DEVELOP METHODOLOGIES FOR ESTIMATING TIME AND LOAD DEPENDENT RISK VALUES

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REFERENCES (1/2)

- Androutsopoulos, K.N. and K.G. Zografos (2012). A Bi-objective Time-Dependent Vehicle Routing and Scheduling Problem for Hazardous Materials Distribution, *EURO Journal on Transportation and Logistics*, available online.
- Chabini, I., (1998). Discrete Dynamic Shortest Path Problems in Transportation Applications, *Transportation Research Record: Journal of the Transportation Research Board*, 1645, pp. 170-175.
- Ehrgott, M. (2005). *Multicriteria Optimization*, Springer Berlin-Heidelberg.
- Erkut, E., S.A. Tjandra, and V. Verter (2007). Hazardous Materials Transportation, Chapter in: *Handbook in OR & MS*, Edited by C. Barnhart and G. Laporte, 14, pp. 539-621.
- Horn, M., (2000). Efficient Modelling of Travel Time in Networks with Time-Varying Link Speeds, *Networks*, 36(2), pp. 80-90.
- Ichoua, S., M. Gendreau and J. Potvin (2003). Vehicle Dispatching with Time-Dependent Travel Times, *European Journal of Operational Research*, 144, 379-396.
- Mainiero, R.J., J.H. Rowland III (2009). A Review of Recent Accidents Involving Explosives Transport, *Journal of Explosives Engineering*, 26(2), pp.6-12.
- Malandraki, C. and M. Daskin (1992). Time-Dependent Vehicle Routing Problems: Formulations, Properties and Heuristic Algorithms, *Transportation Science*, 26(3), pp. 185-200.

REFERENCES (2/2)

- Pallotino, S. and M.G. Scutella (1997). *Shortest Path Algorithms in Transportation Models: Classical and Innovative Aspects*. University of Pisa, Department of Informatics, Technical Report TR-97-06, April 14, 1997.
- U.S. Bureau of Transportation Statistics (2010). 2007 Economic Census, *Transportation, 2007 Commodity Flow Survey*.
- U.S. Code of Federal Regulations, *49CFR ("Transportation")*, 105.
- U.S. Department of Transportation (2011). *Top Consequence Hazardous Materials by Commodities and Failure Modes 2005-2009*, Pipeline and Hazardous Materials Safety Administration, Issue 3, 09/01/2011.
- Zografos, K.G. and K.N. Androutsopoulos (2008). A decision support system for integrated hazardous materials routing and emergency response decisions, *Transportation Research Part C: Emerging Technologies*, 16 (6) , pp. 684-703.
- Zografos, K.G. and C.F. Davis (1989). A Multiobjective Programming Approach for Routing Hazardous Materials, *ASCE Transportation Engineering Journal*, 115(6), pp. 661-673.