Development of a Traffic Incident Management System for Contending with Non-recurrent Highway Congestion

Woon Kim, Directed by Dr. Gang-Len Chang

March 11, 2014

Dept. of Civil and Environmental Engineering
University of Maryland, College Park

Overview

- Introduction
- Component 1: Incident response management strategies
- Component 2: Prediction models for clearance times
- Component 3: A detour decision support system
- Contributions, future research, and conclusions

Research Background

- Non-recurrent traffic congestion due to incidents has contributed **up to 60 percent of the total freeway corridor delay** in the United States (Lindley, 1987).
- **About 25 percent of congestion** in the U.S. is incident-related (FHWA, 2005).

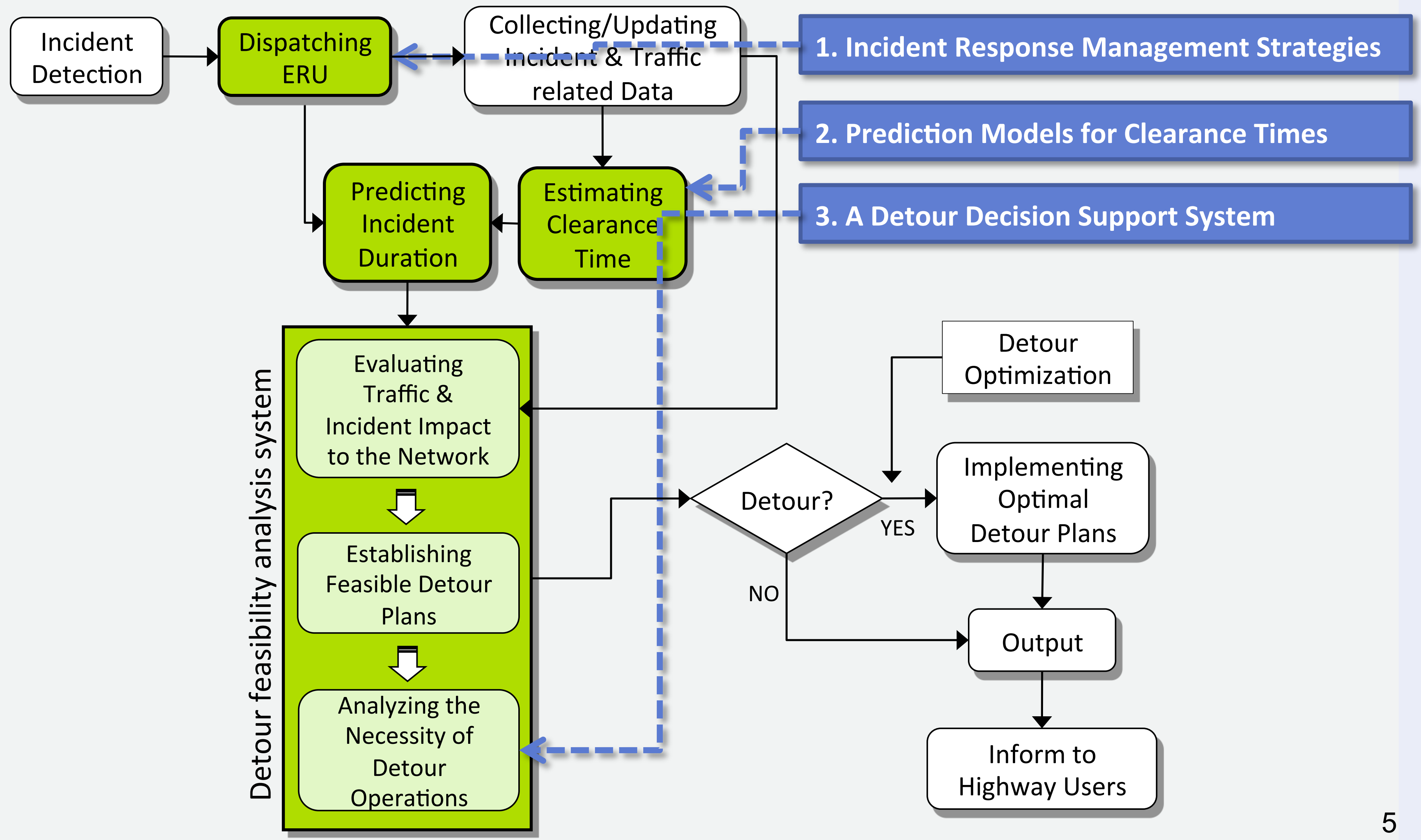
The starting time and duration of non-recurrent congestion, **due mainly to incidents**, are random in nature.

Thus, it is critical to have an efficient and effective incident management system.

Key Tasks in an Incident Management System

- An optimal deployment strategy for response units
- Estimation of required clearance times for reported incidents
- Detour feasibility analysis
- Detour optimization analysis
- Provide travel time information to roadway users
  - queue, delay and travel time analysis

Incident Management System



Needs for Each Component

1. Incident Response Management Strategies

- To maximize contributions of incident response units with limited resources by assigning them to optimal locations.

2. Prediction Models for Clearance Times

- To contend with stochastic nature of clearance times so as to maximize the system's operational reliability.

3. A Detour Decision Support System

- To facilitate responsible agencies to perform efficient traffic management in real time operations.

Research Objectives

1. Incident Response Management Strategies

- Develop a deployment strategy for incident response units to minimize the total incident-induced delay

2. Prediction Models for Clearance Times

- Develop a reliable model to estimate the clearance duration of a detected incident, and to identify critical contributing factors as well as their interrelationships

3. A Detour Decision Support System

- Develop a detour decision support model for control center staff to determine the necessity of detouring traffic

1. Incident Response Management Strategies

Literature Review

- Facility location problem
  - how many response units are needed?
  - where should they be allocated in response to the temporal and spatial distribution of incidents?
    1) Covering models (Toregas et al., 1971; Schilling et al., 1979; Hogan and ReVelle, 1986; Nair and Miller-Hooks, 2009)
    2) P-median models; and (Hakimi, 1964; Carson and Batta, 1990; Haghani et al., 2003; Yang et al., 2005)
    3) P-center models (Sylvester, 1857; Garfinkel et al., 1977; ReVelle and Hogan, 1989; Talwar, 2002)
- Minimize the number of service stations, the total operational costs, or to maximize the demand (incidents) covered by the pre-determined number of facilities

Data Sources

- Incident management program operated by Maryland state highway administration (MDSHA)
  - Coordinated Highways Action Response Team (CHART)
    - Has documented incident-related information over the past two decades
    - Date/time, location, nature, involved vehicles, lane closure…

Effectiveness of CHART

CHART responded approximately **81 % (22,796/28,345)** of incidents during last two years

Does the CHART **involvement** matter?

	w/o CHART	w/ CHART
Mean on CT (mins)	37.91 →	27.51

CHART reduced the avg. clearance time by 27 %

Does the **prompt** CHART response matter?

First responder	Others	CHART
Mean on CT (mins)	39.49 →	21.85

CHART reduced the avg. clearance time by 45 %

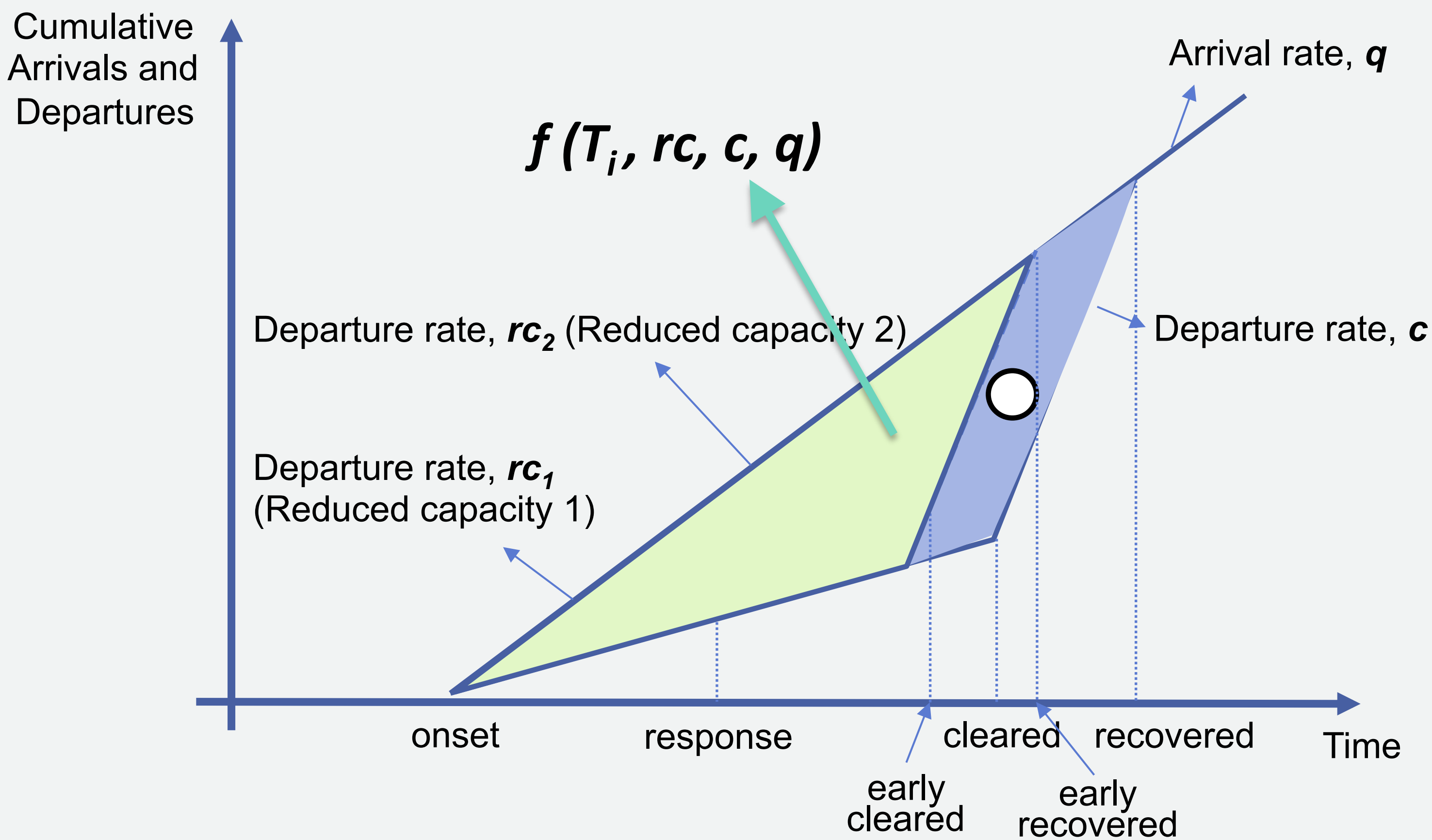
Needs for Research

- The efficient response of CHART can contribute to the reduction **in not only the response time but also the clearance time** → **reduction in delay**
- However, not all incidents can be promptly responded by CHART due to their limited resources
- Therefore, it is critical to develop a strategy to **optimally deploy available response units** so as to maximize their contributions

Model Construction

- **Inputs**
  - Incident distribution, incident duration, lane blockage information, traffic volume, capacity, and available resources
- **Objective function**
  - Minimize the total delay induced by incidents
- **Constraints**
  - Every freeway segment must be served by one unit
  - Response units can only be dispatched from location *i* if they are stationed there
  - The total number of response units is limited by available resources
- **Outputs**
  - Assigned station and coverage for each unit

Relations between Incident Duration and Total Delay



A Reduced delay due to additional lanes open

✓ B Reduced delay due to reduced clearance duration

Model Formulation

Objective Function:* *Min total delay for responded incidents

$$\min_{x,y} \sum_{i} \sum_{j} x_{ij} \cdot f_j \cdot d_j(t_{ij})$$

Total Delay

1. Delay from incidents occurring at node j (Olmstead, 1996)

$$d_j(t_{ij}) = \frac{1}{2} T_{ij}^2 \, (q_j - rc_j)(c_j - rc_j)/(c_j - q_j)$$

T_{ij}: Response Time + Clearance time

Stochastic nature

2. Response time and clearance time (Olmstead, 1996)

$$T_{ij}^2 = \begin{cases} (RT_1 + CT_1)^2 + Var(CT_1) \\ (t_{ij} + CT_{2-1})^2 + Var(CT_{2-1}) \\ (RT_2 + CT_{2-2})^2 + Var(CT_{2-2}) \end{cases}$$

CHART is not involved

CHART is involved and first responder

CHART is involved but not the first responder

- $x_{ij} = 1$ if incidents at j are responded by a response unit at i
- $y_i = 1$ if a response unit is stationed at i
- $G(N,A)$: *a network of freeways, where N and A are the sets of nodes and links*
- i, j: *index for nodes* $i, j \in N$
- f_j: *probability that an incident occurs at node j*
- t_{ij}: *travel time from i to j*
- d_j: *delay from incidents occurring at node j according to* t_{ij}
- T_{ij}: *response time + estimated clearance time according to* t_{ij}
- q_j: *traffic volume at j*
- c_j: *capacity at j*
- rc_j: *reduced capacity at j*

Model Formulation (cont'd)

Constraints:

1. Every freeway segment must be served

$$\sum_i x_{ij} = 1 \quad \forall\ i \in N$$

2. Response units can only be dispatched from location *i* if they are stationed there *(y_i = 1)*

$$x_{ij} \le y_i \quad \forall\ j \in N$$

3. The total number of available response units is limited by available resources *(R)*

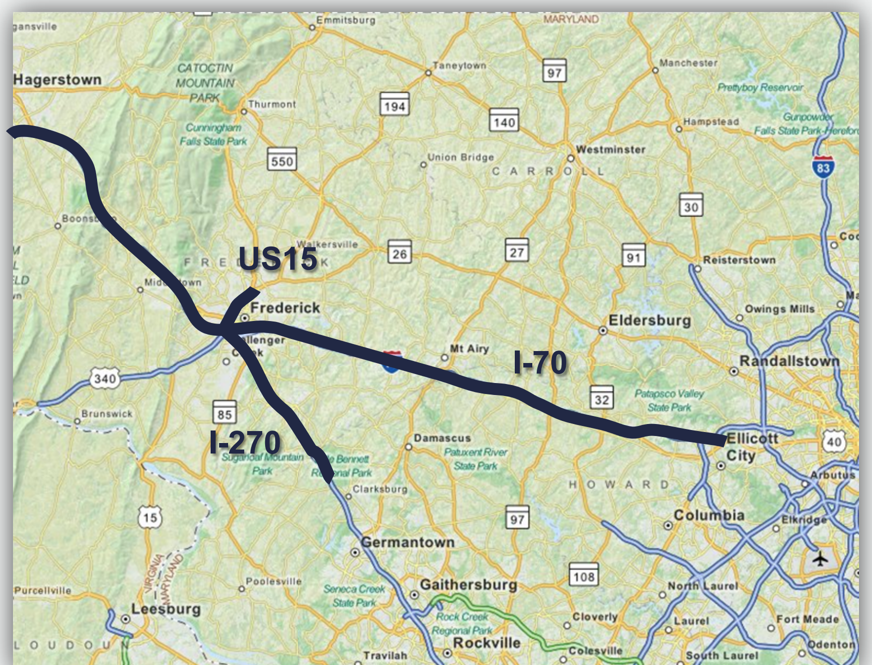
$$\sum_i y_i \le R$$

$$x_{ij} = [0,1]\ \forall\ (i,j) \in N \qquad y_i = [0,1] \quad \forall\ i \in N$$

- $x_{ij} = 1$ if incidents at j are responded by a response unit at i
- $y_i = 1$ if a response unit is stationed at i
- $G(N,A)$: *a network of freeways, where N and A are the sets of nodes and links*
- i, j: *index for nodes i, j* $\in N$
- *R : available resources*

Empirical Study

- Segments of I-70, I-270 and US 15 in MD



Site Characteristics

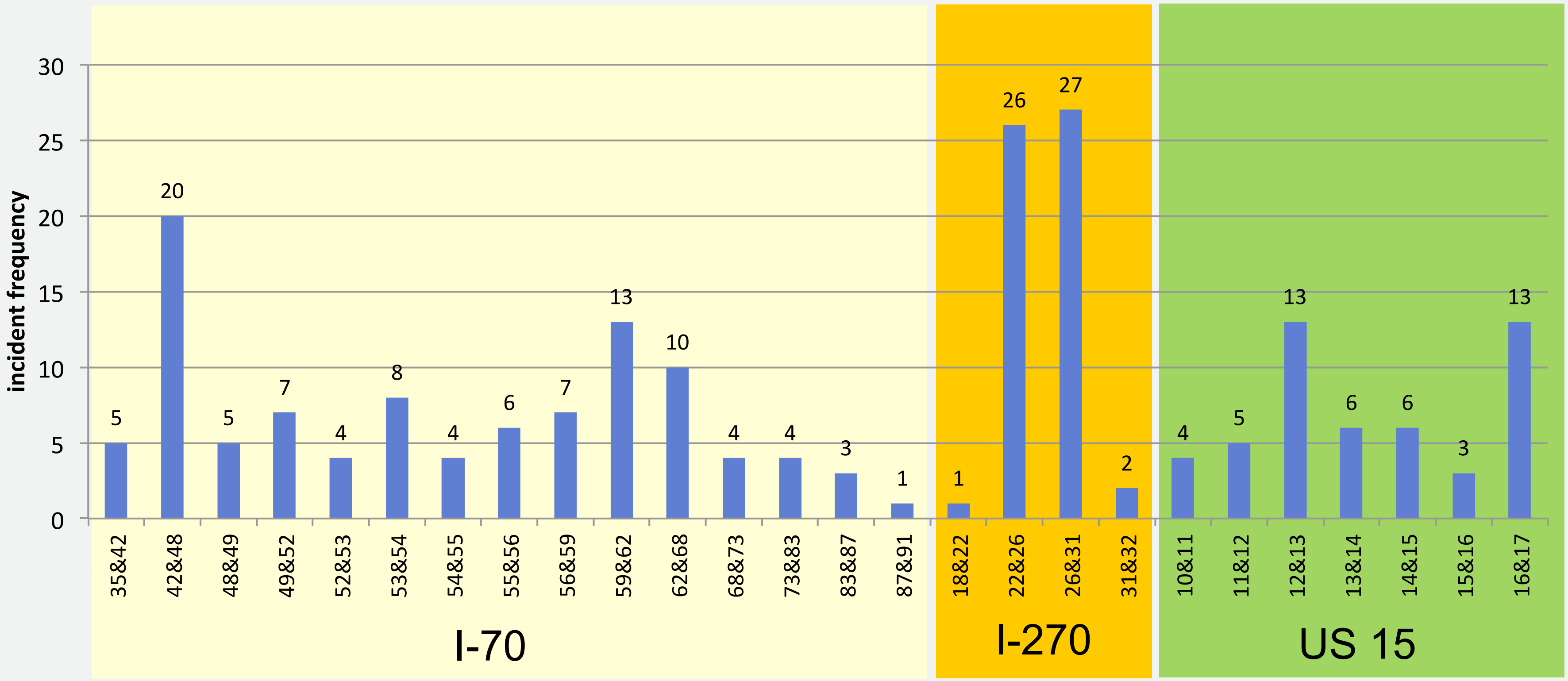
- 63 miles
- Radial shape of roads
- Frederick, Howard, and Carroll Counties

Highway Incident Management

- TOC-7
- 3 units
- Operation Hours:
  5AM – 9PM on weekday
  - **Study Period: AM peak**
    (7AM – 9:30 AM on weekday)

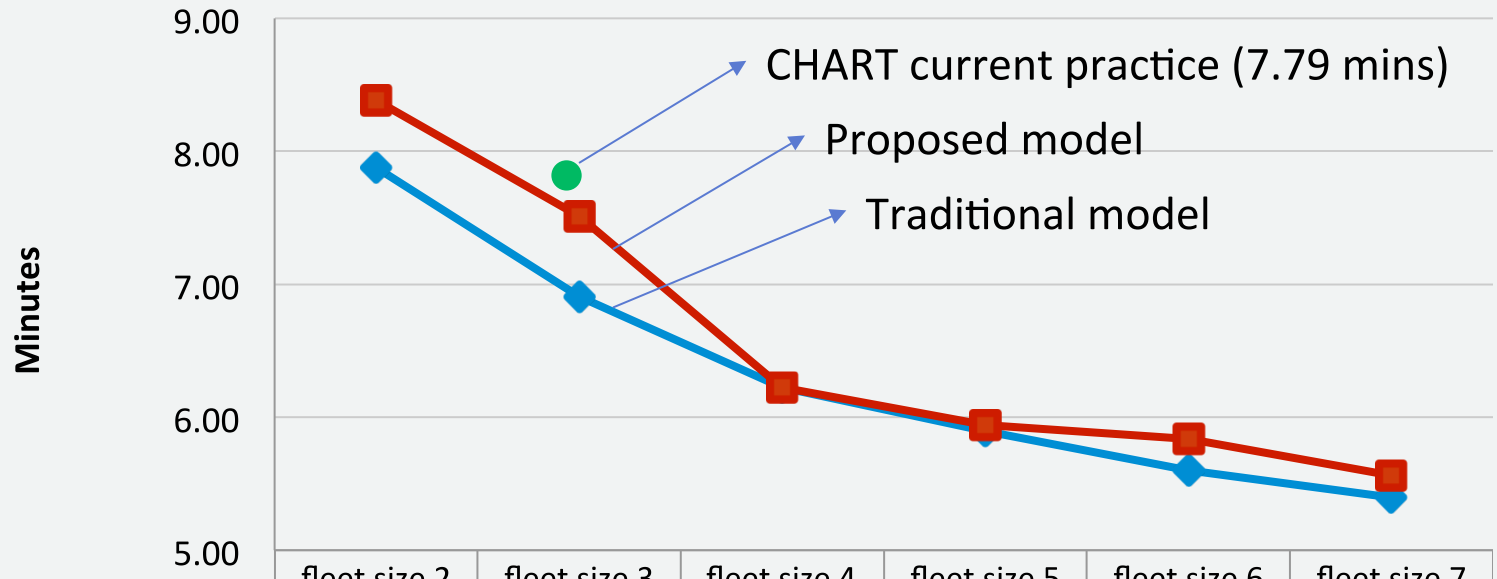
Incident Frequency Distribution

Incident frequencies fluctuate over the network !



Model output Analysis

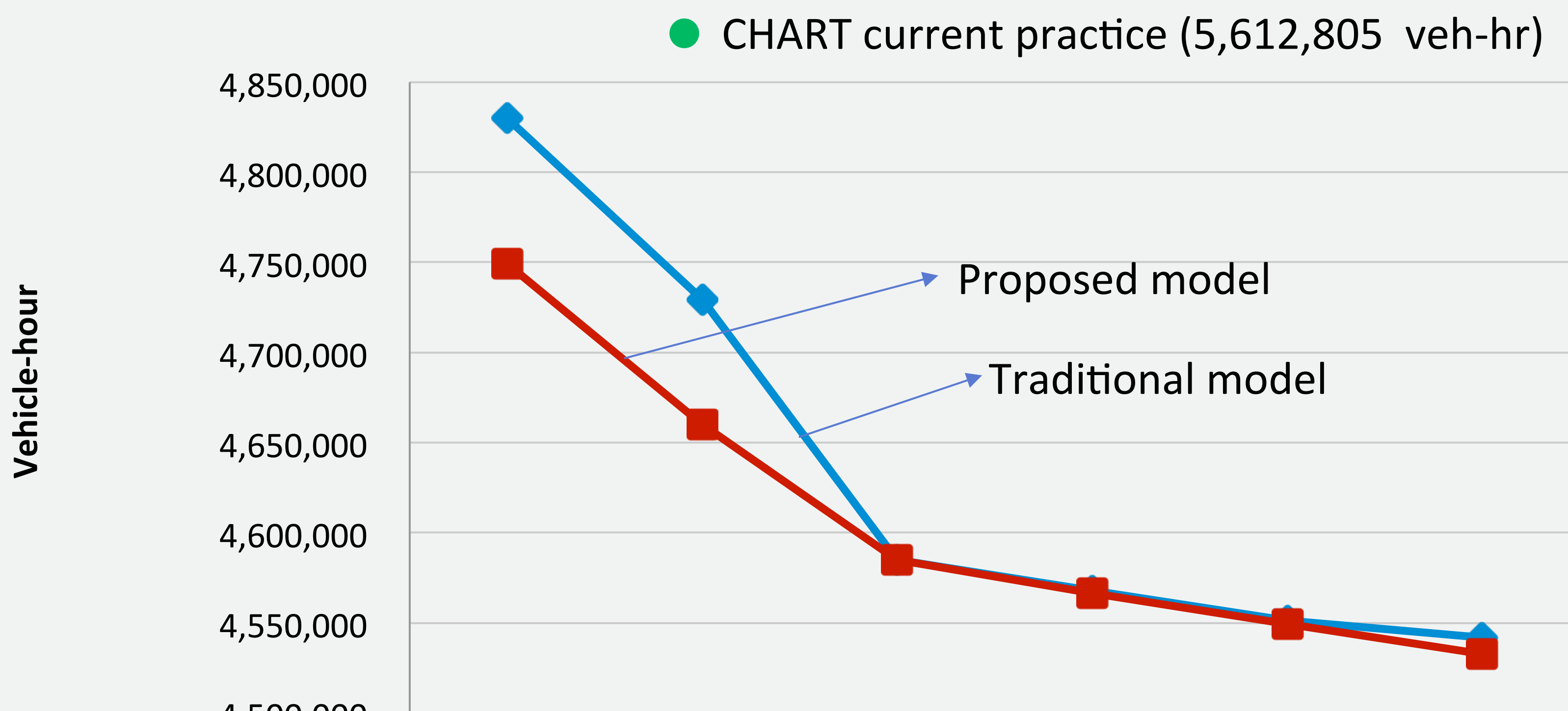
1. Assigned station and service coverage for each unit
2. Average travel time (minutes)



	fleet size 2	fleet size 3	fleet size 4	fleet size 5	fleet size 6	fleet size 7
min.avg. response time	7.88	6.90	6.22	5.89	5.60	5.40
min. total delay	8.38	7.51	6.22	5.94	5.83	5.56

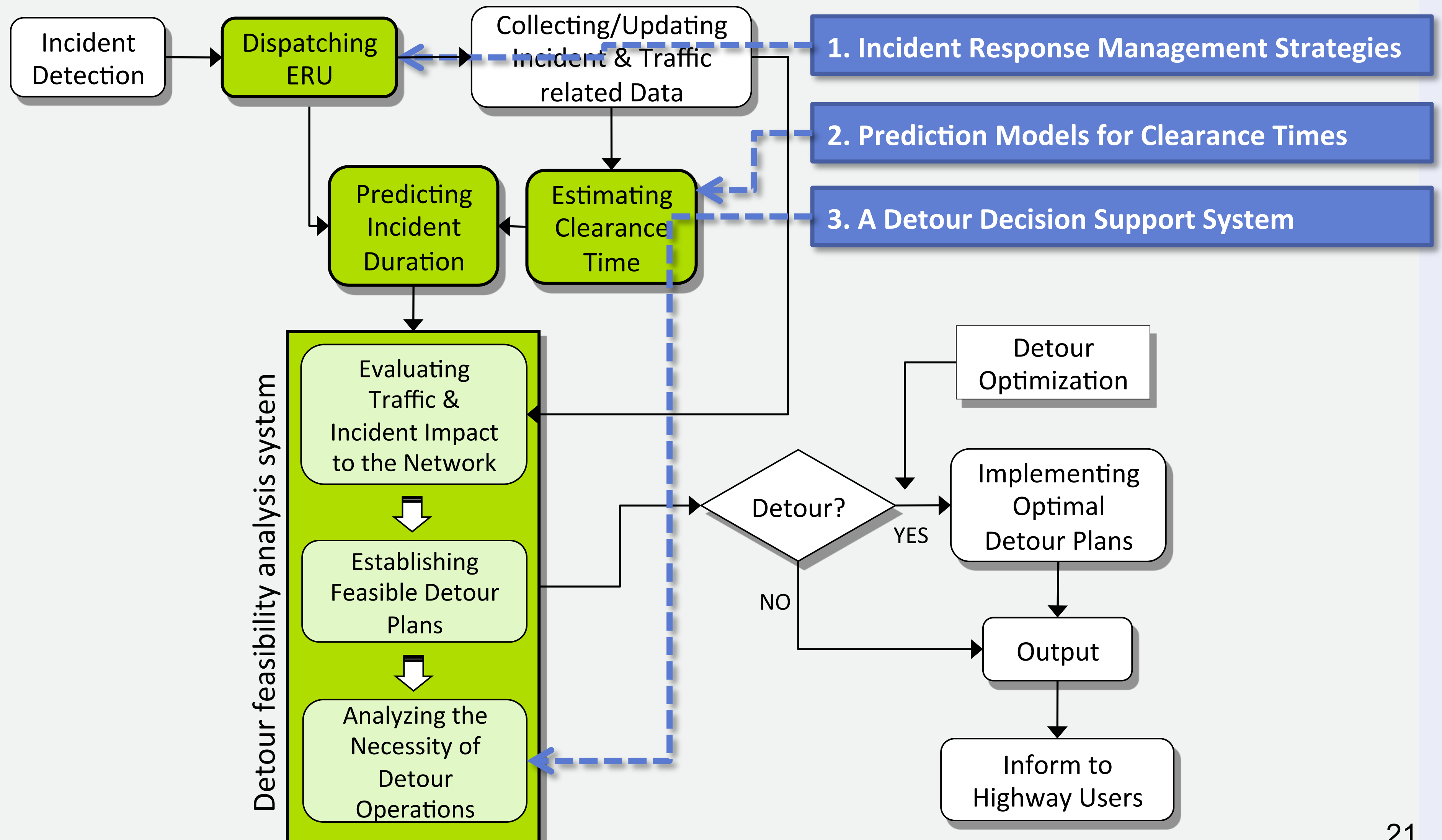
Model output analysis (cont'd)

3. Total delay (veh-hr)



	fleet size 2	fleet size 3	fleet size 4	fleet size 5	fleet size 6	fleet size 7
min.avg. response time	4,829,998	4,729,356	4,584,707	4,567,920	4,551,095	4,541,785
min. total delay	4,749,141	4,659,967	4,584,707	4,566,630	4,549,114	4,532,457

Incident Management System



2. Prediction Models for Clearance Times

A Model for Estimating Clearance Times

Why do we need such a model?

- Key input for the incident management system
  - Optimal deployment strategy analysis
  - Detour feasibility analysis
  - Detour optimization analysis
  - Traveler information – queue, delay and travel time analysis

- **However, the required clearance time for a reported incident is very difficult to reliably predict in advance.**

Challenge to Predict Clearance Times

- Skewed shape and distributed in a wide range

CT (mins)	Frequency	Ratio
<=30	3870	65%
30-60	1176	20%
60-90	397	7%
90-120	138	2%
>120	344	6%
total	5925	100%

- Difficult to fit with a continuous or discrete distribution
- Most statistical models cannot perform well
  - They tend to focus on the major classes of the data

However, most studies in the literature applied statistical approaches to develop a model

Literature Review

1) Probabili… …liano, 1989; Ga… …d Kachroo, 1999)
2) Condition… …ring, 2000; Boyles et al., 2007)
3) Regression Models (Khattak et al., 1995; Giuliano, 1989; Garib et al., 1997; Ozbay and Kachroo, 1999)
4) …
5) …
6) …
7) Unconventional Models (Wang et al., 2005; Wu et al., 2011)

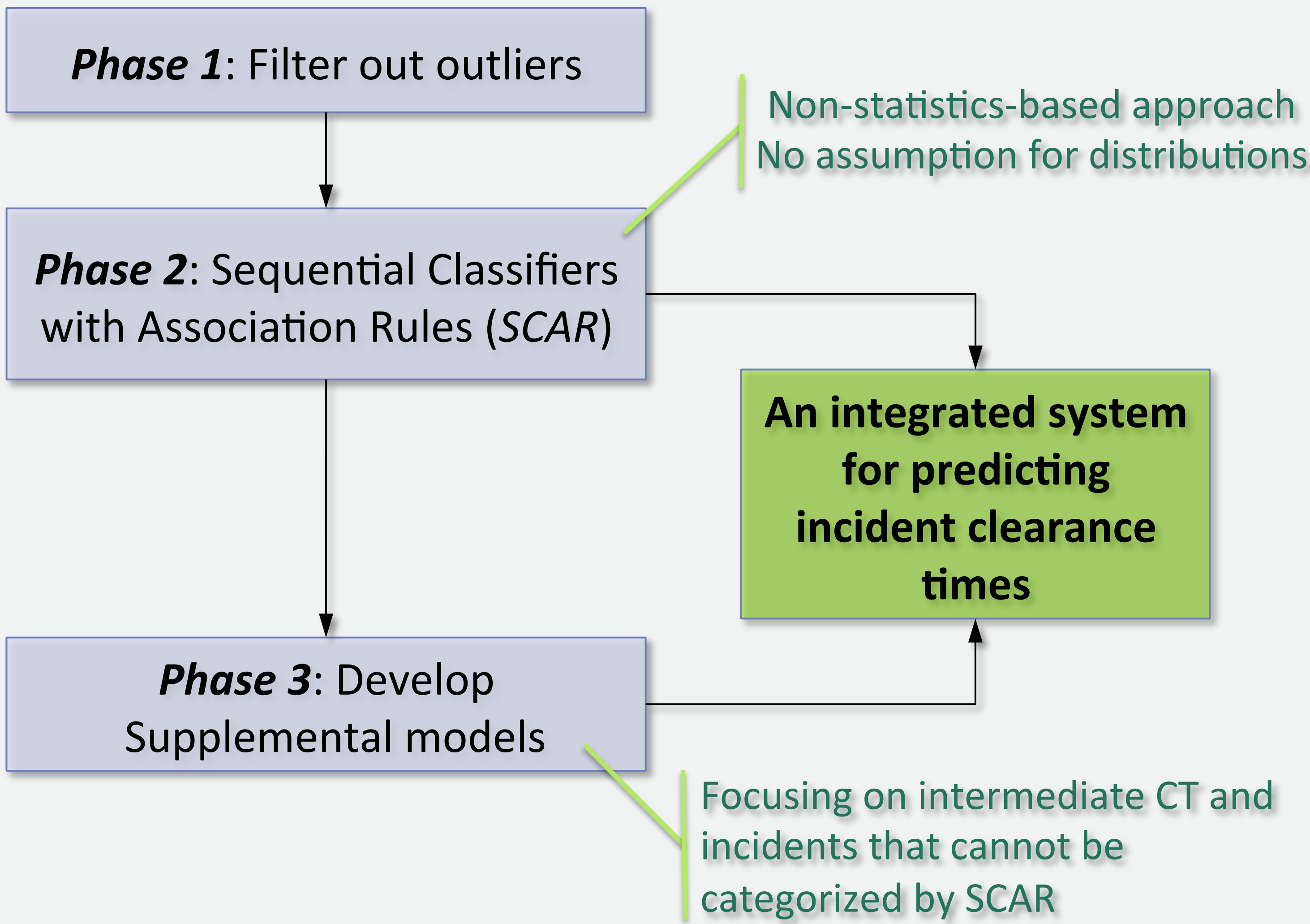
In the most literature

- Using **limited scale data**
- **No validation** for models

The proposed Model is

✓ tackling heterogeneity in most incident data sets
✓ enhancing prediction **accuracies**; and
✓ assessing the prediction model's **robustness** for different data sets

Flowchart to Develop the Proposed Model

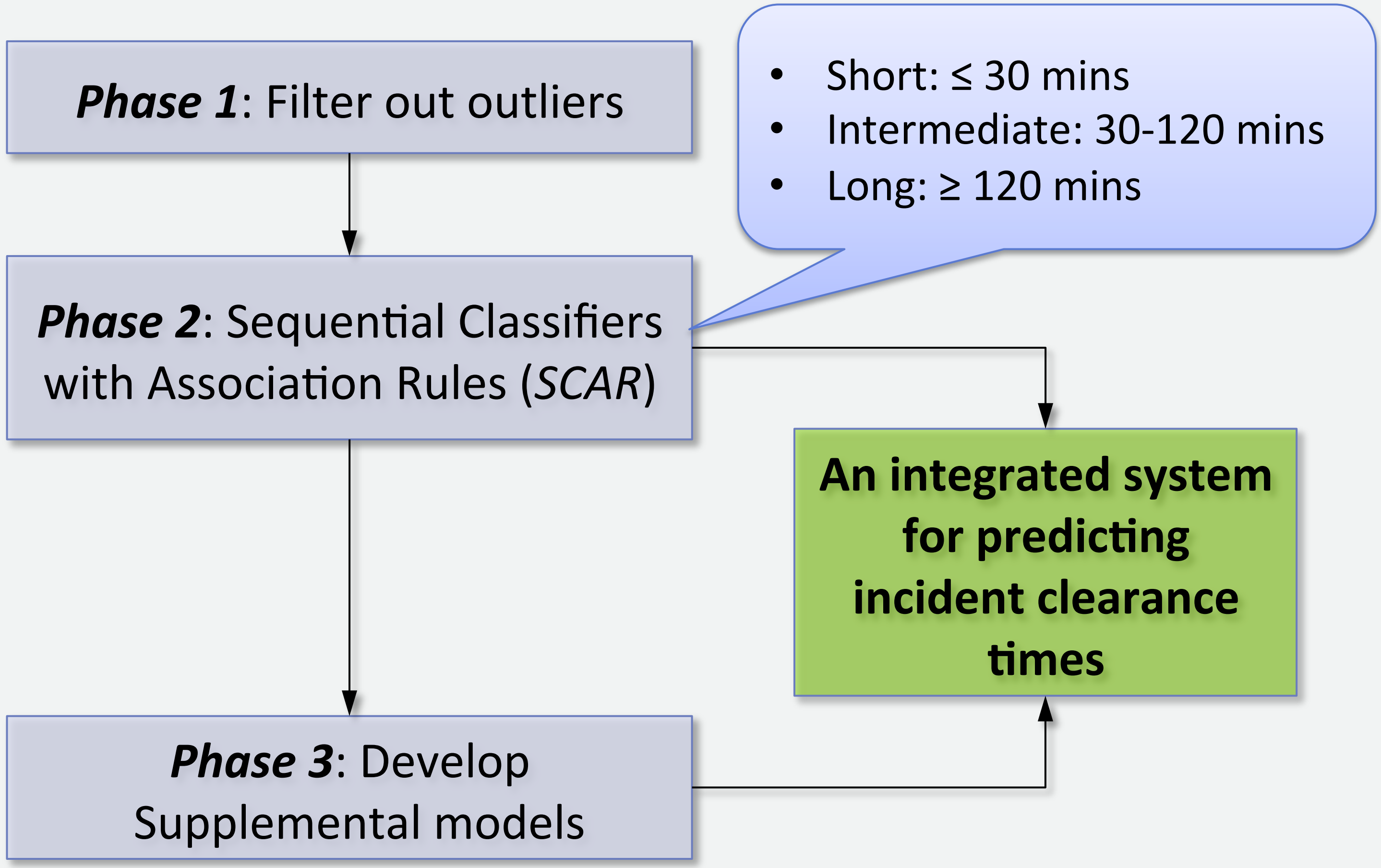


Phase 1 – Filter Out Outliers

- PAM: Partitioning Around Medoids (Kaufman and Rousseeuw, 1990)
  - Medoids: most centrally located elements
  - Goal: detecting a group of clusters including a small number of elements

36/6000 incidents are selected as outliers

Flowchart to Develop the Proposed Model



Association Rules (Agrawal et al., 1993)

- Mining explicit relations between clearance time and associated factors in a format of rules.
  - For example,

{personal injury, rainy} → {intermediate CT}
antecedent *consequent*
LHS RHS
X Y
6 3

  - ***Support*** of an itemset *X* (*supp(X)*): the proportion of data entries in the database which include the itemset *X*
  - ***Confidence*** of a rule: *conf(X→ Y) = supp(X ∪ Y)/supp(X)*

supp(X)=6 supp(X ∪ Y) =3 conf(X→ Y) = 3/6 = 0.5

Procedure to Construct the SCAR System

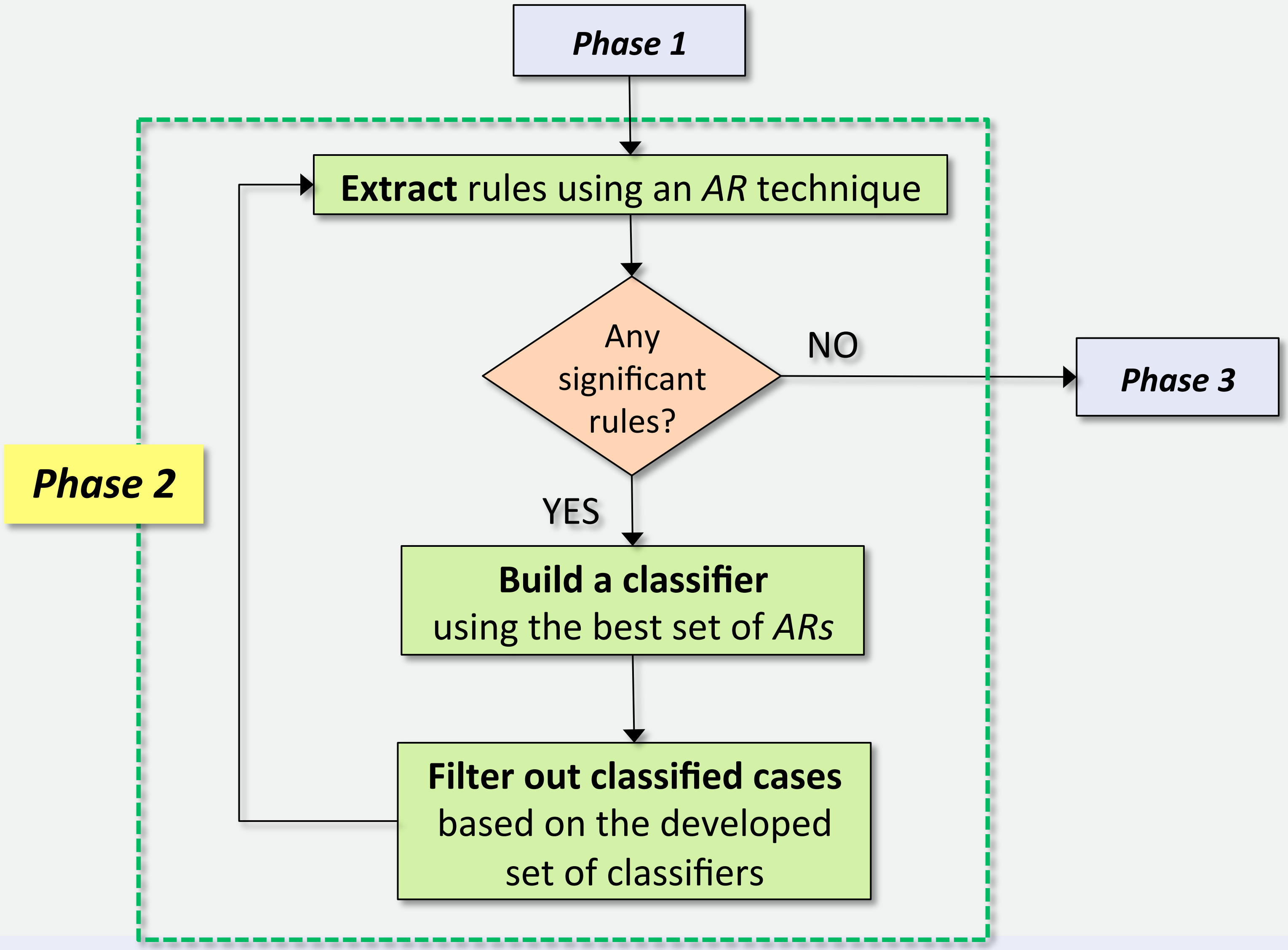


Illustration of the SCAR System

An Incident Is Detected

(TOC3 **&** Minor lane closure **&** no info. for pavement condition) → *AR 1*

or

(AOC **&** 12 lanes on both **&** on US-50) → *AR 2*

or

(on weekday **&** disabled veh **&** CHART detected) → *AR 3*

AR 1, *AR 2*, *AR 3*: ***Classifier 1***

Yes → Short (≤ 30 mins)

No →

(2 veh involved **&** fatality) **or** → *AR 1*

(during daytime **&** minor road **&** fatality) → *AR 2*

AR 1, *AR 2*: ***Classifier 2***

Yes → Short (≤ 30 mins)

No → Continued…

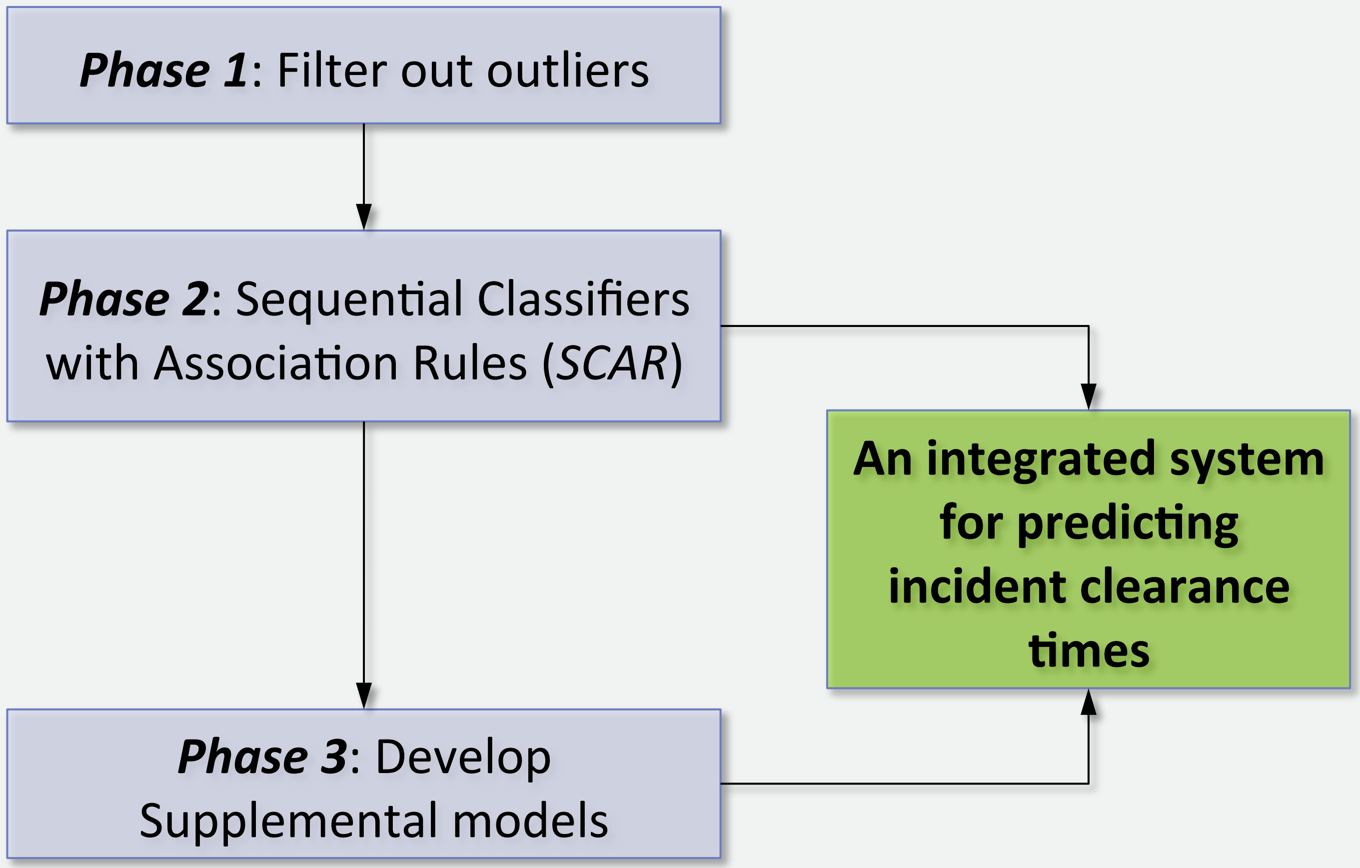
Phase 2 - Model Results

- 44 Classifiers
- Each consists of 2 or 3 ARs
- **About 72% of samples can be explained with SCAR**
- Accuracies for each category of clearance duration

Clearance Time	**Class ratio**	**# of Classifiers**	**Accuracy**	
			Train	Test
Short	64.98%	27	87.70%	90.37%
Intermediate	28.95%	13	90.50%	92.51%
Long	6.07%	4	75.86%	79.66%

30 -120 mins

Flowchart to Develop the Proposed Model



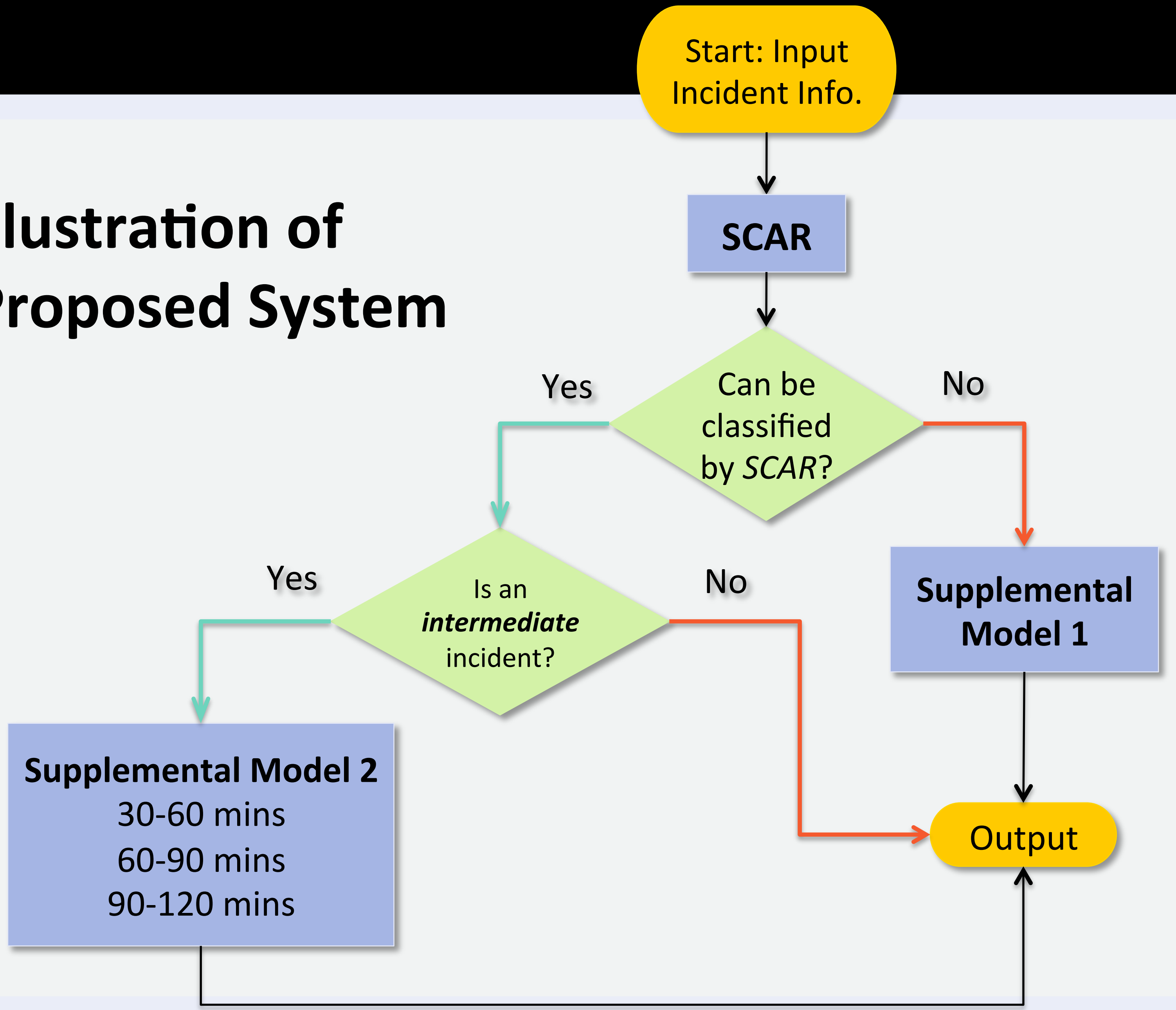
- To predict CT for incidents that ***cannot be classified by SCAR***
- To classify predicted ***intermediate CT*** into shorter intervals

Phase 3 – Developing Supplemental Models

1. A model for data **not classified by SCAR**
   - <= 30 minutes
   - 30 – 60 minutes
   - 60 – 90 minutes
   - 90 – 120 minutes
   - > 120 minutes
2. A model to classify the predicted **intermediate clearance times** into **smaller intervals**
   - Intermediate-sub1: 30 – 60 minutes
   - Intermediate-sub2: 60 – 90 minutes
   - Intermediate-sub3: 90 – 120 minutes

➡ **Support Vector Machine and Random Forests are applied**

Illustration of the Proposed System



MOEs to Evaluate the System's Performance

Contingency Table (c_{ij})

Clearance Duration (minutes)		Observation ≤ 30	30 – 60	60 – 90	90 – 120	> 120
Prediction	≤ 30	1068	95	20	3	11
	30 – 60	130	146	50	16	23
	60 – 90	81	96	33	9	5
	90 – 120	13	37	23	9	5
	> 120	8	12	9	8	60

Accuracy

Weights (w_{ij})

Clearance Duration (minutes)		Observation ≤ 30	30 - 60	60 - 90	90 – 120	> 120
Estimation/ Prediction	≤ 30	1	0	0	0	0
	30 – 60	0.75	1	0	0	0
	60 – 90	0.5	0.75	1	0	0
	90 – 120	0.25	0.5	0.75	1	0
	> 120	0	0.25	0.5	0.75	1

MOEs to Evaluate the System's Performance

Contingency Table (c_{ij})

Clearance Duration (minutes)		Observation				
		≤ 30	30 – 60	60 – 90	90 – 120	> 120
Prediction	≤ 30	1068	95	20	3	11
	30 – 60	130	146	50	16	23
	60 – 90	81	96	33	9	5
	90 – 120	13	37	23	9	5
	> 120	8	12	9	8	60

Acceptability

$$= \sum_{i} \sum_{j} w_{ij} * c_{ij} \; / \sum_{i} \ldots$$

Weights (w_{ij})

Clearance Duration (minutes)		Observation				
		≤ 30	30 - 60	60 - 90	90 – 120	> 120
Estimation/ Prediction	≤ 30	1	0	0	0	0
	30 – 60	0.75	1	0	0	0
	60 – 90	0.5	0.75	1	0	0
	90 – 120	0.25	0.5	0.75	1	0
	> 120	0	0.25	0.5	0.75	1

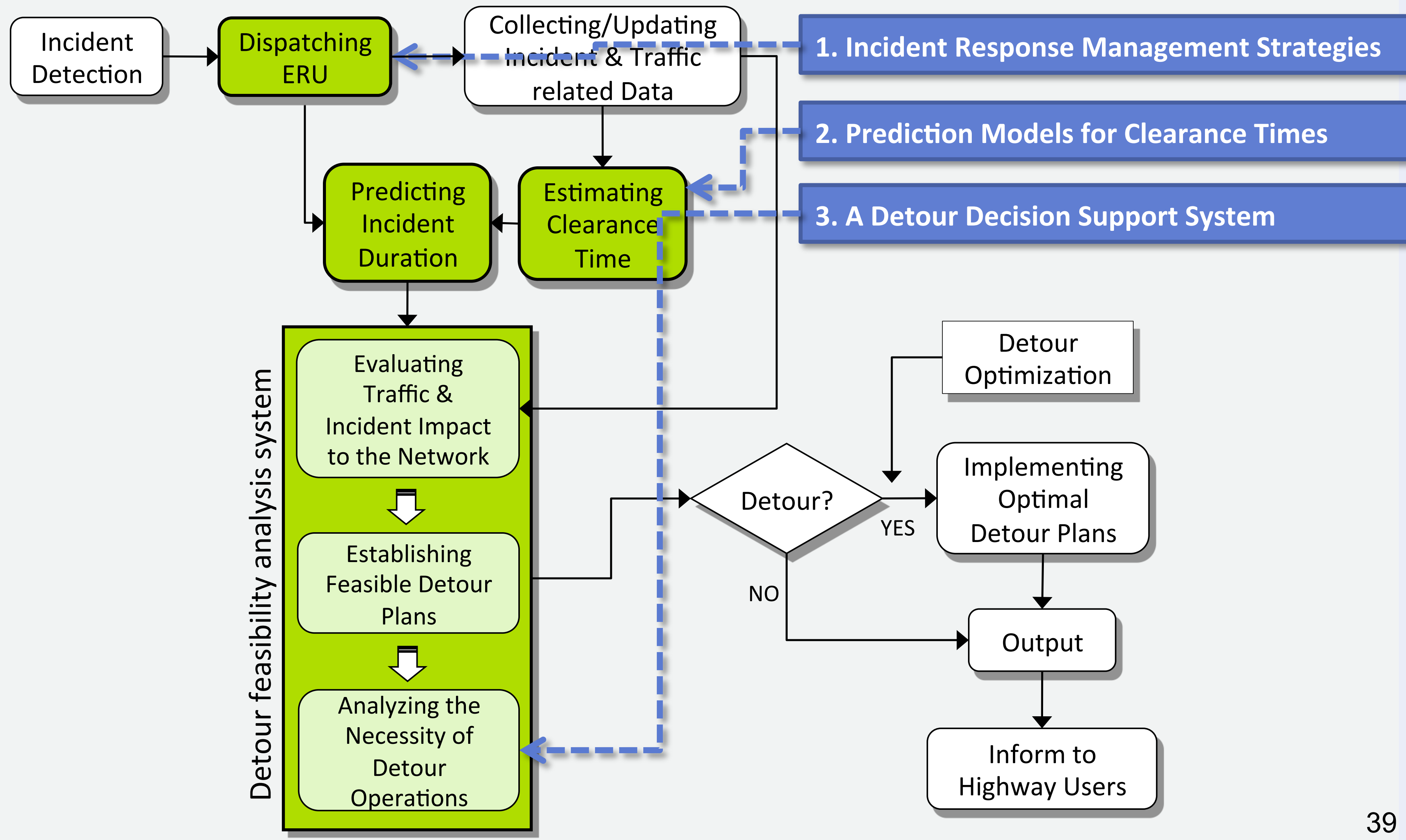
w_{ij}: weights for cells (*i, j*)
c_{ij}: number of cases in a cell (*i, j*)

Overall System Performance

Incident Categories	Clearance Duration (minutes)	Class ratio	Accuracy		Acceptability	
			Train	Test	Train	Test
Minor	<= 30	65.0%	80.3%	82.2%	92.0%	93.0%
Intermediate-sub1	30 – 60	20.0%	38.1%	37.8%	58.0%	62.2%
Intermediate-sub2	60 – 90	6.6%	35.9%	24.4%	45.0%	40.7%
Intermediate-sub3	90 – 120	2.4%	46.2%	20.0%	54.8%	33.3%
Major	120 +	6.0%	57.5%	57.7%	57.5%	57.7%
Total		100.0%	**66.7%**	**66.8%**	**79.1%**	**80.2%**

- **Better** than five comparable models developed using support vector regression, random forests, and multiple linear regression, **in terms of accuracy and acceptability**

Incident Management System



3. A Detour Decision Support System

Study Background

Most states consider only

- Incident duration > 30 minutes
- Complete road closure

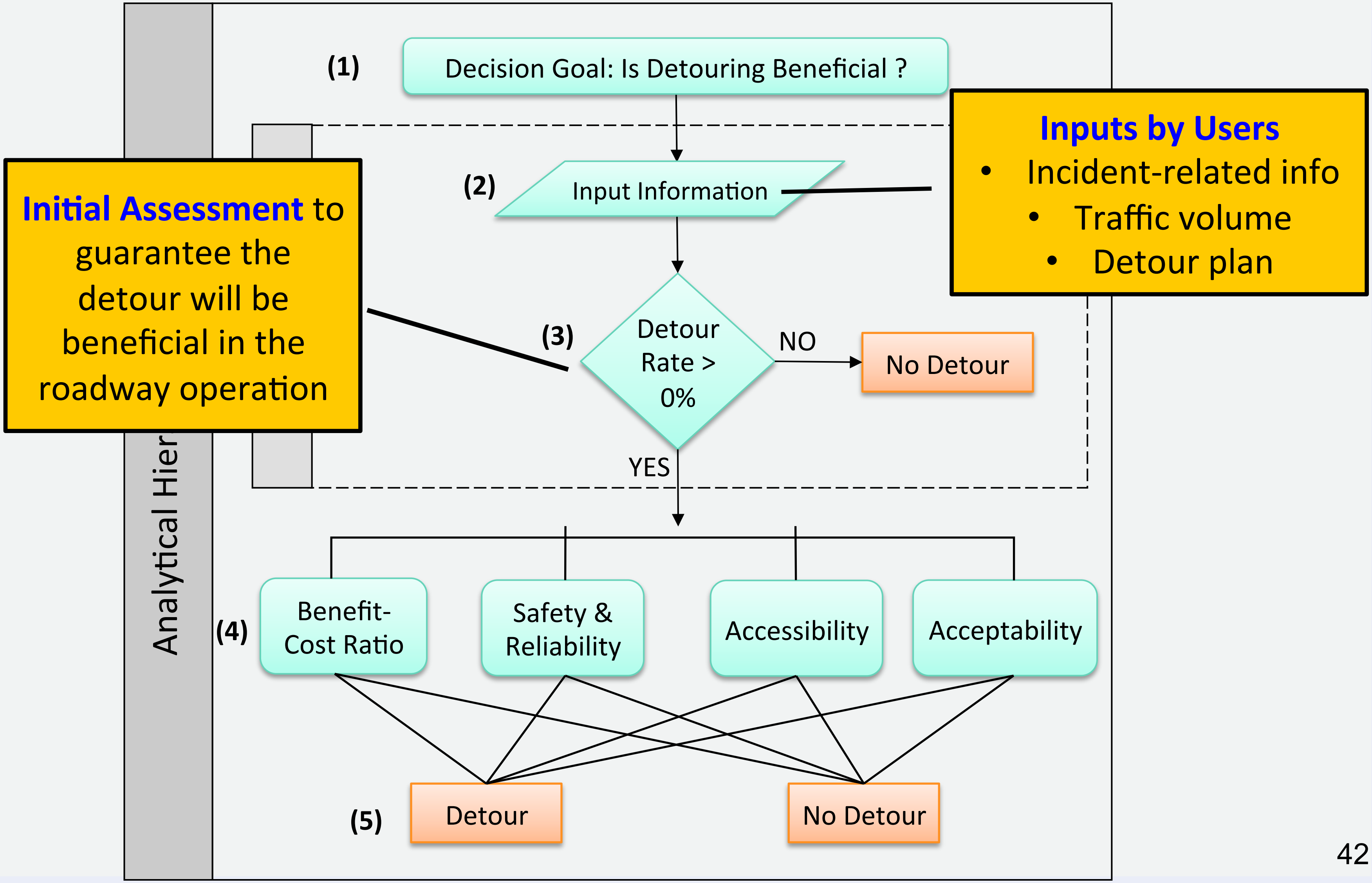
The proposed model :

✓ **Account for more critical factors**

- Traffic volumes, benefit, cost, safety, travel times, etc.

✓ **Allow the decision maker to place different weights to different factors,** based on the either resource constraints or priority.

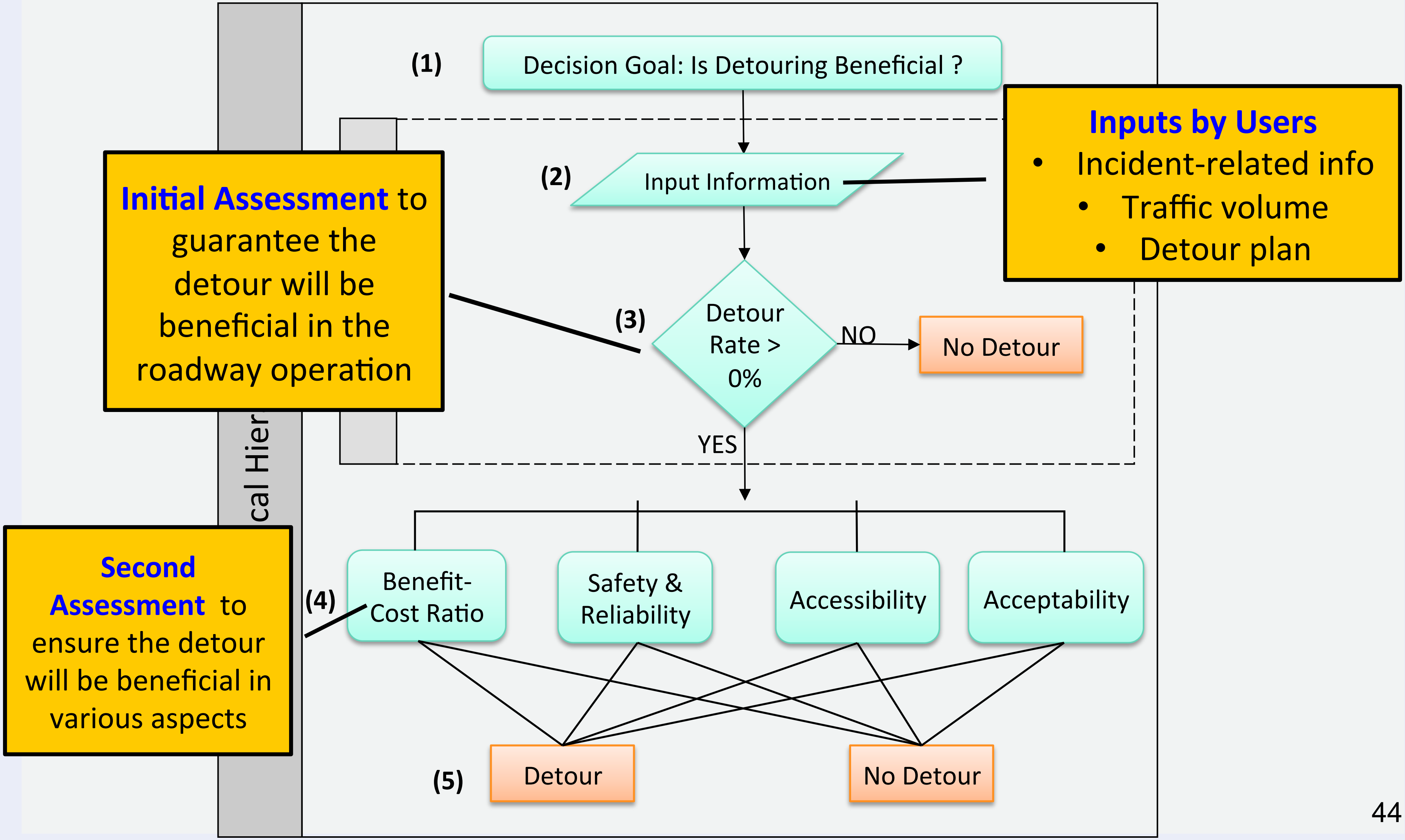
The Proposed System Architecture



Simulation-based Analysis

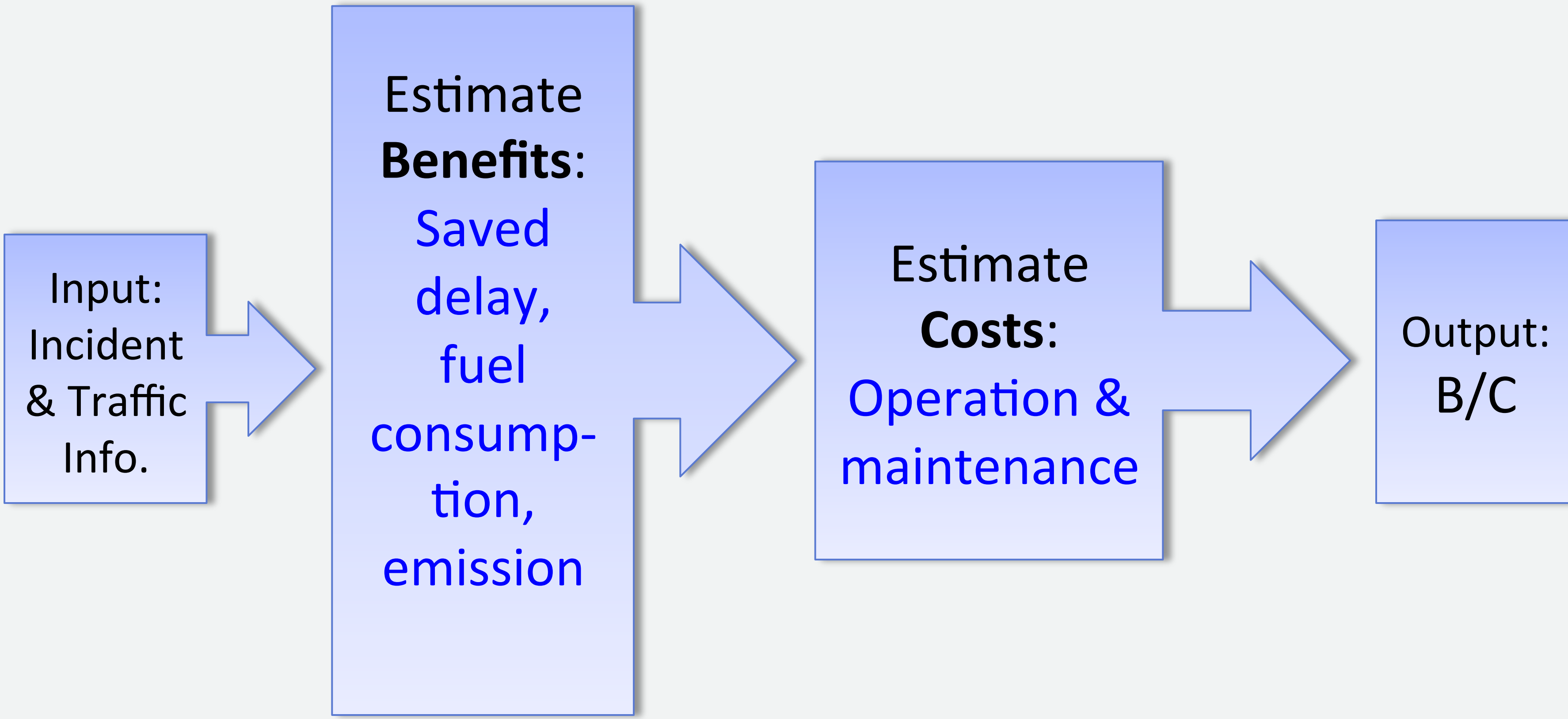
- **To estimate the optimal diversion rate** from the freeway mainline to mitigate the congestion at the incident segment
  - Concurrently adjust signal timings at the arterial intersections to best accommodate the detour traffic
  - Multi-objective functions
    - Max total throughput of the freeway corridor
    - Min total time of detour travelers on the detour route
  - Constraints
    - Control for signal timing (**min green time**)
    - Control diverging traffic (**max diverging rate**)

The Proposed System Architecture



Decision Criteria on the Second Assessment

- Benefit-Cost Ratio



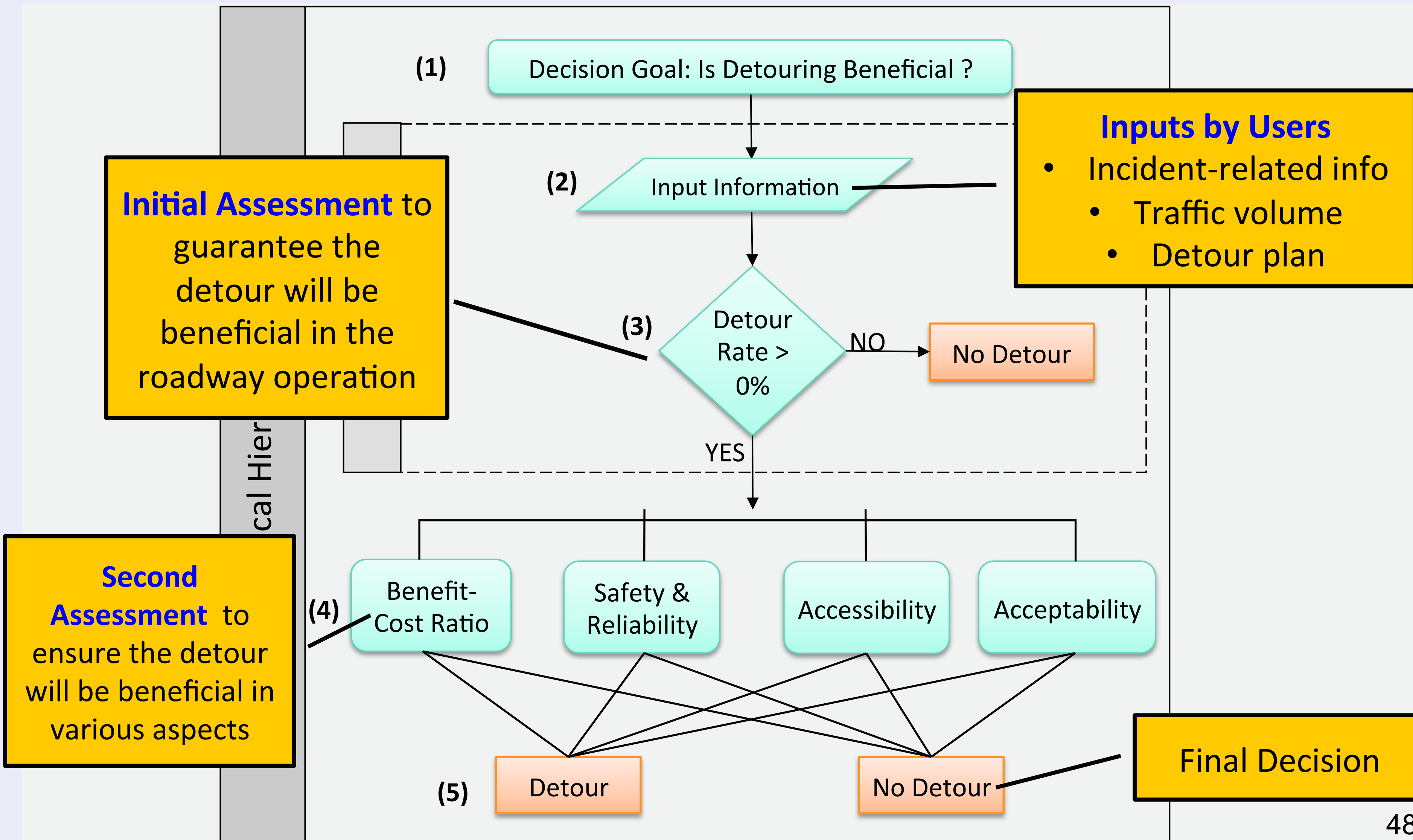
Decision Criteria on the Second Assessment

- Safety and Reliability
  - Impacted area → reduction in secondary incidents
  - Measured by the max queue length
    - A multiple linear regression model based on numerous variables regarding incident, location, heavy vehicle volumes, and traffic volumes (Kim et al. 2013)

Decision Criteria on the Second Assessment

- Accessibility
  - Traffic signals, stop signs and speed limits on the detour route
  - Measured by travel time
- Acceptability
  - Depend on the characteristics of driving populations and timely supply of the real-time traffic information
  - Measured by the anticipated compliance rate (user input)

The Proposed System Architecture



Case Study

Weights for Criteria

- Benefit-cost ratio: 0.31
- Safety and reliability :0.31
- Accessibility: 0.18
- Acceptability: 0.20

Scenario 1

- A Full Road Closure (3/3)
- 60 minute-incident duration
- System Recommendation: **Detour operations are beneficial** (recommended) with 60% confidence.
- # of signals on detour route: 2
- Speed limit on detour route: 50 mph

Scenario 2

- A Full Road Closure (3/3)
- 90 minute-incident duration
- System Recommendation: **Detour operations are NOT beneficial** (recommended) with 62% confidence.
- # of signals on detour route: 5
- Speed limit on detour route: 40 mph

Comparisons of Decisions by Agency

	Scenario No.	1	2
Decision Criteria (used by agencies in the literature)	Lane Blockage (# of closed lane(s)/total # of lanes)	3/3	
	Incident Duration (minutes)	60	
Decisions by Agency	NC DOT-main office	Y	
	NC DOT-Charlotte	Y	
	NJ DOT	Y	
	Oregon DOT	Y	
	NY DOT	Y	
	FL DOT	N	
	ARTIMIS (Ohio/Kentucky)	Y	
	Idaho (Ada County)	Y	
	Wisconsin DOT	Not clear	Not clear
Decision by Proposed System		**Y**	**N**

Scenario No.	1	2
optimal detour flow	0.85	0.54
total travel time (hr) w/ detour	3,232	10,163
total travel time (hr) w/o detour	3,617	10,182
saved travel time (hr)	386	19
B/C w/ detour	14.74	0.60
B/C w/o detour	0.07	1.68
max queue w/ detour (mile)	1.37	2.24
max queue w/o detour (mile)	1.66	2.59
travel time (min) via freeway	2.52	2.52
travel time (min) via detour	6.55	7.52

The System Flexibility with Relative Importance

- Base scenario
  - 15 minutes incident duration with full lane blockage (3/3)

Weights	Case	Description
B/C: 0.31 **S&R: 0.31** Acces: 0.18 Accep: 0.20	Case A	• Higher weights on **B/C** and **safety and reliability** • *Detour operations are **recommended** with **58% confidence**.*
B/C: 0.18 S&R: 0.20 **Acces: 0.31** **Accep: 0.31**	Case B	• Higher weights on **accessibility** and **acceptability** • *Detour operations are **Not recommended** with **53% confidence.***
B/C: 0.25 **S&R: 0.25** **Acces: 0.25** **Accep: 0.25**	Case C	• **Equal** weights on all factors • *Detour operations are **recommended** with **53% confidence.***

Contributions, Future Research, and Conclusions

Contributions

- Empirically investigated **the effectiveness** of a well-operated incident response program
  - An efficient response operation can also reduce the incident clearance duration and produce significant benefits.
- Developed **an efficient model** for optimally allocating the available response units **from a new perspective** of minimizing the total incident-induced delay
  - The developed model's performance and robustness have been confirmed from the extensive numerical results and the comparative study with the existing models and the current practice in Maryland

Contributions (cont'd)

- Developed an integrated system to provide **a reliable prediction** of the clearance duration for a detected incident.
  - Incident clearance duration is one of the essential parameters for estimating the resulting traffic impacts and assessing the operational efficiency
- Provided some **insightful information** on the interrelationships between key factors contributed to incident duration and their collective impacts on clearance times
  - Would be useful for traffic agencies to plan and improve their incident management programs.

Contributions (cont'd)

- Provided operational **guidelines and tools** for responsible agencies to conduct their assessment of traffic diversion plans as well as design of control strategies during the incident management period
- Developed an integrated system that can assess the necessity of traffic detour/diversion **based on the comprehensive review** of associated factors

Future Research

- Enhancing **reliability** of the incident response management strategy
  - Considering the **likelihood** of having **multiple incidents** over a short time period
  - Taking into account of **the stochastic nature of incident patterns**
  - Investigating the pros and cons **between the dispatching and patrolling** strategies for different times of a day under various traffic conditions and incident patterns
  - Studying **the optimal fleet size** based on the benefit-cost analysis for a given incident distribution, resource constraints, and operational costs

Future Research (cont'd)

- Enhancing **computational efficiency** for real-time operations of the detour decision support system
  - To supplement or replace simulation- or optimization-based models
  - To generate key traffic control parameters such as **optimal diversion rate** and **reduced total travel time** by detour operations.

Conclusions

- My field experimental analysis has confirmed the need to contend daily non-recurrent congestion with an efficient and effective incident management program.
  - An efficient incident management needs to optimal use available resources, and best coordinate all responsible agencies.

Conclusions (cont'd)

- This study **enhanced the efficiency and effectiveness** of the current traffic incident management system in Maryland by developing more reliable models embedded in the system.
  - An incident management system with the proposed key models, incident detection, and detour optimization tools can substantially reduce the delay, fuel consumption, and emission caused by incidents.
  - Such a system, if properly integrated with travel time information system, can substantially improve the quality and efficiency of commuters over congested highways.

Thank You
Q & A