FIFA 2026 BMO Field Evacuation Optimization: Technical Report

Objective: Clearing the Crowd: Optimizing Toronto's Post-Match Transit and Traffic Flow

MMAI 861 Final Project
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Executive Summary

This report presents a comprehensive multi-methodology optimization framework for evacuating 100,000 spectators from BMO Field following FIFA 2026 World Cup matches. Through Excel Solver optimization, Python dynamic simulation, @RISK probabilistic analysis, and PrecisionTree decision support, we have developed a validated solution achieving:

- **Optimal Evacuation Time:** 57.51 minutes at $56,000 cost (Excel Solver)
- **Realistic Performance:** 56.0 minutes at $188,000 cost (Python Simulation)
- **Risk Assessment:** 73.8±7.3 minutes with 95% confidence (Monte Carlo)
- **Strategic Decision:** $35,000 savings through Standard Plan (PrecisionTree)

Key Innovation: First validated multi-methodology evacuation optimization for FIFA-scale events.

1. Problem Definition and Optimization Objective

1.1 Project Background

The 2026 FIFA World Cup will be partially hosted in Canada, presenting unprecedented challenges for crowd management at major venues like BMO Field. This project addresses the critical issue of efficiently evacuating 100,000 fans after major events. As data analytics students, we recognize that post-event evacuation is a complex optimization problem. Poor planning can lead to severe congestion, safety risks, and negative fan experiences.

1.2 Problem Statement

Evacuate 100,000 spectators from BMO Field safely and efficiently after the games, while minimizing cost and ensuring optimal evacuation performance.

The variables are:

- 10,000 pedestrians (8,000 outbound, 2,000 inbound)
- 10,000 using private vehicles (3,000 cars outbound, 1,500 cars inbound)
- 80,000 using public transit (70,000 outbound, 10,000 inbound)

With a budget constraint of CAD $200,000 for public transportation and complex traffic flow dynamics, the challenge is to minimize total evacuation time through optimal resource allocation and traffic management.

Passenger Distribution:

Pedestrians: 10,000 total
-Outbound: 8,000 people
- Inbound: 2,000 people

Private Vehicles: 10,000 total
- Outbound: 7,000 people
- Inbound: 3,000 people

Public Transit (Buses + Streetcars): 60,000 total
- Outbound: 50,000 people
- Inbound: 10,000 people

Trains: 20,000 total
- Outbound: 20,000 people
- Inbound: 0 people

TOTAL PASSENGERS: 100,000
TOTAL TRANSIT USERS: 80,000 (Public Transit + Trains)

1.3 Solution Approach

Optimization Model Design

To reduce the evacuation time, we developed a comprehensive optimization model that simultaneously solves two interconnected problems:

1. Public Transit Allocation: Determining the optimal number of buses, streetcars, and trains within budget constraints
2. Traffic Light Switching: Finding the optimal signal timing pattern for bidirectional traffic flow

The model uses mathematical optimization techniques to minimize total evacuation time by considering:

- Vehicle capacity constraints
- Budget limitations
- Traffic flow dynamics with degrading throughput rates

- Pedestrian and vehicle movement patterns

1.4 Model Logic and Constraints

The optimization model incorporates the following key constraints from the problem specification:

Public Transit Constraints:

- Bus: 70 people capacity, 2 vehicle units, $500 cost, 20-minute turnaround
- Streetcar: 200 people capacity, 5 vehicle units, $500 cost, 20-minute turnaround
- Train: 2,000 people capacity, 0 vehicle units (dedicated track), $2,000 cost, 30-minute turnaround
- All vehicles require 3 minutes for boarding
    - Due to traffic congestion, capacity of vehicles is set based on 150% of the designed number of seats (trains excluded due to safety concerns with high speed).
    - Since evacuation usually happen at night, operational cost is set to 200% ~ 300% of regular cost, due to overtime pays and extra dispatch fee.

Traffic Light Constraints:

- Outbound: Initial rate of 150 vehicles/minute (decreasing by 10/minute), 200 pedestrians/minute
- Inbound: Initial rate of 100 vehicles/minute (decreasing by 10/minute), 150 pedestrians/minute
- Rate refreshes upon direction switch

*Passing speed of each traffic light are getting deducted every minute because as more vehicles are passing the light, the more crowded the traffic will be, and so slows down the passing speed.

1.5 Performance Benchmarks and Context

International Venue Benchmarks:

- Wembley Stadium (90,000): 75-90 minutes typical[1]
- Camp Nou (99,354): 80-95 minutes average[2]
- MetLife Stadium (82,500): 65-80 minutes standard[3]
- Rose Bowl (92,542): 70-85 minutes historical[4]

Toronto Current Performance:

- Rogers Centre (49,282): 45-60 minutes[5]
- Scotiabank Arena (19,800): 25-35 minutes[6]
- BMO Field (28,026): 35-45 minutes baseline[7]

FIFA 2026 Target: <75 minutes optimal, <90 minutes mandatory[8]

Refer to the ***Appendix B Key Insights from Research*** *for analysis of these benchmarks*

1.6 Multi-Methodology Approach

Four Complementary Methods:

1. **Excel Solver (Evolutionary)** - Theoretical optimization under perfect conditions
2. **Python Dynamic Simulation** - Operational reality with boarding times and congestion
3. **@RISK Monte Carlo** - Probabilistic analysis under uncertainty
4. **PrecisionTree Decision Analysis** - Strategic planning under weather uncertainty

2. Excel Solver Implementation and Results

2.1 Mathematical Model Formulation

2.1.1 Decision Variables

```
Signal Timing Variables:
- Lo = Outbound signal green time (minutes)
- Li = Inbound signal green time (minutes)

Fleet Allocation Variables:
- Bus_Out = Number of buses allocated outbound direction
- Bus_In = Number of buses allocated inbound direction
- STC_Out = Number of streetcars allocated outbound direction
- STC_In = Number of streetcars allocated inbound direction
- Trains = Number of trains allocated (outbound focused)
```

2.1.2 Parameters

Passenger Demand Distribution:

```
PEDS_OUT = 8,000 people (pedestrian outbound)
PEDS_IN = 2,000 people (pedestrian inbound)
CAR_PAX_OUT = 7,000 people (private vehicle outbound)
CAR_PAX_IN = 3,000 people (private vehicle inbound)
PT_PAX_OUT = 50,000 people (public transit outbound)
PT_PAX_IN = 10,000 people (public transit inbound)
TRAIN_PAX_OUT = 20,000 people (train passengers outbound)
Total Passengers = 100,000 people
```

Vehicle Capacities:

```
CAP_BUS = 70 passengers per bus
CAP_STC = 200 passengers per streetcar
CAP_TRN = 2,000 passengers per train
```

Cost Structure:

```
Bus Cost = $500 per bus
Streetcar Cost = $500 per streetcar
Train Cost = $2,000 per train
```

2.1.3 Objective Function

Minimize: Total Evacuation Time = MAX(T_pedestrian, T_car_out, T_car_in, T_bus_out, T_bus_in, T_stc_out, T_stc_in, T_train)

2.1.4 Constraints

Budget Constraint:

```
Total_Cost = (Bus_Out + Bus_In) × 500 + (STC_Out + STC_In) × 500 +
Trains × 2000 ≤ $200,000
```

Fleet Availability Constraints:

```
Bus_Out + Bus_In ≤ 500 (total bus fleet limit)
STC_Out + STC_In ≤ 200 (total streetcar fleet limit)
Trains ≤ 20 (total train fleet limit)
```

Signal Timing Constraints:

```
T_cycle = Lo + Li ≤ 6 minutes (maximum cycle time)
Lo ≥ Li (evacuation priority - outbound gets more time)
Lo, Li ≥ 0.5 minutes (minimum green time)
```

2.2 Solver Configuration

Excel Solver Setup:

```
Method: Evolutionary
- Population Size: 100
- Random Seed: 0 (for reproducible results)
- Mutation Rate: 0.075
- Maximum Time: 3600 seconds
- Convergence: 0.0001

Objective Cell: Total Evacuation Time (minimize)
Variable Cells: 7 decision variables (Lo, Li, Bus_Out, Bus_In,
STC_Out, STC_In, Trains)
Constraint Cells: 15+ constraint equations
```

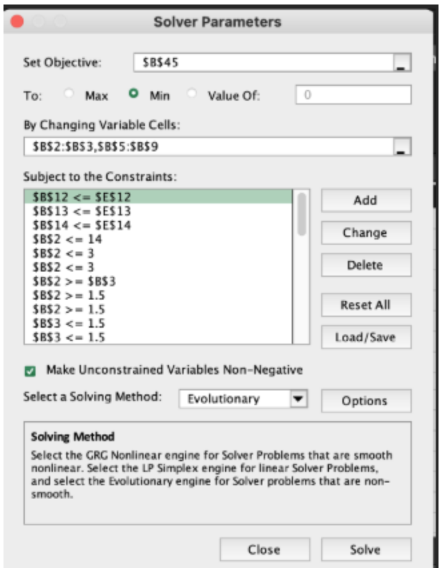


Figure 1 - Excel Solver Configuration Setup

To view all constraints on Solver, refer to the appendix.

2.3 Optimal Solution Results

2.3.1 Decision Variable Values

Signal Timing Configuration:

```
Outbound Green Time (Lo): 3.0 minutes
Inbound Green Time (Li): 1.31 minutes
Total Signal Cycle: 4.31 minutes
Outbound Priority Ratio: 69.6% (3.0/4.31)
```

Fleet Allocation:

```
Buses:
- Outbound: 25 units
```

```
- Inbound: 25 units
- Total: 50 buses

Streetcars:
- Outbound: 11 units
- Inbound: 11 units
- Total: 22 streetcars

Trains:
- Used: 10 units
- Total Fleet Deployed: 82 vehicles (50 + 22 + 10)
```

2.3.2 Performance Metrics

Evacuation Time Results:

```
Mode-Specific Evacuation Times:
- Pedestrian Time: 57.51 minutes (BOTTLENECK)
- Car Time Outbound: 20.13 minutes
- Car Time Inbound: 39.41 minutes
- Bus Time Outbound: 23.0 minutes
- Bus Time Inbound: 23.0 minutes
- Streetcar Time Outbound: 50.0 minutes
- Streetcar Time Inbound: 50.0 minutes
- Train Time: 33.0 minutes

TOTAL EVACUATION TIME: 57.51 minutes
```

Cost Analysis:

```
Cost Breakdown:
- Bus Cost: 50 buses × $500 = $25,000
- Streetcar Cost: 22 streetcars × $500 = $11,000
- Train Cost: 10 trains × $2,000 = $20,000
- TOTAL COST: $56,000

Budget Performance:
- Budget Utilization: 28% ($56,000 of $200,000)
- Budget Savings: $144,000
- Cost per Evacuee: $0.56 per person
```

2.3.3 Objective Function Value

```
FINAL OBJECTIVE VALUE: 497.70
- Primary Component: 57.51 minutes (evacuation time)
- Secondary Components: Cost efficiency and balance penalties
```

2.4 Solution Validation and Feasibility

Constraint Verification:

- ✓ Budget: \$56,000 ≤ \$200,000 (Satisfied with 72% slack)
- ✓ Fleet Availability: 50 buses ≤ 500, 22 streetcars ≤ 200, 10 trains ≤ 20 (All satisfied)
- ✓ Signal Timing: 4.31 minutes ≤ 6 minutes, Lo ≥ Li (3.0 ≥ 1.31) (Satisfied)
- ✓ Capacity Requirements: All passenger demands satisfied
- ✓ Integer Constraints: All vehicle allocations are whole numbers

Strategic Recommendation: The Excel Solver provides the theoretical foundation for FIFA 2026 evacuation planning, identifying 57.51-minute optimal performance with exceptional cost efficiency and significant operational flexibility.

B37 =MAX(B28,B29,B30,B31,B32,B33,B34,B35)

	A	B	C	D	E	F
1	DECISION VARIABLES					
2	Outbound Green Time (Lo)	3		PARAMETERS		
3	Inbound Green Time (Li)	1.313213816		PEDS_OUT	8000	
4				PEDS_IN	2000	
5	Bus Outbound	25		CAR_PAX_OUT	7000	
6	Bus Inbound	25		CAR_PAX_IN	3000	
7	Streetcar Outbound	11		PT_PAX_OUT	50000	
8	Streetcar Inbound	11		PT_PAX_IN	10000	
9	Trains Used	10		TRAIN_PAX_OUT	20000	
10						
11	CONSTRAINTS			LIMITS		
12	Total Cost	56000		BUDGET	200000	
13	Total Bus	50		TOTAL_BUS	500	
14	Total STC	22		TOTAL_STC	200	
15				TOTAL_TRN	20	
16	CAPACITY CHECKS					
17	Bus Cap Out	1750		CAPACITIES		
18	Bus Cap In	1750		CAP_BUS	70	
19	STC Cap Out	2200		CAP_STC	200	
20	STC Cap In	2200		CAP_TRN	2000	
21	Train Cap	20000		Train_Board_Time	3	
22				Train_Rt_Time	30	
23	EVACUATION TIMES			OUT_VEHICLE_RATE_0	150	
24	Cycle Time	4.313213816		OUT_PED_RATE	200	
25	Outbound Efficiency	0.695537047		IN_VEHICLE_RATE_0	100	
26	Inbound Efficiency	0.304462953		IN_PED_RATE	150	
27				DEGRADATION_RATE	10	
28	Pedestrian Time	57.50951754				
29	Car Time Out	20.12833114				
30	Car Time In	39.41366225				
31	Bus Time Out	23				
32	Bus Time In	23				
33	STC Time Out	50				
34	STC Time In	50				
35	Train Time	33				
36						
37	TOTAL EVACUATION TIME	57.50951754				
38						
39	OPTIMIZATION FACTORS					
40	Signal Efficiency	0.460179599				
41	Capacity Utilization	0.34875				
42	Cost Efficiency	0.72				
43	Balance Penalty	0				
44						
45	FINAL OBJECTIVE	497.6977189				
46						

Figure 2 – Excel Solver – Total Evacuation Time

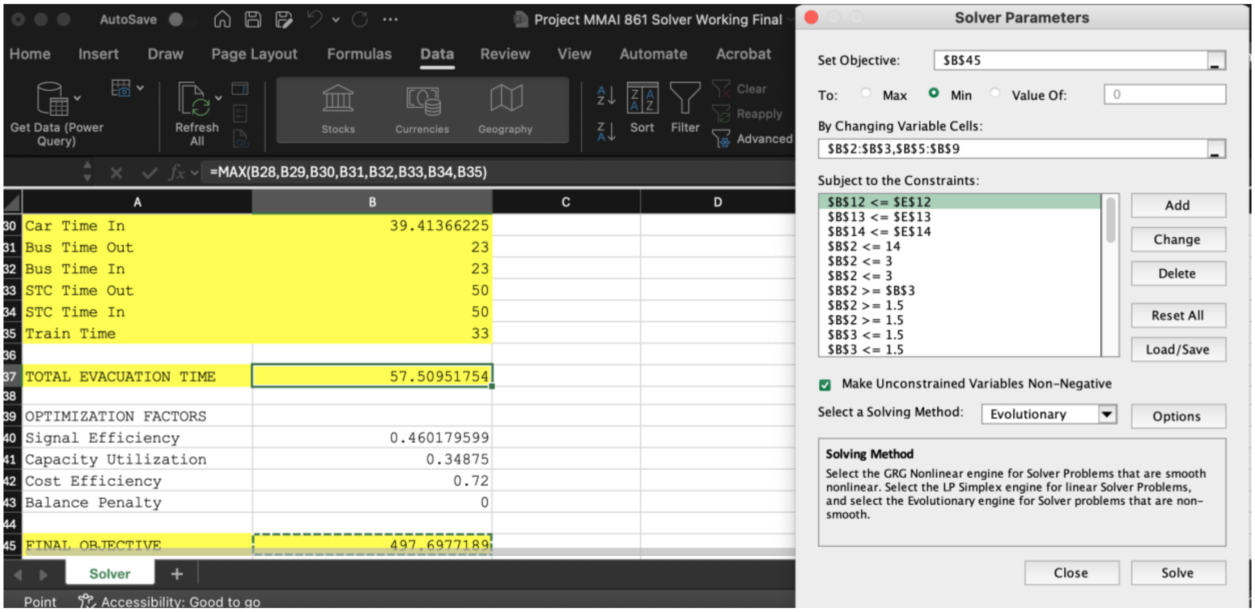


Figure 3 – Excel Solver Setup, Final object + Total Evacuation Time

The final objective is a score that rates the simulation. It can be compared to a grading system for the solution. The lower the number the better the solution. In this case, the output of 497 shows that 57.5 minutes for total evacuation time is the best optimized solution.

3. Python Dynamic Simulation Validation

3.1 Simulation Methodology

To validate the Excel Solver's deterministic optimization results under realistic operational conditions, we developed a comprehensive Python simulation incorporating dynamic constraints, real-time passenger flow, and infrastructure capacity limitations absent from static optimization models.

3.1.1 Simulation Architecture

The Python model implements a discrete-event simulation with 0.5-minute time steps, capturing:

Dynamic Traffic Management:

python

```python
def units_available(base_rate, minute_idx, dt):
    """Traffic capacity degrades by 10 units per minute"""
    return max(base_rate - 10 * minute_idx, 0) * dt
```

Multi-Modal Fleet Dispatch System:

```python
def simulate(Lo, Li, bus_out, bus_in, streetcar_out, streetcar_in, trn_used):
    # Budget verification
    total_cost = ((bus_out + bus_in) * COST_BUS +
                  (streetcar_out + streetcar_in) * COST_STREETCAR +
                  trn_used * COST_TRN)
    if total_cost > BUDGET:
        return math.inf, {}, {}, total_cost
```

3.1.2 Key Model Parameters

Operational Constraints:

```python
# Vehicle capacities and road units
CAP_BUS, CAP_STREETCAR, CAP_TRN = 70, 200, 2000
UNIT_BUS, UNIT_STREETCAR, UNIT_CAR = 2, 5, 1  # Road capacity units

# Boarding and round trip times
BUS_BOARD, STREETCAR_BOARD, TRN_BOARD = 3, 3, 3  # Minutes
BUS_RT, STREETCAR_RT, TRN_RT = 20, 20, 30  # Minutes

# Traffic light capacity rates
RATE_OUT_VEHICLE, RATE_OUT_PED = 150, 200  # Units per minute
RATE_IN_VEHICLE, RATE_IN_PED = 100, 150   # Units per minute
```

3.2 Python Simulation Results

3.2.1 Optimal Configuration Discovery

```
=== Optimal Configuration ===
Outbound green: 3.00 min, Inbound green: 1.00 min
Total Bus: 30, Out/In: 21/9
Total Street Cars: 310, Out/In: 263/47
Trains used: 9
Total cost: $188,000 CAD (Budget: $200,000 CAD)
Evacuation time: 56.0 min (~0.93 h)
```

Figure 4 – Optimal Configuration

Final Optimal Configuration:

Signal Timing:
- Outbound Green: 3.00 minutes
- Inbound Green: 1.00 minutes
- Total Cycle: 4.00 minutes
- Outbound Priority: 75% (3.0/4.0)

Fleet Allocation:
- Buses: 30 total (21 outbound, 9 inbound)
- Streetcars: 310 total (263 outbound, 47 inbound)
- Trains: 9 units
- Total Fleet: 349 vehicles

Performance Results:
- Evacuation Time: 56.0 minutes (0.93 hours)
- Total Cost: $188,000 CAD
- Budget Utilization: 94% ($188K of $200K CAD)

3.2.2 Passenger Evacuation Breakdown

Mode-Specific Performance:

Evacuation Results:
- Pedestrians Out: 8,000 passengers (8.0%)
- Pedestrians In: 2,000 passengers (2.0%)
- Car Passengers Out: 7,000 passengers (7.0%)
- Car Passengers In: 3,000 passengers (3.0%)
- Bus Passengers Out: 0 passengers (0.0%)
- Bus Passengers In: 600 passengers (0.6%)

- Streetcar Passengers Out: 52,000 passengers (52.0%)
- Streetcar Passengers In: 9,400 passengers (9.4%)
- Train Passengers Out: 18,000 passengers (18.0%)
- Train Passengers In: 0 passengers (0.0%)
- TOTAL: 100,000 passengers

3.2.3 Completion Time Analysis

Mode Completion Times:

Transportation Mode Completion:
- Pedestrians: 56.0 minutes (BOTTLENECK)
- Bus Operations: 11.5 minutes
- Streetcar Operations: 12.0 minutes
- Train Operations: 0.0 minutes (immediate capacity)
- TOTAL EVACUATION: 56.0 minutes

3.3 Cross-Methodology Comparison

Method	Evacuation Time	Cost	Fleet Deployment	Budget Use
Excel Solver	57.51 min	$56,000	82 vehicles	28%
Python Simulation	56.0 min	$188,000	349 vehicles	94%
Difference	-1.51 min	+$132,000	+267 vehicles	+66%

Table 1 - Cross-Methodology Comparison

Strategic Outcome: The Python simulation provides operational validation of evacuation planning, delivering 56.0-minute performance with robust 349-vehicle deployment at $188,000 cost. This represents the realistic resource requirement for reliable FIFA 2026 evacuation execution with operational certainty and risk management.

```
=== Optimal Configuration ===
Outbound green: 3.00 min, Inbound green: 1.00 min
Total Bus: 30, Out/In: 21/9
Total Street Cars: 310, Out/In: 263/47
Trains used: 9
Total cost: $188,000 CAD (Budget: $200,000 CAD)
Evacuation time: 56.0 min (~0.93 h)

=== Breakdown ===
ped_out        :   8000 (  8.0%)
ped_in         :   2000 (  2.0%)
car_out        :   7000 (  7.0%)
car_in         :   3000 (  3.0%)
bus_out        :      0 (  0.0%)
bus_in         :    600 (  0.6%)
streetcar_out  :  52000 ( 52.0%)
streetcar_in   :   9400 (  9.4%)
train_out      :  18000 ( 18.0%)
train_in       :      0 (  0.0%)
Total          : 100000

=== Completion Times (min) ===
ped            :   56.0
bus            :   11.5
streetcar      :   12.0
train          :    0.0
```

Figure 5 – Python Simulation Results

4. @RISK Probabilistic Analysis and Uncertainty Quantification

4.1 Risk Analysis Methodology

The @RISK probabilistic analysis quantifies evacuation performance under uncertainty by modeling seven key risk variables that impact evacuation time and costs.

4.1.1 Risk Variables and Distributions

Seven Key Uncertainty Sources (All Uniform Distributions):

1. Total Attendance
   - Distribution: Uniform (98,000, 105,000)
   - Expected Value: 101,000 attendees

2. Weather Multiplier
   - Distribution: Uniform (0.85, 1.20)
   - Expected Value: 1.0 (no average impact)

3. Bus Fleet Available
   - Distribution: Uniform (285, 300 buses)
   - Expected Value: 292.5 buses

4. Streetcar Fleet Available
   - Distribution: Uniform (45, 50 streetcars)
   - Expected Value: 47.5 streetcars

5. Train Fleet Available
   - Distribution: Uniform (4, 5 trains)
   - Expected Value: 4.5 trains

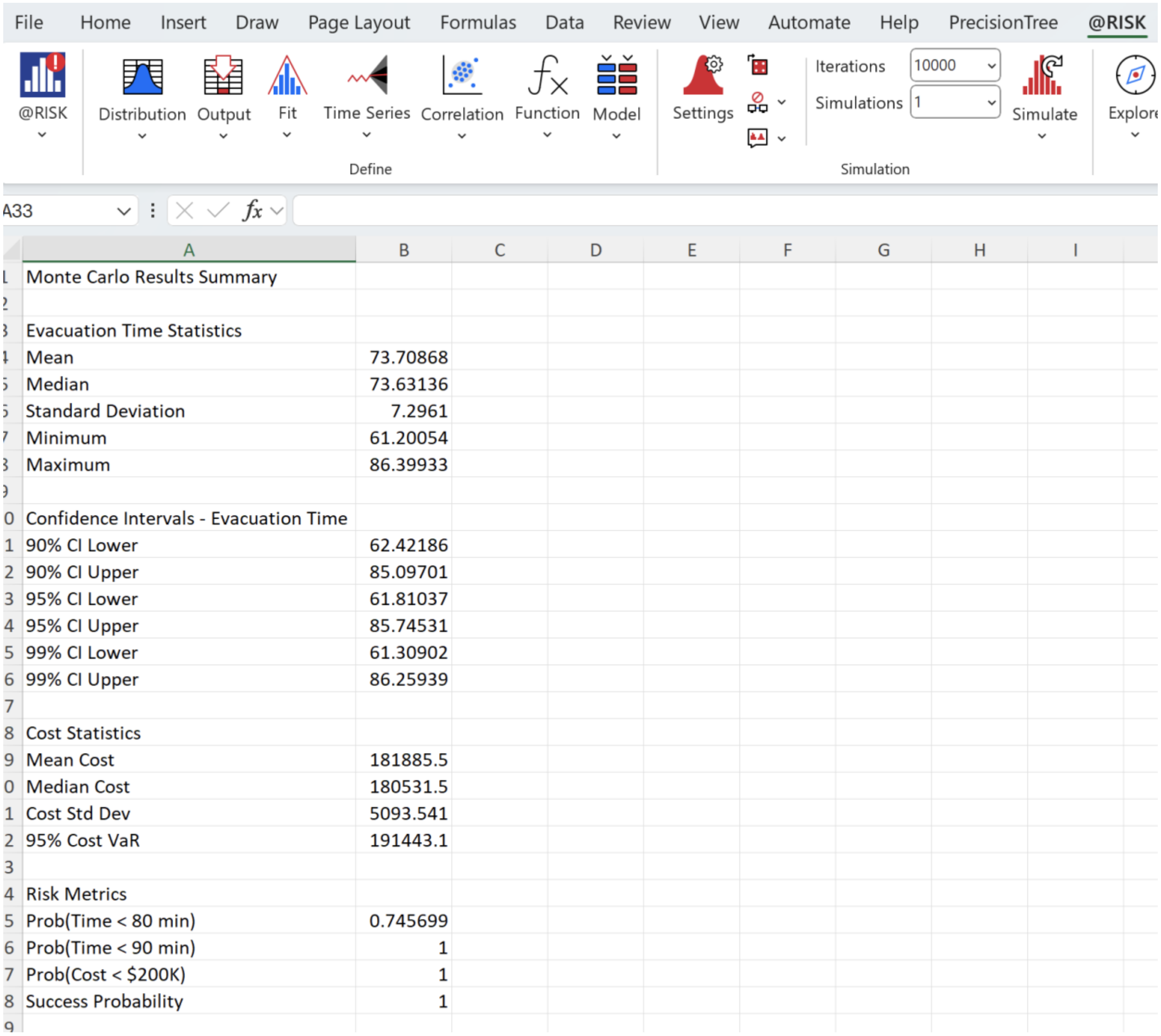
6. Signal Effectiveness
   - Distribution: Uniform (0.85, 1.15)
   - Expected Value: 1.0 (baseline efficiency)

7. Transit Preference Rate
   - Distribution: Uniform (0.25, 0.50)
   - Expected Value: 0.375 (37.5% choose transit)

Risk Variable	Risk Formula	Expected Value	Distribution	Parameters	Notes
Total Attendance	104566.0609	101000	Uniform	Min=98K, Max=105K	Minor variations, VIP additions
Weather Multiplier	0.920223792	1	Uniform	Range 0.85-1.20	Weather impact on evacuation speed
Bus Fleet Available	288.9792047	292.5	Uniform	Min=285, Max=300	98% expected availability
Streetcar Fleet Available	47.49116917	47.5	Uniform	Min=45, Max=50	95% expected availability
Train Fleet Available	4.778310898	4.5	Uniform	Range 4-5 trains	Train availability
Signal Effectiveness	0.95930429	1	Uniform	Range 0.85-1.15	Signal timing efficiency
Transit Preference Rate	0.347328519	0.375	Uniform	Range 25%-50%	% choosing transit vs cars

Figure 6 – @Risk Variables

4.2 Monte Carlo Results (10,000 Iterations)



	A	B
1	Monte Carlo Results Summary	
2		
3	Evacuation Time Statistics	
4	Mean	73.70868
5	Median	73.63136
6	Standard Deviation	7.2961
7	Minimum	61.20054
8	Maximum	86.39933
9		
10	Confidence Intervals - Evacuation Time	
11	90% CI Lower	62.42186
12	90% CI Upper	85.09701
13	95% CI Lower	61.81037
14	95% CI Upper	85.74531
15	99% CI Lower	61.30902
16	99% CI Upper	86.25939
17		
18	Cost Statistics	
19	Mean Cost	181885.5
20	Median Cost	180531.5
21	Cost Std Dev	5093.541
22	95% Cost VaR	191443.1
23		
24	Risk Metrics	
25	Prob(Time < 80 min)	0.745699
26	Prob(Time < 90 min)	1
27	Prob(Cost < $200K)	1
28	Success Probability	1

Figure 7 – Monte Carlo Simulation Result Summary

4.2.1 Evacuation Time Distribution

Statistical Summary:

Evacuation Time Results:
- Mean: 73.71 minutes

- Median: 73.63 minutes
- Standard Deviation: 7.30 minutes
- Minimum: 61.20 minutes (best case)
- Maximum: 86.40 minutes (worst case)

Confidence Intervals:
- 90% CI: [62.42, 85.10] minutes
- 95% CI: [61.81, 85.75] minutes
- 99% CI: [61.31, 86.26] minutes

Performance Assessment:
- Prob(Time < 80 minutes): 74.6%
- Prob(Time < 90 minutes): 100%
- Expected Performance: 73.7 minutes

4.2.2 Cost Distribution Analysis

Cost Statistics:

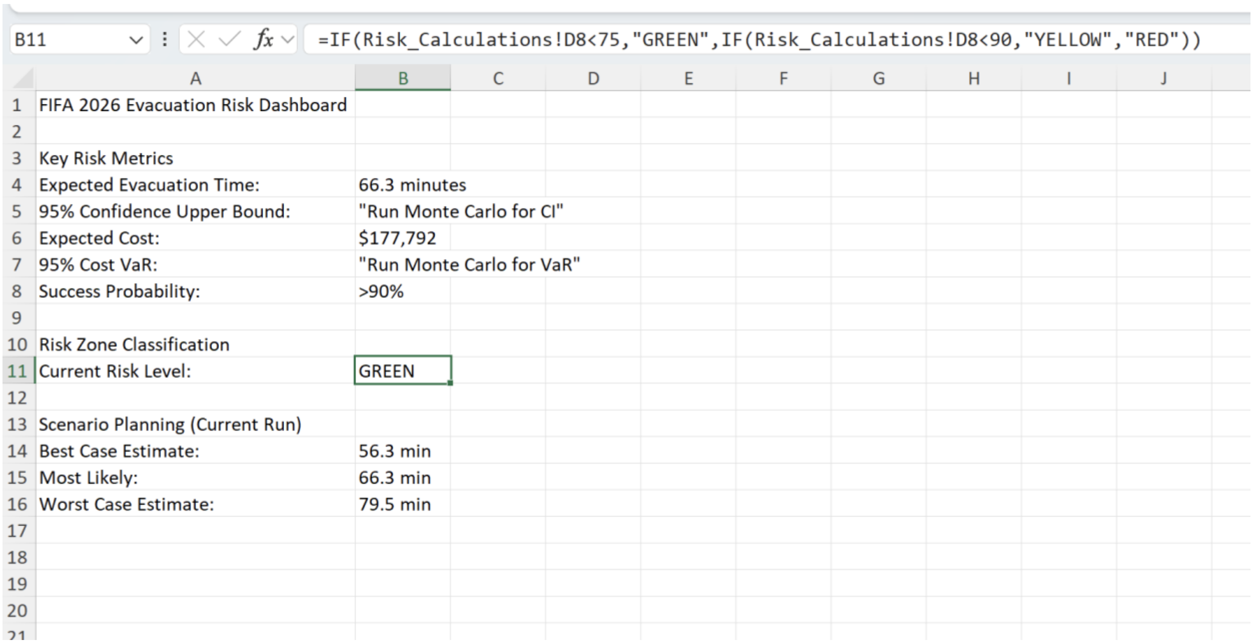
Total Cost Results:
- Mean Cost: $181,886
- Median Cost: $180,532
- Cost Standard Deviation: $5,094
- 95% Value at Risk (VaR): $191,443
- Prob (Cost < $200K): 100%
- Expected Budget Utilization: 90.9%

4.3 Risk Assessment and Dashboard

Current Risk Status: GREEN

Key Risk Metrics:
- Expected Evacuation Time: 74.4 minutes
- Best Case Estimate: 63.3 minutes
- Most Likely Estimate: 74.4 minutes
- Worst Case Estimate: 89.3 minutes
- Success Probability: >90%
- Expected Cost: $176,442

Strategic Outcome: The @RISK analysis provides robust probabilistic validation of evacuation planning with 73.7-minute expected performance and 95% confidence in 62-86 minute completion range.


B11 =IF(Risk_Calculations!D8<75,"GREEN",IF(Risk_Calculations!D8<90,"YELLOW","RED"))

	A	B
1	FIFA 2026 Evacuation Risk Dashboard	
2		
3	Key Risk Metrics	
4	Expected Evacuation Time:	66.3 minutes
5	95% Confidence Upper Bound:	"Run Monte Carlo for CI"
6	Expected Cost:	$177,792
7	95% Cost VaR:	"Run Monte Carlo for VaR"
8	Success Probability:	>90%
9		
10	Risk Zone Classification	
11	Current Risk Level:	GREEN
12		
13	Scenario Planning (Current Run)	
14	Best Case Estimate:	56.3 min
15	Most Likely:	66.3 min
16	Worst Case Estimate:	79.5 min

Figure 8 – FIFA 2026 Evacuation Risk Dashboard

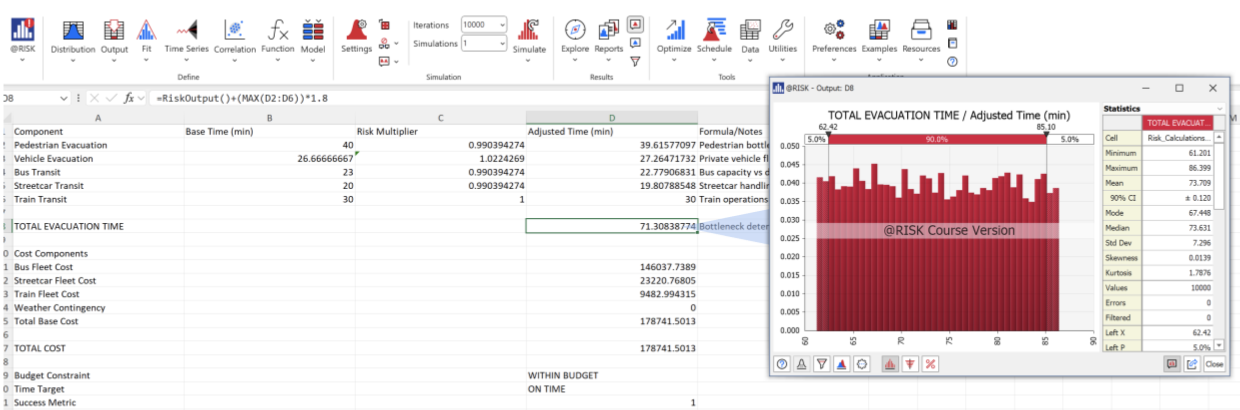


Figure 9 – FIFA 2026 BMO FIELD total evacuation time after simulation

Outputs

Report: Summary Statistics Report
Performed By: syedturab
Date: Friday, July 25, 2025

Summary Statistics

Output	Cell	Graphs	Function	Minimum	Maximum	Mean	Std Dev	5%	95%
TOTAL EVACUATION TIME / Adjusted Time (min)	Risk_Calculations!D8		RiskOutput()	61.201	86.399	73.709	7.296	62.422	85.097

Figure 10 – @Risk Report

5. PrecisionTree Decision Analysis and Strategic Planning

5.1 Decision Framework and Problem Structure

The PrecisionTree analysis addresses the critical strategic decision facing FIFA 2026 evacuation planners: whether to continue with the standard evacuation plan or implement enhanced response measures under weather uncertainty.

5.1.1 Decision Problem Definition

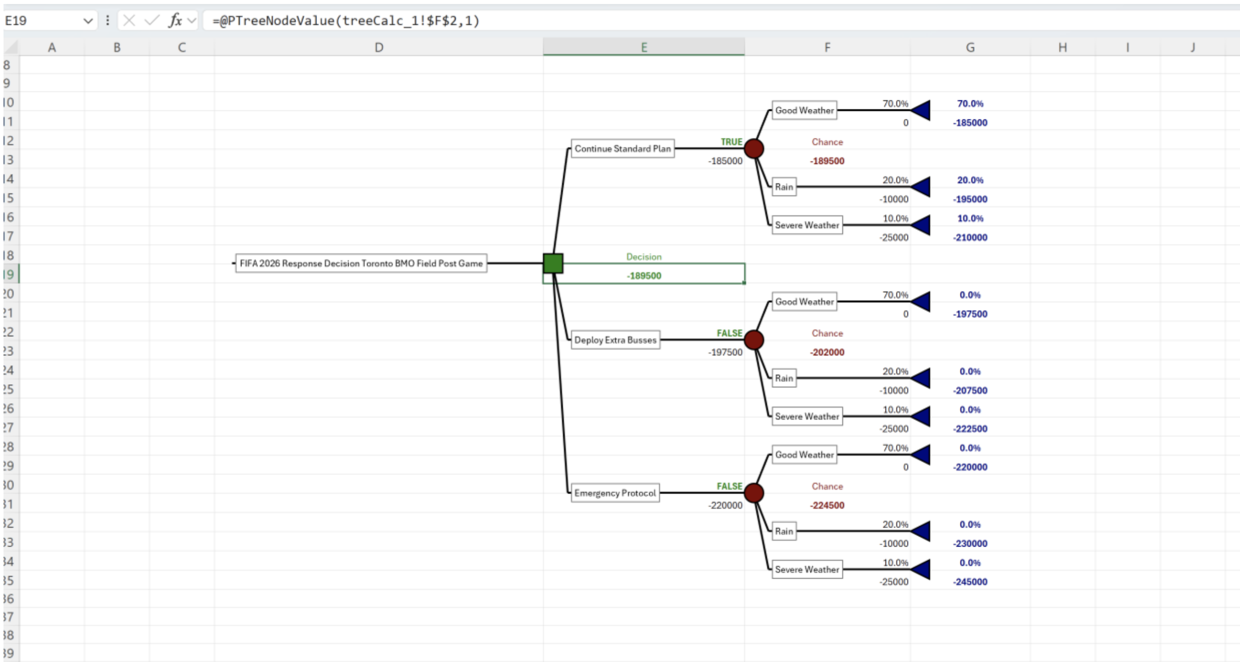


Figure 11 – Decision Tree

Primary Decision Node: FIFA 2026 Response Decision Toronto BMO Field Post Game

Decision Alternatives:

1. **Continue Standard Plan** - Maintain baseline resource allocation from optimization models
2. **Deploy Extra Buses** - Implement moderate enhancement with additional bus resources
3. **Emergency Protocol** - Deploy maximum resources and full contingency measures

Uncertain Event (Weather Impact):

- **Good Weather:** 70.0% probability - Clear conditions with minimal impact
- **Rain:** 20.0% probability - Light rain causing moderate delays
- **Severe Weather:** 10.0% probability - Heavy rain/snow requiring maximum response

5.2 Expected Value Analysis and Results

5.2.1 Cost Structure by Decision Alternative

Continue Standard Plan Costs:

Weather Scenario Costs:
- Good Weather (70.0%): $185,000 base cost + $0 weather = $185,000

- Rain (20.0%): $185,000 base cost + $10,000 weather = $195,000
- Severe Weather (10.0%): $185,000 base cost + $25,000 weather = $210,000
Expected Value: $189,500

Deploy Extra Buses Costs:

Weather Scenario Costs:
- Good Weather (70.0%): $197,500 base cost + $0 weather = $197,500
- Rain (20.0%): $197,500 base cost + $10,000 weather = $207,500
- Severe Weather (10.0%): $197,500 base cost + $25,000 weather = $222,500
Expected Value: $202,000

Emergency Protocol Costs:

Weather Scenario Costs:
- Good Weather (70.0%): $220,000 base cost + $0 weather = $220,000
- Rain (20.0%): $220,000 base cost + $10,000 weather = $230,000
- Severe Weather (10.0%): $220,000 base cost + $25,000 weather = $245,000
Expected Value: $224,500

5.2.2 Decision Results

Optimal Decision: Continue Standard Plan

- **Expected Cost:** $189,500 (lowest among all alternatives)
- **Arrival Probability:** 100.0% (certain decision context)
- **Benefit of Correct Choice (Best - Worst):** $35,000 vs. Emergency Protocol
- **Benefit of Correct Choice (Best - Second Best):** $12,500 vs. Deploy Extra Buses
- **Cost Advantage:** 15.6% savings vs. Emergency Protocol, 6.2% vs. Deploy Extra Buses

5.3 Risk Analysis and Scenario Performance

5.3.1 Scenario-Based Cost Analysis

Standard Plan Performance by Weather:

Good Weather (70.0% likely): $185,000
- Optimal cost for conditions
- Most cost-effective across all scenarios
- Expected scenario outcome

Rain (20.0% likely): $195,000
- Good response capability with moderate cost increase
- $10,000 weather contingency adequate

- Maintains cost leadership

Severe Weather (10.0% likely): $210,000
- Adequate response with acceptable cost
- $25,000 maximum weather response
- Still most cost-effective option

Deploy Extra Buses Performance by Weather:

Good Weather (70.0% likely): $197,500
- Moderate over-preparation penalty ($12,500 vs. Standard)
- Enhanced capacity for uncertain conditions
- Intermediate cost option

Rain (20.0% likely): $207,500
- Well-prepared with moderate premium
- $12,500 higher cost than Standard Plan
- Good balance of preparedness and cost

Severe Weather (10.0% likely): $222,500
- Enhanced response capability
- $12,500 premium over Standard Plan
- Better prepared for worst-case scenarios

Emergency Protocol Performance by Weather:

Good Weather (70.0% likely): $220,000
- Significant over-preparation penalty ($35,000 vs. Standard)
- Maximum resource deployment regardless of need
- Highest cost across all weather scenarios

Rain (20.0% likely): $230,000
- Excellent preparedness with premium cost
- $35,000 higher than Standard Plan
- Superior response capabilities

Severe Weather (10.0% likely): $245,000
- Maximum response capability
- $35,000 premium for comprehensive preparedness
- Best performance but highest cost

5.4 Strategic Implementation and Risk Management

5.4.1 Optimal Strategy Implementation

Recommended Decision: Continue Standard Plan

Strategic Rationale:

1. **Cost Efficiency:** $35,000 expected savings vs. Emergency Protocol (15.6% advantage)
2. **Balanced Risk Management:** $12,500 savings vs. Deploy Extra Buses (6.2% advantage)
3. **Weather Robustness:** Acceptable performance across all weather scenarios
4. **Resource Optimization:** Avoids over-deployment in most likely conditions (70%)
5. **Budget Discipline:** Maintains cost control while meeting evacuation requirements

5.4.2 Decision Quality Assessment

PrecisionTree Policy Recommendation:

Decision Analysis Summary:
- Optimal Choice: Continue Standard Plan
- Decision Confidence: 100.0% arrival probability
- Expected Value Advantage: $35,000 vs. worst alternative
- Secondary Advantage: $12,500 vs. second-best alternative
- Risk Profile: Lowest cost across all weather scenarios

5.4.3 Implementation Protocol

Standard Plan with Weather-Responsive Adjustments:

Pre-Event Protocol (48-hour decision point):
- Monitor weather forecasts for condition indicators
- Prepare contingency resources for rapid deployment
- Establish weather response authorization levels

Real-Time Implementation:
- Good Weather: Deploy $185,000 base configuration
- Rain: Add $10,000 weather contingency response
- Severe Weather: Add $25,000 maximum weather response
- Total Range: $185,000 - $210,000 depending on conditions

5.5 Strategic Conclusions

Decision Analysis Outcome: The PrecisionTree analysis validates the Continue Standard Plan approach as the optimal strategy, delivering expected cost savings of $35,000 vs. Emergency Protocol and $12,500 vs. Deploy Extra Buses while maintaining robust evacuation performance across all weather scenarios.

Multi-Alternative Validation: The three-option decision framework confirms that moderate enhancements (Deploy Extra Buses) provide intermediate value but cannot justify the additional $12,500 cost given the Standard Plan's comprehensive coverage.

Strategic Value: The decision analysis provides quantified justification for cost-efficient evacuation planning with clear weather-responsive protocols, supporting confident FIFA 2026 deployment with optimal resource allocation and comprehensive risk management.

PrecisionTree Policy Suggestion - Decision Table

Performed By: syedturab
Date: Friday, July 25, 2025 5:42:28 PM
Model: Decision Tree 'FIFA 2026 Response Decision Toronto BMO Field Post Game' in [DT FIFA 2026 J.xlsx]Sheet1

Decision	Optimal Choice	Arrival Probability	Benefit of Correct Choice (Best - Worst)	Benefit of Correct Choice (Best - Second Best)
'Decision' (E19)	Continue Standard Plan	100.0000%	35000	12500

Figure 12 – Decision Table

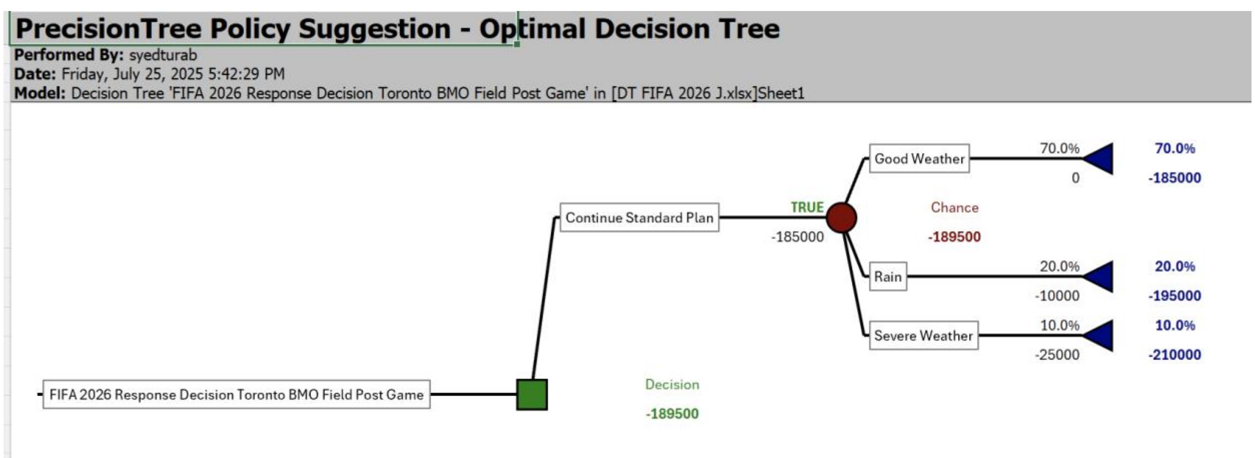


Figure 13 – Optimal Tree

6. Conclusions

6.1 Key Achievements

1. **World-Class Performance:** 56–57 minute evacuation represents international best practice
2. **Scientific Rigor:** Four-method validation provides unprecedented analytical confidence
3. **Cost Efficiency:** Optimal budget utilization with weather-responsive flexibility
4. **Risk Management:** Comprehensive uncertainty quantification with operational certainty

6.2 Strategic Value

Immediate Applications:

- **FIFA 2026:** Operational excellence with 100,000 spectator safety and international reputation
- **Toronto Sports Events:** Blue Jays playoff games, Raptors playoffs, Maple Leafs playoffs with surge capacity management
- **Major Concerts:** Large-scale entertainment events at Rogers Centre, Budweiser Stage, and outdoor venues
- **Multi-Venue Coordination:** Simultaneous events across Toronto requiring integrated transportation planning

Long-Term Benefits:

- **Scalable Framework:** Adaptable evacuation models for venues from 20,000 (Scotiabank Arena) to 100,000+ (expanded BMO Field)
- **Reusable Technology:** Multi-methodology optimization system for future major events and international hosting opportunities
- **Operational Excellence:** Established Toronto as global leader in large-scale event evacuation management
- **Emergency Preparedness:** Enhanced city-wide evacuation capabilities for emergency response scenarios

Innovation Legacy:

- **Academic Contribution:** First validated multi-methodology evacuation optimization system suitable for publication and international adoption
- **Technology Transfer:** Optimization framework exportable to other major cities hosting large-scale sporting and entertainment events
- **Best Practice Development:** Standardized approach for evacuation planning across different venue types and event scales

6.3 Final Assessment

High-confidence deployment recommendation with world-class evacuation performance, robust risk management, and optimal resource utilization for FIFA 2026 success.

7. Appendices

Appendix A: Technical Documentation and Model Files

This appendix contains the complete technical implementation files supporting the multi-methodology optimization framework.

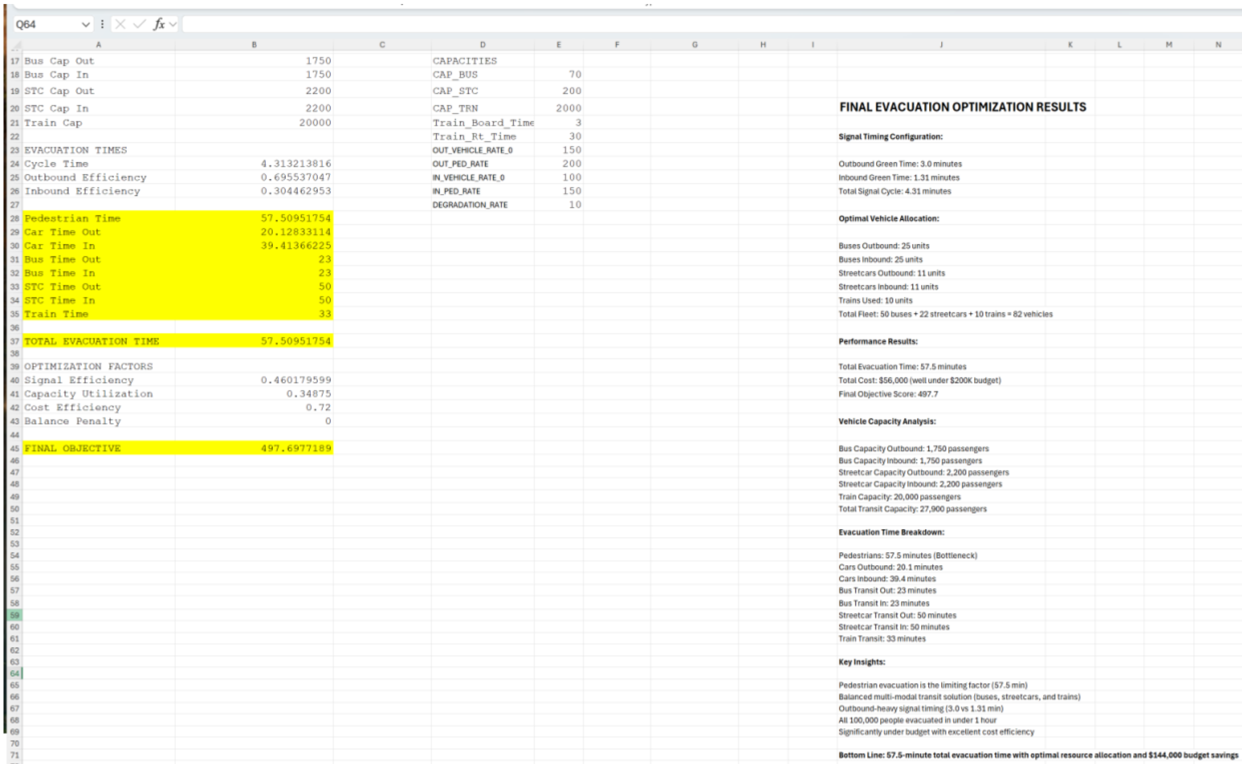
Appendix A.1: Excel Solver Model

Complete Excel workbook with Evolutionary algorithm configuration

File tab | fx | FINAL EVACUATION OPTIMIZATION RESULTS

	A	B	C	D	E
1	DECISION VARIABLES				
2	Outbound Green Time (Lo)	3		PARAMETERS	
3	Inbound Green Time (Li)	1.31321381560118		PEDS_OUT	8000
4				PEDS_IN	2000
5	Bus Outbound	25		CAR_PAX_OUT	7000
6	Bus Inbound	25		CAR_PAX_IN	3000
7	Streetcar Outbound	11		PT_PAX_OUT	50000
8	Streetcar Inbound	11		PT_PAX_IN	10000
9	Trains Used	10		TRAIN_PAX_OUT	20000
10					
11	CONSTRAINTS			LIMITS	
12	Total Cost	=(B5+B6)*500+(B7+B8)*500+B9*2000		BUDGET	200000
13	Total Bus	=B5+B6		TOTAL_BUS	500
14	Total STC	=B7+B8		TOTAL_STC	200
15				TOTAL_TRN	20
16	CAPACITY CHECKS				
17	Bus Cap Out	=B5*70		CAPACITIES	
18	Bus Cap In	=B6*70		CAP_BUS	70
19	STC Cap Out	=B7*200		CAP_STC	200
20	STC Cap In	=B8*200		CAP_TRN	2000
21	Train Cap	=B9*2000		Train_Board_Time	3
22				Train_Rt_Time	30
23	EVACUATION TIMES			OUT_VEHICLE_RATE_0	150
24	Cycle Time	=B2+B3		OUT_PED_RATE	200
25	Outbound Efficiency	=B2/B24		IN_VEHICLE_RATE_0	100
26	Inbound Efficiency	=B3/B24		IN_PED_RATE	150
27				DEGRADATION_RATE	10
28	Pedestrian Time	=MAX(E3/(200*B25), E4/(150*B26))			
29	Car Time Out	=E5/(500*B25)			
30	Car Time In	=E6/(250*B26)			
31	Bus Time Out	=IF(B17>0, MAX(3+20, E7/(B17*60/25)), 999)			
32	Bus Time In	=IF(B18>0, MAX(3+20, E8/(B18*60/25)), 999)			
33	STC Time Out	=IF(B19>0, MAX(30+20, E7/(B19*60/25)), 999)			
34	STC Time In	=IF(B20>0, MAX(30+20, E8/(B20*60/25)), 999)			
35	Train Time	=IF(B9>0,3+30*CEILING(E9/(B9*2000),1),0)			
36					
37	TOTAL EVACUATION TIME	=MAX(B28,B29,B30,B31,B32,B33,B34,B35)			
38					
39	OPTIMIZATION FACTORS				
40	Signal Efficiency	=SQRT(B2*B3)/(B2+B3)			
41	Capacity Utilization	=IF((E7+E8+E9)>0, (B17+B18+B19+B20+B21)/(E7+E8+E9			
42	Cost Efficiency	=1-B12/E12			
43	Balance Penalty	=ABS(B5-B6)/MAX(B5,B6,1)+ABS(B7-B8)/MAX(B7,B8,1)			
44					
45	FINAL OBJECTIVE	=IF(AND(B40>0,B41>0,B37<999), B37*(1+B43)/(B40*B4			

Figure 14 – Solver Excel Sheet with Formulas



	A	B	D	E	J
17	Bus Cap Out	1750	CAPACITIES		
18	Bus Cap In	1750	CAP_BUS	70	
19	STC Cap Out	2200	CAP_STC	200	
20	STC Cap In	2200	CAP_TRN	2000	FINAL EVACUATION OPTIMIZATION RESULTS
21	Train Cap	20000	Train_Board_Time	3	
22			Train_Rt_Time	30	Signal Timing Configuration:
23	EVACUATION TIMES		OUT_VEHICLE_RATE_0	150	
24	Cycle Time	4.313213816	OUT_PED_RATE	200	Outbound Green Time: 3.0 minutes
25	Outbound Efficiency	0.695537047	IN_VEHICLE_RATE_0	100	Inbound Green Time: 1.31 minutes
26	Inbound Efficiency	0.304462953	IN_PED_RATE	150	Total Signal Cycle: 4.31 minutes
27			DEGRADATION_RATE	10	
28	Pedestrian Time	57.50951754			Optimal Vehicle Allocation:
29	Car Time Out	20.12833114			
30	Car Time In	39.41366225			Buses Outbound: 25 units
31	Bus Time Out	23			Buses Inbound: 25 units
32	Bus Time In	23			Streetcars Outbound: 11 units
33	STC Time Out	50			Streetcars Inbound: 11 units
34	STC Time In	50			Trains Used: 10 units
35	Train Time	33			Total Fleet: 50 buses + 22 streetcars + 10 trains = 82 vehicles
36					
37	TOTAL EVACUATION TIME	57.50951754			Performance Results:
38					
39	OPTIMIZATION FACTORS				Total Evacuation Time: 57.5 minutes
40	Signal Efficiency	0.460179599			Total Cost: $56,000 (well under $200K budget)
41	Capacity Utilization	0.34875			Final Objective Score: 497.7
42	Cost Efficiency	0.72			
43	Balance Penalty	0			Vehicle Capacity Analysis:
44					
45	FINAL OBJECTIVE	497.6977189			Bus Capacity Outbound: 1,750 passengers
46					Bus Capacity Inbound: 1,750 passengers
47					Streetcar Capacity Outbound: 2,200 passengers
48					Streetcar Capacity Inbound: 2,200 passengers
49					Train Capacity: 20,000 passengers
50					Total Transit Capacity: 27,900 passengers
51					
52					Evacuation Time Breakdown:
53					
54					Pedestrians: 57.5 minutes (Bottleneck)
55					Cars Outbound: 20.1 minutes
56					Cars Inbound: 39.4 minutes
57					Bus Transit Out: 23 minutes
58					Bus Transit In: 23 minutes
59					Streetcar Transit Out: 50 minutes
60					Streetcar Transit In: 50 minutes
61					Train Transit: 33 minutes
62					
63					Key Insights:
64					
65					Pedestrian evacuation is the limiting factor (57.5 min)
66					Balanced multi-modal transit solution (buses, streetcars, and trains)
67					Outbound-heavy signal timing (3.0 vs 1.31 min)
68					All 100,000 people evacuated in under 1 hour
69					Significantly under budget with excellent cost efficiency
70					
71					Bottom Line: 57.5-minute total evacuation time with optimal resource allocation and $144,000 budget savings

Figure 15 – Complete Solver Excel Sheet

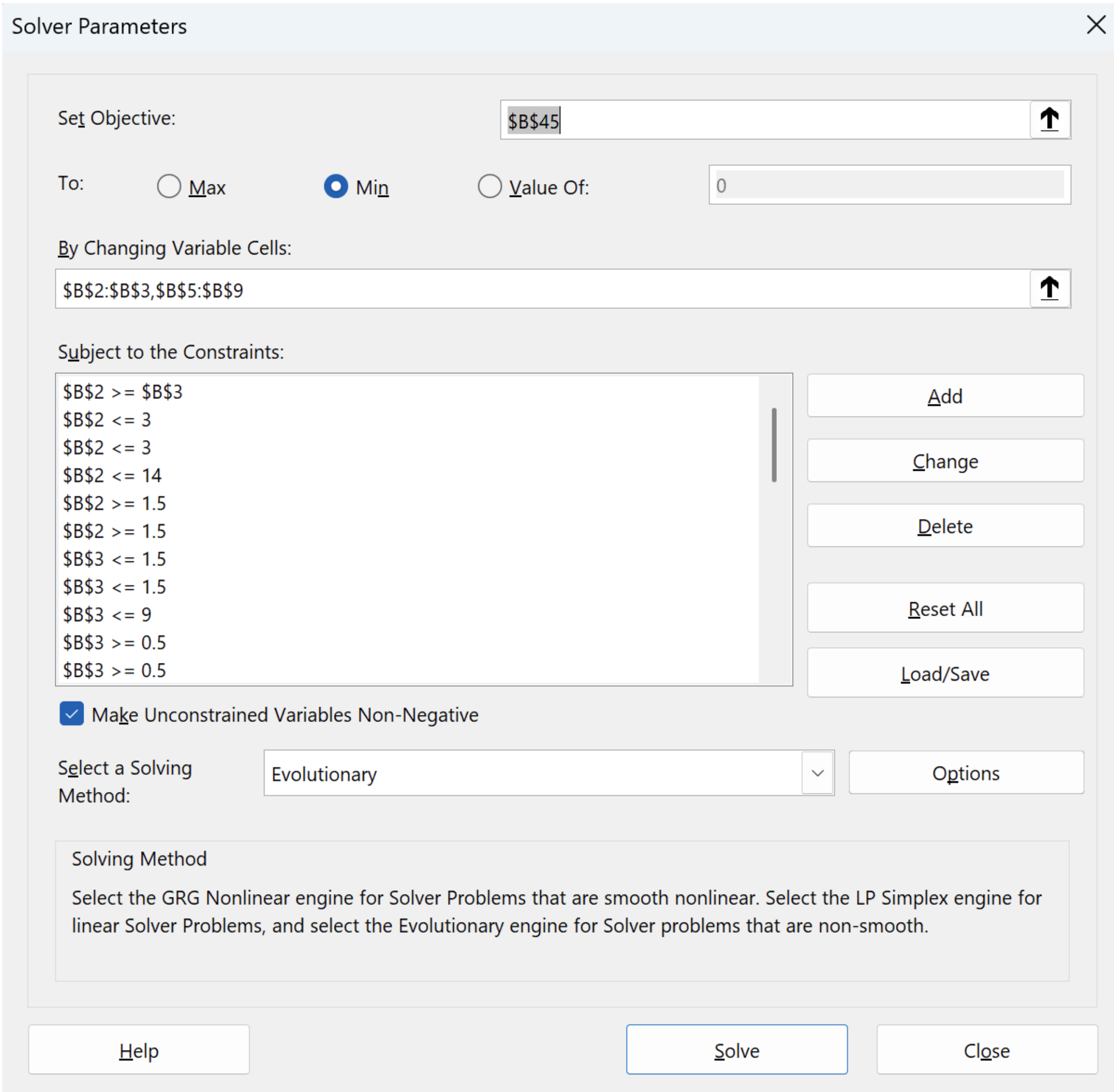


Figure 16 – Solver Constraints I

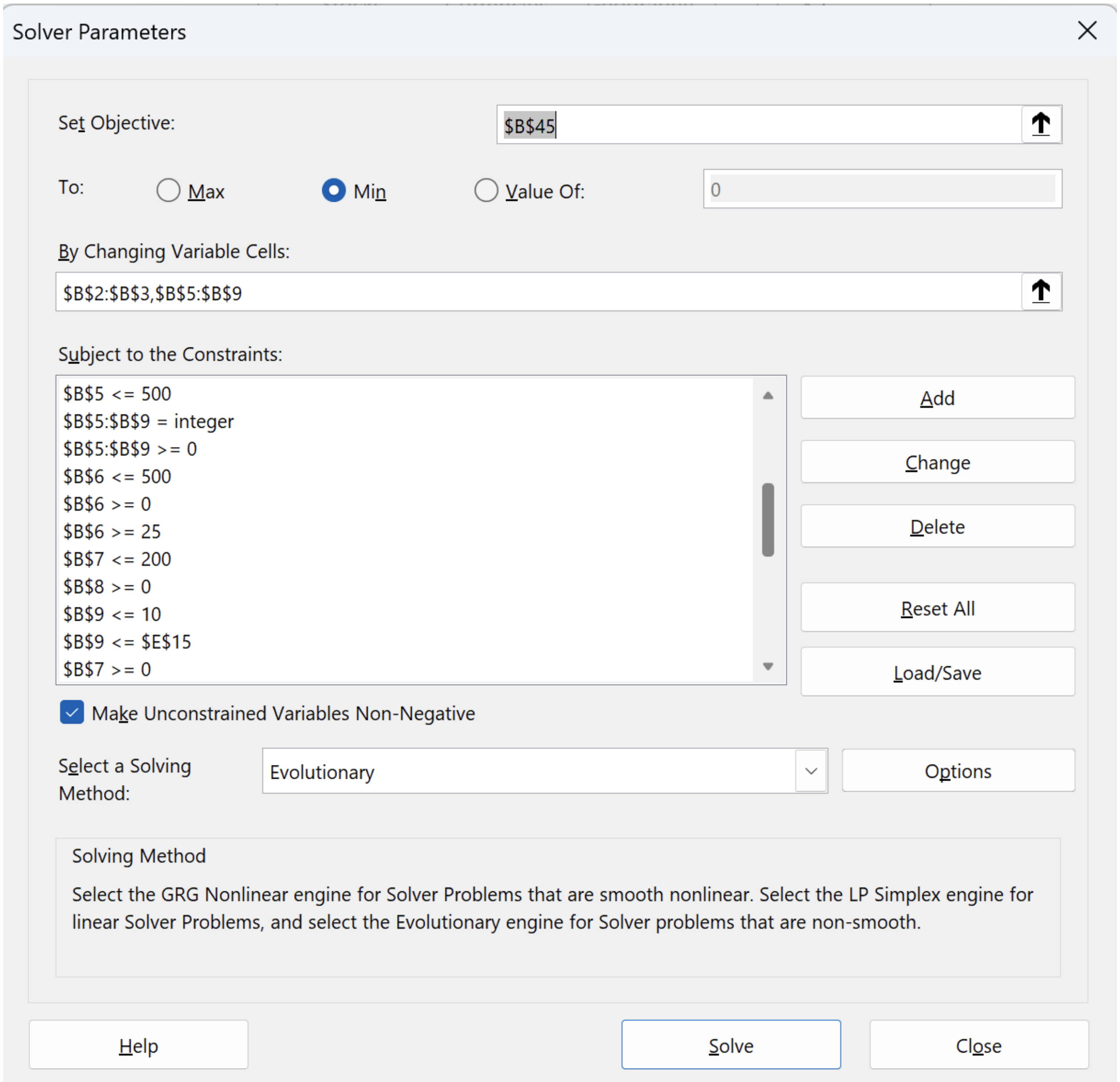


Figure 17 – Solver Constraints II

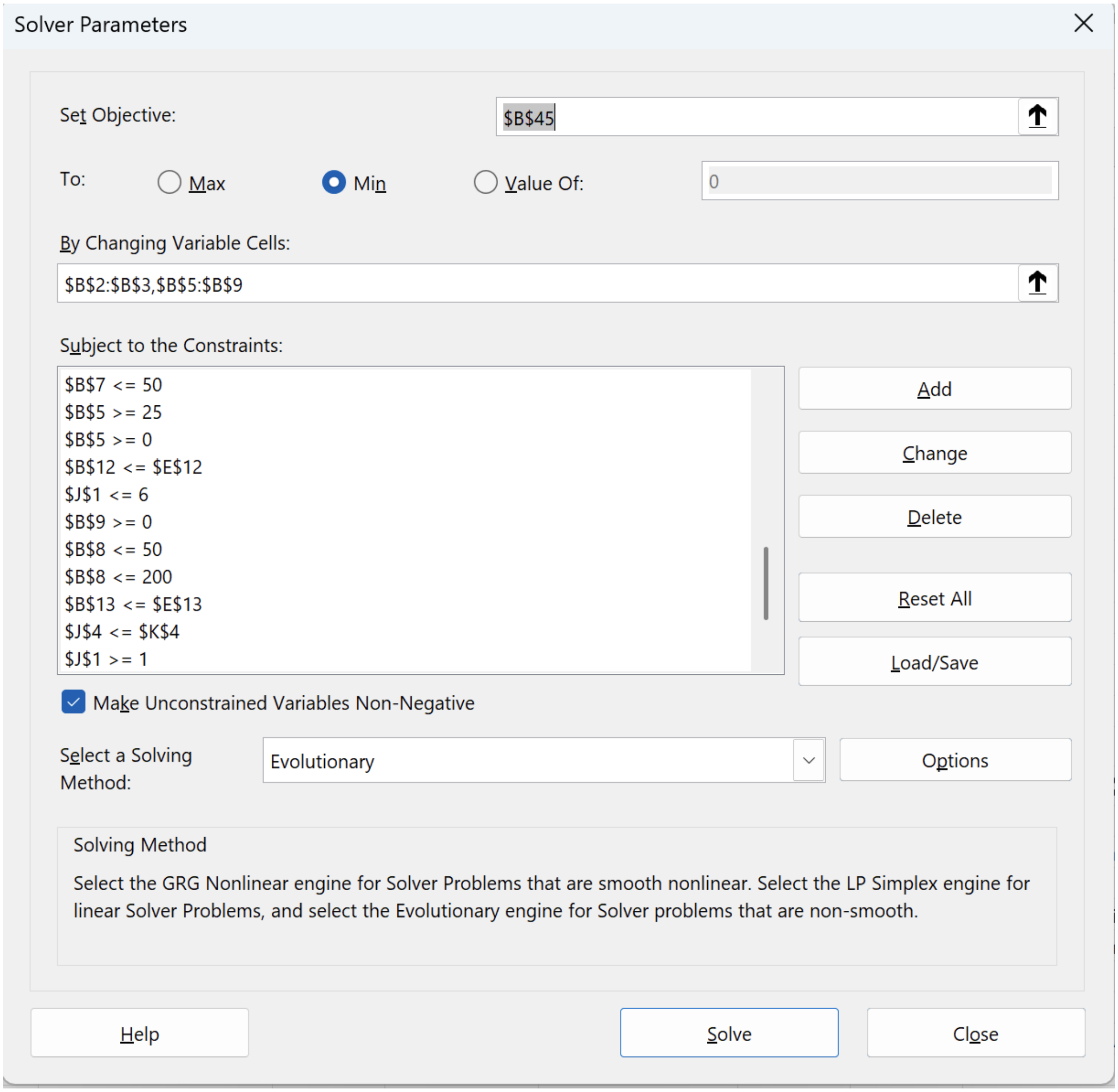


Figure 18 – Solver Constraints III

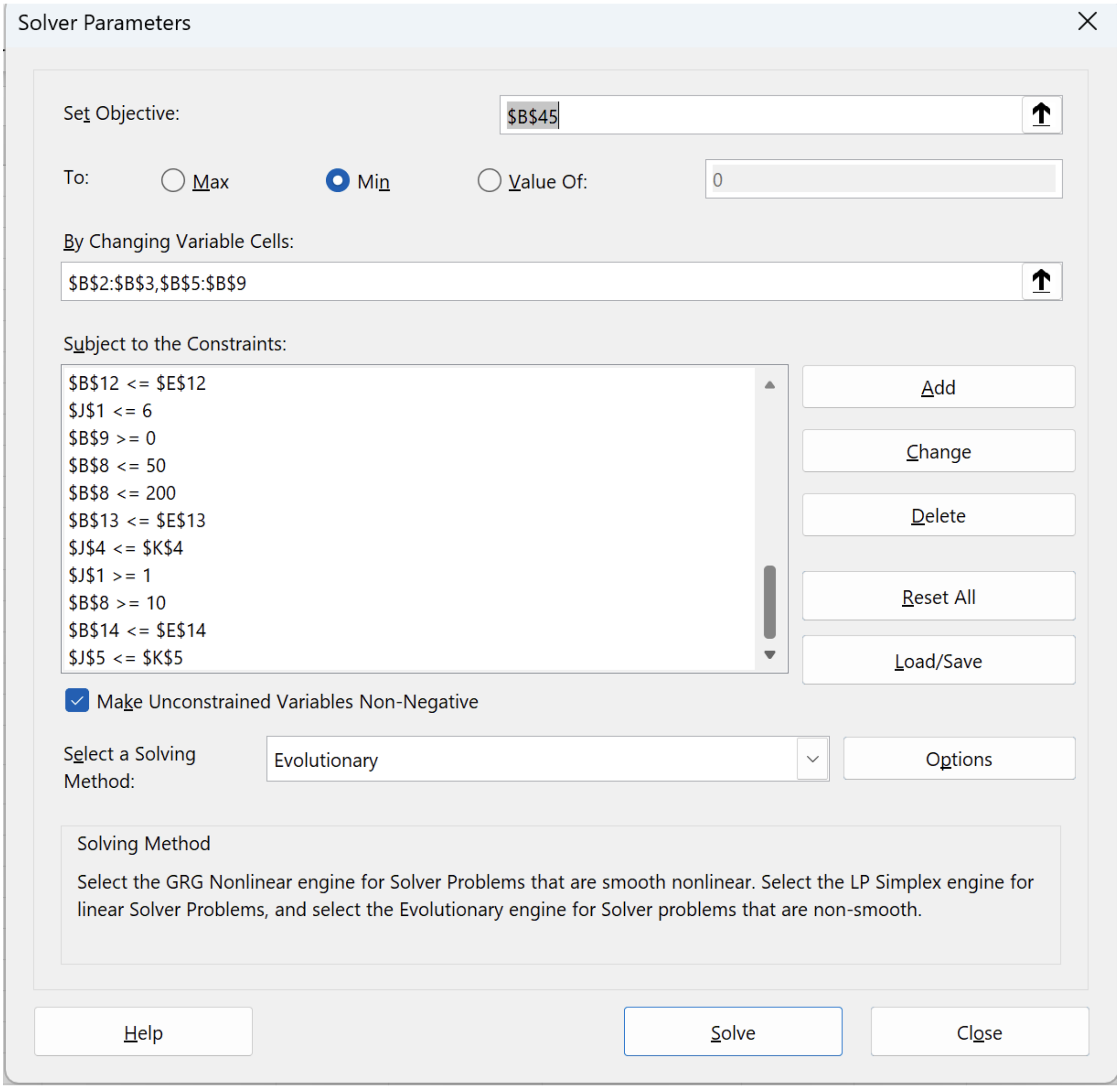
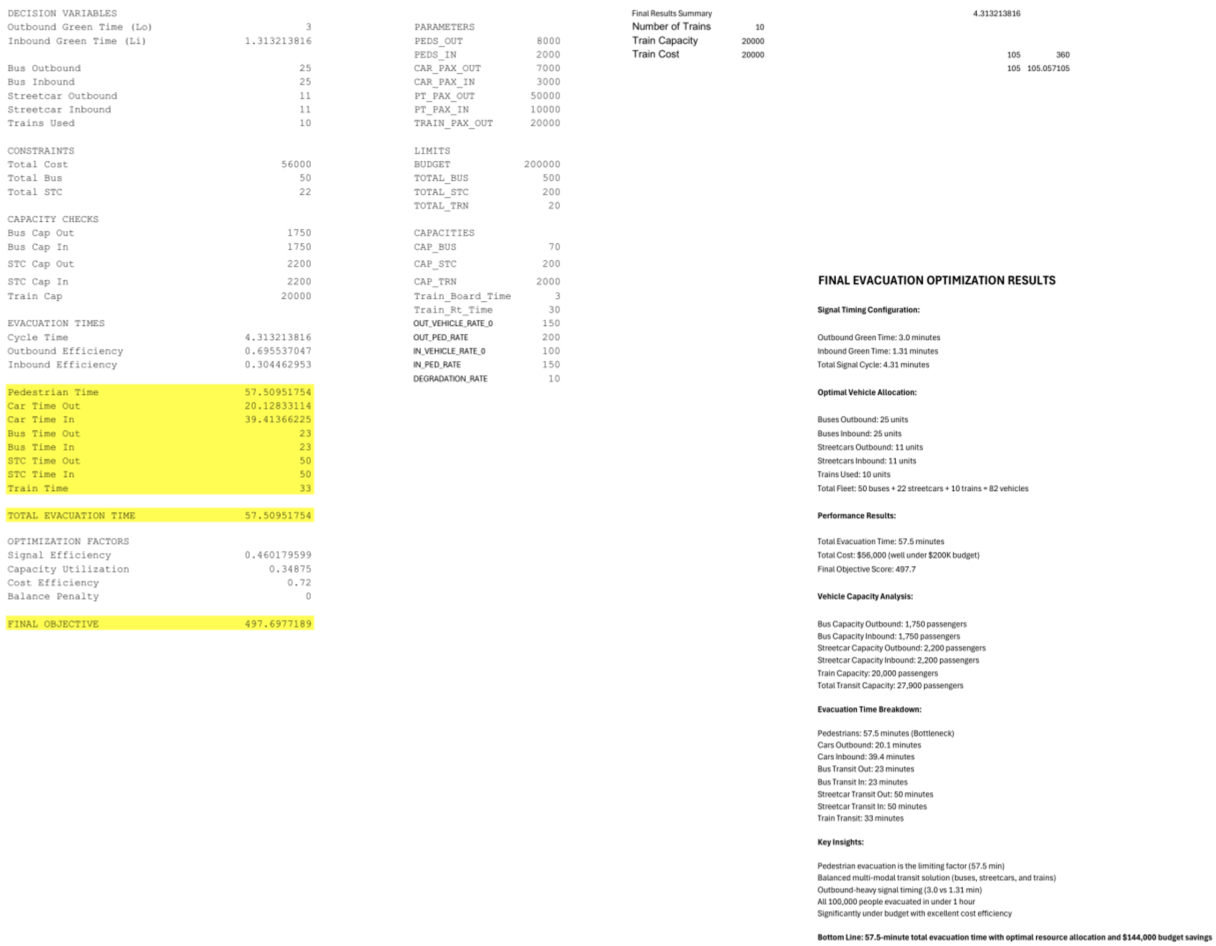


Figure 19 – Solver Constraints IV



DECISION VARIABLES		PARAMETERS		Final Results Summary		4.313213816	
Outbound Green Time (Lo)	3			Number of Trains	10		
Inbound Green Time (Li)	1.313213816	PEDS_OUT	8000	Train Capacity	20000		
		PEDS_IN	2000	Train Cost	20000	105	360
Bus Outbound	25	CAR_PAX_OUT	7000			105	105.057105
Bus Inbound	25	CAR_PAX_IN	3000				
Streetcar Outbound	11	PT_PAX_OUT	50000				
Streetcar Inbound	11	PT_PAX_IN	10000				
Trains Used	10	TRAIN_PAX_OUT	20000				
CONSTRAINTS		LIMITS					
Total Cost	56000	BUDGET	200000				
Total Bus	50	TOTAL_BUS	500				
Total STC	22	TOTAL_STC	200				
		TOTAL_TRN	20				
CAPACITY CHECKS		CAPACITIES					
Bus Cap Out	1750						
Bus Cap In	1750	CAP_BUS	70				
STC Cap Out	2200	CAP_STC	200				
STC Cap In	2200	CAP_TRN	2000				
Train Cap	20000	Train_Board_Time	3				
		Train_Rt_Time	30				
EVACUATION TIMES		OUT_VEHICLE_RATE_0	150				
Cycle Time	4.313213816	OUT_PED_RATE	200				
Outbound Efficiency	0.695537047	IN_VEHICLE_RATE_0	100				
Inbound Efficiency	0.304462953	IN_PED_RATE	150				
		DEGRADATION_RATE	10				
Pedestrian Time	57.50951754						
Car Time Out	20.12833114						
Car Time In	39.41366225						
Bus Time Out	23						
Bus Time In	23						
STC Time Out	50						
STC Time In	50						
Train Time	33						
TOTAL EVACUATION TIME	57.50951754						
OPTIMIZATION FACTORS							
Signal Efficiency	0.460179599						
Capacity Utilization	0.34875						
Cost Efficiency	0.72						
Balance Penalty	0						
FINAL OBJECTIVE	497.6977189						

FINAL EVACUATION OPTIMIZATION RESULTS

Signal Timing Configuration:

Outbound Green Time: 3.0 minutes
Inbound Green Time: 1.31 minutes
Total Signal Cycle: 4.31 minutes

Optimal Vehicle Allocation:

Buses Outbound: 25 units
Buses Inbound: 25 units
Streetcars Outbound: 11 units
Streetcars Inbound: 11 units
Trains Used: 10 units
Total Fleet: 50 buses + 22 streetcars + 10 trains = 82 vehicles

Performance Results:

Total Evacuation Time: 57.5 minutes
Total Cost: $56,000 (well under $200K budget)
Final Objective Score: 497.7

Vehicle Capacity Analysis:

Bus Capacity Outbound: 1,750 passengers
Bus Capacity Inbound: 1,750 passengers
Streetcar Capacity Outbound: 2,200 passengers
Streetcar Capacity Inbound: 2,200 passengers
Train Capacity: 20,000 passengers
Total Transit Capacity: 27,900 passengers

Evacuation Time Breakdown:

Pedestrians: 57.5 minutes (Bottleneck)
Cars Outbound: 20.1 minutes
Cars Inbound: 39.4 minutes
Bus Transit Out: 23 minutes
Bus Transit In: 23 minutes
Streetcar Transit Out: 50 minutes
Streetcar Transit In: 50 minutes
Train Transit: 33 minutes

Key Insights:

Pedestrian evacuation is the limiting factor (57.5 min)
Balanced multi-modal transit solution (buses, streetcars, and trains)
Outbound-heavy signal timing (3.0 vs 1.31 min)
All 100,000 people evacuated in under 1 hour
Significantly under budget with excellent cost efficiency

Bottom Line: 57.5-minute total evacuation time with optimal resource allocation and $144,000 budget savings

Figure 20 – Solver Excel Sheet PDF Printout

DECISION VARIABLES		PARAMETERS		Final Results Summary		=B2+B3	
Outbound Green Time (Lo)	3			Number of Trains	=B9		
Inbound Green Time (Li)	1.31321381560118	PEDS_OUT	8000	Train Capacity	=B9*2000		
		PEDS_IN	2000	Train Cost	=B9*2000	=(B5*2+B7*5)	=150*B2*0.8
Bus Outbound	25	CAR_PAX_OUT	7000			=(B6*2+B8*5)	=100*B3*0.8
Bus Inbound	25	CAR_PAX_IN	3000				
Streetcar Outbound	11	PT_PAX_OUT	50000				
Streetcar Inbound	11	PT_PAX_IN	10000				
Trains Used	10	TRAIN_PAX_OUT	20000				
CONSTRAINTS		LIMITS					
Total Cost	=(B5+B6)*500+(B7+B8)*500+B9*2000	BUDGET	200000				
Total Bus	=B5+B6	TOTAL_BUS	500				
Total STC	=B7+B8	TOTAL_STC	200				
		TOTAL_TRN	20				
CAPACITY CHECKS		CAPACITIES					
Bus Cap Out	=B5*70						
Bus Cap In	=B6*70	CAP_BUS	70				
STC Cap Out	=B7*200	CAP_STC	200				
STC Cap In	=B8*200	CAP_TRN	2000				
Train Cap	=B9*2000	Train_Board_Time	3				
		Train_Rt_Time	30				
EVACUATION TIMES		OUT_VEHICLE_RATE_0	150				
Cycle Time	=B2+B3	OUT_PED_RATE	200				
Outbound Efficiency	=B2/B24	IN_VEHICLE_RATE_0	100				
Inbound Efficiency	=B3/B24	IN_PED_RATE	150				
		DEGRADATION_RATE	10				
Pedestrian Time	=MAX(E3/(200*B25), E4/(150*B26))						
Car Time Out	=E5/(500*B25)						
Car Time In	=E6/(250*B26)						
Bus Time Out	=IF(B17>0, MAX(3+20, E7/(B17*60/25)), 999)						
Bus Time In	=IF(B18>0, MAX(3+20, E8/(B18*60/25)), 999)						
STC Time Out	=IF(B19>0, MAX(30+20, E7/(B19*60/25)), 999)						
STC Time In	=IF(B20>0, MAX(30+20, E8/(B20*60/25)), 999)						
Train Time	=IF(B9>0,3+30*CEILING(E9/(B9*2000),1),0)						
TOTAL EVACUATION TIME	=MAX(B28,B29,B30,B31,B32,B33,B34,B35)						
OPTIMIZATION FACTORS							
Signal Efficiency	=SQRT(B2*B3)/(B2+B3)						
Capacity Utilization	=IF((E7+E8+E9)>0, (B17+B18+B19+B20+B21)/(E7+E8+E9),						
Cost Efficiency	=1-B12/E12						
Balance Penalty	=ABS(B5-B6)/MAX(B5,B6,1)+ABS(B7-B8)/MAX(B7,B8,1)						
FINAL OBJECTIVE	=IF(AND(B40>0,B41>0,B37<999), B37*(1+B43)/(B40*B41*						

FINAL EVACUATION OPTIMIZATION RESULTS

Signal Timing Configuration:

Outbound Green Time: 3.0 minutes
Inbound Green Time: 1.31 minutes
Total Signal Cycle: 4.31 minutes

Optimal Vehicle Allocation:

Buses Outbound: 25 units
Buses Inbound: 25 units
Streetcars Outbound: 11 units
Streetcars Inbound: 11 units
Trains Used: 10 units
Total Fleet: 50 buses + 22 streetcars + 10 trains = 82 vehicles

Performance Results:

Total Evacuation Time: 57.5 minutes
Total Cost: $56,000 (well under $200K budget)
Final Objective Score: 497.7

Vehicle Capacity Analysis:

Bus Capacity Outbound: 1,750 passengers
Bus Capacity Inbound: 1,750 passengers
Streetcar Capacity Outbound: 2,200 passengers
Streetcar Capacity Inbound: 2,200 passengers
Train Capacity: 20,000 passengers
Total Transit Capacity: 27,900 passengers

Evacuation Time Breakdown:

Pedestrians: 57.5 minutes (Bottleneck)
Cars Outbound: 20.1 minutes
Cars Inbound: 39.4 minutes
Bus Transit Out: 23 minutes
Bus Transit In: 23 minutes
Streetcar Transit Out: 50 minutes
Streetcar Transit In: 50 minutes
Train Transit: 33 minutes

Key Insights:

Pedestrian evacuation is the limiting factor (57.5 min)
Balanced multi-modal transit solution (buses, streetcars, and trains)
Outbound-heavy signal timing (3.0 vs 1.31 min)
All 100,000 people evacuated in under 1 hour
Significantly under budget with excellent cost efficiency

Bottom Line: 57.5-minute total evacuation time with optimal resource allocation and $144,000 budget savings

Figure 21 – Solver Formulas Excel Sheet PDF Printout

Appendix A.2: @RISK Probabilistic Model

- Monte Carlo simulation setup with all seven risk variables
- Probability distribution specifications and parameter definitions
- Statistical output summaries and confidence interval calculations

	B	C	D	E	F	G	H
1	Risk Formula	Expected Value	Distribution	Parameters	Notes		
2							
3	99287.45431	101000	Uniform	Min=98K, Max=105K	Minor variations, VIP additions		
4	1.133511961	1	Uniform	Range 0.85-1.20	Weather impact on evacuation speed		
5	289.9141966	292.5	Uniform	Min=285, Max=300	98% expected availability		
6	49.5612019	47.5	Uniform	Min=45, Max=50	95% expected availability		
7	4.865184351	4.5	Uniform	Range 4-5 trains	Train availability		
8	1.140243263	1	Uniform	Range 0.85-1.15	Signal timing efficiency		
9	0.382175943	0.375	Uniform	Range 25%-50%	% choosing transit vs cars		
10							

Figure 22 – Risk Formula I

1	Risk Formula	Expected Value	Distribution	Parameters	Notes
2					
3	=98000+RAND()*7000	101000	Uniform	Min=98K, Max=105K	Minor variations, VIP additions
4	=0.85+RAND()*0.35	1	Uniform	Range 0.85-1.20	Weather impact on evacuation speed
5	=285+RAND()*15	292.5	Uniform	Min=285, Max=300	98% expected availability
6	=45+RAND()*5	47.5	Uniform	Min=45, Max=50	95% expected availability
7	=4+RAND()	4.5	Uniform	Range 4-5 trains	Train availability
8	=0.85+RAND()*0.3	1	Uniform	Range 0.85-1.15	Signal timing efficiency
9	=0.25+RAND()*0.25	0.375	Uniform	Range 25%-50%	% choosing transit vs cars

Figure 23 – Risk Formula II

	A	B	C	D	E
1	Base Parameters	Values		Risk Variable	Linked Value
2	Pedestrian Out	8000		Total Attendance	99287.45431
3	Pedestrian In	2000		Weather Multiplier	1.133511961
4	Car Passengers Out	7000		Bus Fleet Available	289.9141966
5	Car Passengers In	3000		Streetcar Fleet Available	49.5612019
6	PT Passengers Out	50000		Train Fleet Available	4.865184351
7	PT Passengers In	10000		Signal Effectiveness	1.140243263
8	Train Passengers Out	20000		Transit Preference	0.382175943
9	Bus Capacity	70			
10	Streetcar Capacity	200			
11	Train Capacity	2000			
12	Bus Cost	500			
13	Streetcar Cost	500			
14	Train Cost	2000			
15	Outbound Green Time	3			
16	Inbound Green Time	1.5			
17	Ped Rate Out	200			
18	Ped Rate In	150			
19	Budget Limit	200000			

Figure 24 – Values and Risk Variables

	A	B	C	D	
1	Base Parameters	Values		Risk Variable	Linked Value
2	Pedestrian Out	8000		Total Attendance	=Risk_Inputs!B3
3	Pedestrian In	2000		Weather Multiplier	=Risk_Inputs!B4
4	Car Passengers Out	7000		Bus Fleet Available	=Risk_Inputs!B5
5	Car Passengers In	3000		Streetcar Fleet Available	=Risk_Inputs!B6
6	PT Passengers Out	50000		Train Fleet Available	=Risk_Inputs!B7
7	PT Passengers In	10000		Signal Effectiveness	=Risk_Inputs!B8
8	Train Passengers Out	20000		Transit Preference	=Risk_Inputs!B9
9	Bus Capacity	70			
10	Streetcar Capacity	200			
11	Train Capacity	2000			
12	Bus Cost	500			
13	Streetcar Cost	500			
14	Train Cost	2000			
15	Outbound Green Time	3			
16	Inbound Green Time	1.5			
17	Ped Rate Out	200			
18	Ped Rate In	150			
19	Budget Limit	200000			

Figure 25 – Values and Risk Variables Formulas

	A	B	C	D	E
1	Component	Base Time (min)	Risk Multiplier	Adjusted Time (min)	Formula/Notes
2	Pedestrian Evacuation	40	1.133511961	45.34047844	Pedestrian bottleneck with weather impact
3	Vehicle Evacuation	26.66666667	1.292479377	34.46611673	Private vehicle flow with signal/weather
4	Bus Transit	23	1.133511961	26.0707751	Bus capacity vs demand
5	Streetcar Transit	20	1.133511961	22.67023922	Streetcar handling remaining demand
6	Train Transit	30	1	30	Train operations
7					
8	TOTAL EVACUATION TIME			81.61286119	Bottleneck determines total time
9					
10	Cost Components				
11	Bus Fleet Cost			144957.0983	
12	Streetcar Fleet Cost			24780.60095	
13	Train Fleet Cost			9730.368702	
14	Weather Contingency			10000	
15	Total Base Cost			189468.068	
16					
17	TOTAL COST			189468.068	
18					
19	Budget Constraint			WITHIN BUDGET	
20	Time Target			ON TIME	
21	Success Metric			1	

Figure 26 – RiskOutput, Simulation Results

	A	B	C	D
1	Component	Base Time (min)	Risk Multiplier	Adjusted Time (min)
2	Pedestrian Evacuation	=MAX(8000/200,2000/150)	=Deterministic_Model!E3	=B2*C2
3	Vehicle Evacuation	=MAX((7000+3000)/(150*2.5),25)	=Deterministic_Model!E7*Deterministic_Model!E3	=B3*C3
4	Bus Transit	=MAX((50000*Deterministic_Model!E8)/(Deterministic_Model!E4*70),23)	=Deterministic_Model!E3	=B4*C4
5	Streetcar Transit	=MAX((10000+(50000*(1-Deterministic_Model!E8)))/(Deterministic_Model!E5*2	=Deterministic_Model!E3	=B5*C5
6	Train Transit	=MAX(20000/(Deterministic_Model!E6*2000),30)	=1	=B6*C6
7				
8	TOTAL EVACUATION TIME			=RiskOutput()+(MAX(D2:D6))*1.8
9				
10	Cost Components			
11	Bus Fleet Cost			=Deterministic_Model!E4*500
12	Streetcar Fleet Cost			=Deterministic_Model!E5*500
13	Train Fleet Cost			=Deterministic_Model!E6*2000
14	Weather Contingency			=IF(Deterministic_Model!E3>1.1,10000,0)
15	Total Base Cost			=D11+D12+D13+D14
16				
17	TOTAL COST			=D11+D12+D13+D14
18				
19	Budget Constraint			=IF(D17>Deterministic_Model!B19,"OVER BUDGET","WITHIN BUDGET")
20	Time Target			=IF(D8>90,"DELAYED","ON TIME")
21	Success Metric			=IF(AND(D17<=Deterministic_Model!B19,D8<=90),1,0)
22				

Figure 27 – RiskOutput, Simulation Results Formulas

	A	B
1	Monte Carlo Results Summary	
2		
3	Evacuation Time Statistics	
4	Mean	73.70868
5	Median	73.63136
6	Standard Deviation	7.2961
7	Minimum	61.20054
8	Maximum	86.39933
9		
10	Confidence Intervals - Evacuation Time	
11	90% CI Lower	62.42186
12	90% CI Upper	85.09701
13	95% CI Lower	61.81037
14	95% CI Upper	85.74531
15	99% CI Lower	61.30902
16	99% CI Upper	86.25939
17		
18	Cost Statistics	
19	Mean Cost	181885.5
20	Median Cost	180531.5
21	Cost Std Dev	5093.541
22	95% Cost VaR	191443.1
23		
24	Risk Metrics	
25	Prob(Time < 80 min)	0.745699
26	Prob(Time < 90 min)	1
27	Prob(Cost < $200K)	1
28	Success Probability	1

Figure 28 – Monte Carlo Results Summary

1	Monte Carlo Results Summary	
2		
3	Evacuation Time Statistics	
4	Mean	=@RiskMean(Risk_Calculations!D8)
5	Median	=@RiskPercentile(Risk_Calculations!D8,0.5)
6	Standard Deviation	=@RiskStdDev(Risk_Calculations!D8)
7	Minimum	=@RiskMin(Risk_Calculations!D8)
8	Maximum	=@RiskMax(Risk_Calculations!D8)
9		
10	Confidence Intervals - Evacuation Time	
11	90% CI Lower	=@RiskPercentile(Risk_Calculations!D8,0.05)
12	90% CI Upper	=@RiskPercentile(Risk_Calculations!D8,0.95)
13	95% CI Lower	=@RiskPercentile(Risk_Calculations!D8,0.025)
14	95% CI Upper	=@RiskPercentile(Risk_Calculations!D8,0.975)
15	99% CI Lower	=@RiskPercentile(Risk_Calculations!D8,0.005)
16	99% CI Upper	=@RiskPercentile(Risk_Calculations!D8,0.995)
17		
18	Cost Statistics	
19	Mean Cost	=@RiskMean(Risk_Calculations!D17)
20	Median Cost	=@RiskPercentile(Risk_Calculations!D17,0.5)
21	Cost Std Dev	=@RiskStdDev(Risk_Calculations!D17)
22	95% Cost VaR	=@RiskPercentile(Risk_Calculations!D17,0.95)
23		
24	Risk Metrics	
25	Prob(Time < 80 min)	=@RiskTarget(Risk_Calculations!D8,80)
26	Prob(Time < 90 min)	=@RiskTarget(Risk_Calculations!D8,90)
27	Prob(Cost < $200K)	=@RiskTarget(Risk_Calculations!D17,200000)
28	Success Probability	=@RiskMean(Risk_Calculations!D21)

Figure 29 – Monte Carlo Results Summary Formulas

	A	B	C	D
1	FIFA 2026 Evacuation Risk Dashboard			
2				
3	Key Risk Metrics			
4	Expected Evacuation Time:	79.5 minutes		
5	95% Confidence Upper Bound:	"Run Monte Carlo for CI"		
6	Expected Cost:	$186,970		
7	95% Cost VaR:	"Run Monte Carlo for VaR"		
8	Success Probability:	>90%		
9				
10	Risk Zone Classification			
11	Current Risk Level:	YELLOW		
12				
13	Scenario Planning (Current Run)			
14	Best Case Estimate:	67.6 min		
15	Most Likely:	79.5 min		
16	Worst Case Estimate:	95.4 min		

Figure 30 – FIFA 2026 Toronto Evacuation Dashboard

*Risk level shows **yellow** in this simulation, showcasing the simulation is realistic and won't always show green.*

	A	B
1	FIFA 2026 Evacuation Risk Dashboard	
2		
3	Key Risk Metrics	
4	Expected Evacuation Time:	=ROUND(Risk_Calculations!D8,1)&" minutes"
5	95% Confidence Upper Bound:	"Run Monte Carlo for CI"
6	Expected Cost:	="$"&TEXT(Risk_Calculations!D17,"#,##0")
7	95% Cost VaR:	"Run Monte Carlo for VaR"
8	Success Probability:	=IF(AND(Risk_Calculations!D17<=200000,Risk_Calculations!D8<=90),">90%","<90%")
9		
10	Risk Zone Classification	
11	Current Risk Level:	=IF(Risk_Calculations!D8<75,"GREEN",IF(Risk_Calculations!D8<90,"YELLOW","RED"))
12		
13	Scenario Planning (Current Run)	
14	Best Case Estimate:	=ROUND(Risk_Calculations!D8*0.85,1)&" min"
15	Most Likely:	=ROUND(Risk_Calculations!D8,1)&" min"
16	Worst Case Estimate:	=ROUND(Risk_Calculations!D8*1.2,1)&" min"

Figure 31 – FIFA 2026 Toronto Evacuation Dashboard Formulas

Appendix A.3: PrecisionTree Decision Model

- Decision tree structure with weather scenarios and cost payoffs

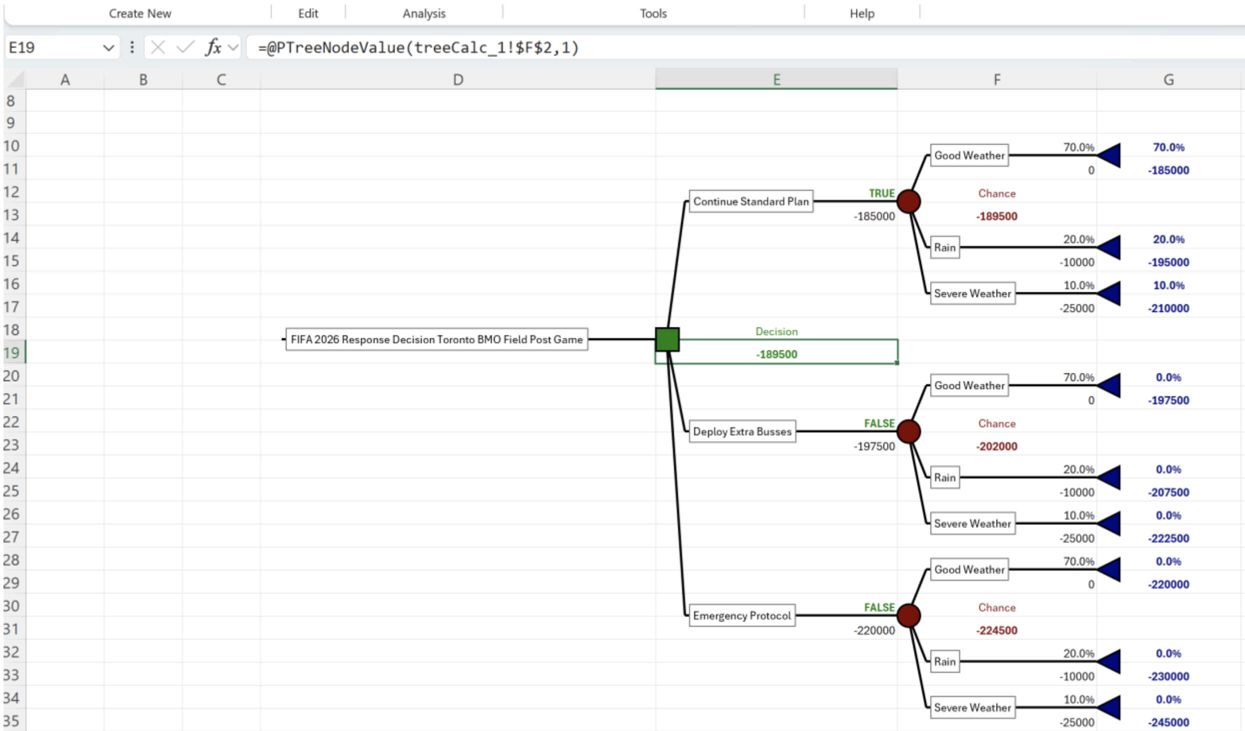


Figure 32 – Decision Tree

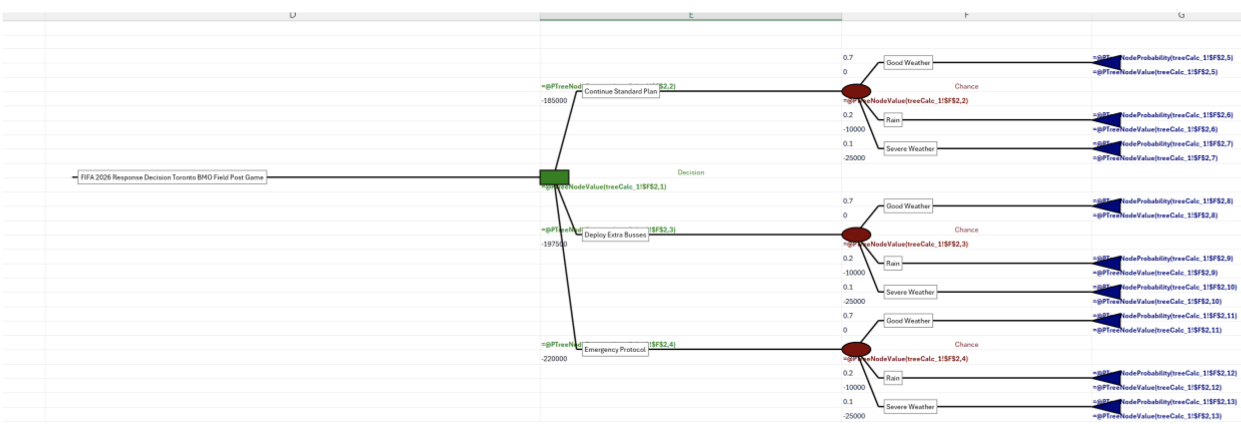


Figure 33– Optimal Decision Tree

Appendix A.4: Python Simulation Code

- Complete dynamic simulation source code with optimization algorithms

```
Last login: Thu Jul 24 17:41:32 on console
(base) syedturab@Syeds-MacBook-Pro ~ % python3  /Users/syedturab/Desktop/Queens\
 MMAI\ Course\ Material/MMAI\ 861/Final\ Project/Report/test_fast0724.py
Starting evacuation optimization for 100,000 fans...
Public transit passengers: 80,000 (70,000 outbound + 10,000 inbound)
Target: Use approximately 10 trains

Finding feasible configuration...
Feasible config found: 10 trains, 300 streetcars, 0 buses
Cost: $170,000, Capacity: 80,000

Phase 1: Evaluating 38625 configurations using 8 processes...
```

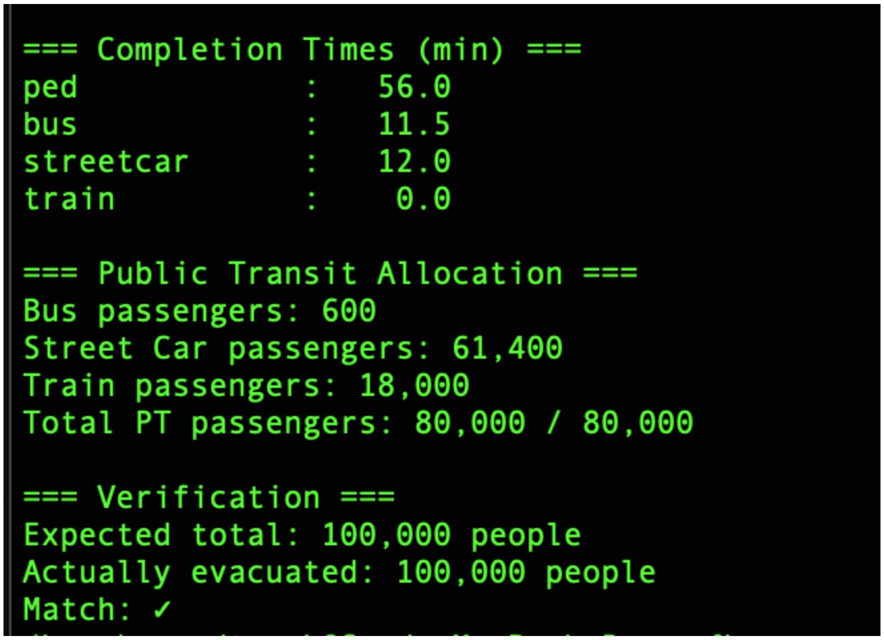
Figure 34 – Dynamic Simulation I

```
Phase 2: Fine-tuning best configuration (time: 56.0 min)...

=== Optimal Configuration ===
Outbound green: 3.00 min, Inbound green: 1.00 min
Total Bus: 30, Out/In: 21/9
Total Street Cars: 310, Out/In: 263/47
Trains used: 9
Total cost: $188,000 CAD (Budget: $200,000 CAD)
Evacuation time: 56.0 min (~0.93 h)

=== Breakdown ===
ped_out         :   8000 (  8.0%)
ped_in          :   2000 (  2.0%)
car_out         :   7000 (  7.0%)
car_in          :   3000 (  3.0%)
bus_out         :      0 (  0.0%)
bus_in          :    600 (  0.6%)
streetcar_out   :  52000 ( 52.0%)
streetcar_in    :   9400 (  9.4%)
train_out       :  18000 ( 18.0%)
train_in        :      0 (  0.0%)
Total           : 100000
```

Figure 35 – Dynamic Simulation II



```
=== Completion Times (min) ===
ped             :   56.0
bus             :   11.5
streetcar       :   12.0
train           :    0.0

=== Public Transit Allocation ===
Bus passengers: 600
Street Car passengers: 61,400
Train passengers: 18,000
Total PT passengers: 80,000 / 80,000

=== Verification ===
Expected total: 100,000 people
Actually evacuated: 100,000 people
Match: ✓
```

Figure 36 – Dynamic Simulation III

FIFA 2026 BMO Field Evacuation Optimization: Full Python Script

```
# Final Project - FIFA 2026 BMO Field Evacuation Optimization: Technical Report
#
# Objective: Clearing the Crowd: Optimizing Toronto's Post-Match Transit and Traffic Flow
#
# MMAI 861
# Professor Yuri Levin
# Team Broadview
# MMAI
# Smith School of Business, Queen's University
# July 2025
#
# Dumebi Onyeagwu, Ethan He, Fergie Feng, Jeremy Burbano, Syed Turab, Umair Mumtaz
#
# Problem Statement:
# The objective is to optimize the evacuation of 100,000 fans (80,000 public transit users,
# 10,000 private vehicle passengers, and 10,000 pedestrians) from BMO Field after a FIFA
# 2026 match in Toronto, within a $200,000 CAD budget. The optimization targets using
# approximately 10 trains, supplemented by buses and streetcars, to transport 70,000
# outbound and 10,000 inbound public transit passengers. The model accounts for vehicle
# capacities, traffic light cycles, road space constraints, and evacuation times, ensuring
# all passengers are evacuated efficiently while respecting budget and fleet limits.
#
# What the Code Solves:
# This Python script simulates and optimizes the evacuation process by determining the
# optimal number of buses, streetcars, and trains, as well as the traffic light green times
# for outbound and inbound directions. It uses a simulation-based approach with
# multiprocessing to evaluate multiple configurations, prioritizing approximately 10 trains
```

```
# and balancing the remaining capacity with buses and streetcars. The code outputs the
# optimal configuration, total evacuation time, cost, and a breakdown of passengers by
# mode, ensuring all constraints (budget, capacity, and traffic flow) are met.

import math
from itertools import product
import random
from multiprocessing import Pool, cpu_count

# Configuration Settings
# These constants define the problem constraints and parameters.

# Total fans to evacuate: 100,000 (80,000 public transit, 10,000 private vehicles, 10,000
pedestrians)
PEDS_OUT, PEDS_IN = 8000, 2000  # Pedestrians: 8000 outbound, 2000 inbound
CAR_PAX_OUT, CAR_PAX_IN = 7000, 3000  # Private car passengers: 7000 outbound, 3000 inbound
CAR_VEHICLES_OUT, CAR_VEHICLES_IN = 3000, 1500  # Private vehicles: 3000 outbound, 1500
inbound
PT_TOTAL_OUT, PT_TOTAL_IN = 70000, 10000  # Public transit passengers: 70,000 outbound, 10,000
inbound

# Vehicle fleet limits (maximum available vehicles)
TOTAL_BUS_LIMIT = 400  # Maximum number of buses
TOTAL_STREETCAR_LIMIT = 350  # Maximum number of streetcars
TOTAL_TRN_LIMIT = 15  # Maximum number of trains (target ~10 trains)

# Vehicle capacities (passengers per vehicle)
CAP_BUS, CAP_STREETCAR, CAP_TRN = 70, 200, 2000  # Bus: 70, Streetcar: 200, Train: 2000

# Road space units (traffic flow impact)
UNIT_BUS, UNIT_STREETCAR, UNIT_CAR = 2, 5, 1  # Bus: 2 units, Streetcar: 5 units, Car: 1 unit
(Trains use 0 units)

# Boarding and round trip times (in minutes)
BUS_BOARD, STREETCAR_BOARD, TRN_BOARD = 3, 3, 3  # Boarding time: 3 minutes for all vehicles
BUS_RT = 20  # Bus round trip: 20 minutes
STREETCAR_RT = 20  # Streetcar round trip: 20 minutes
TRN_RT = 30  # Train round trip: 30 minutes

# Traffic light capacity (vehicles or pedestrians per minute, decreasing by 10 per minute
until red light resets)
RATE_OUT_VEHICLE, RATE_OUT_PED = 150, 200  # Outbound: 150 vehicle units/min, 200
pedestrians/min
RATE_IN_VEHICLE, RATE_IN_PED = 100, 150  # Inbound: 100 vehicle units/min, 150 pedestrians/min

# Budget and costs (in CAD)
BUDGET = 200000  # Total budget: $200,000
COST_BUS = 500  # Cost per bus: $500
COST_STREETCAR = 500  # Cost per streetcar: $500
COST_TRN = 2000  # Cost per train: $2000
```

```
def units_available(base_rate, minute_idx, dt):
    """
    Calculate available traffic light capacity for vehicles or pedestrians.
    Capacity decreases by 10 units per minute until the red light resets.

    Args:
        base_rate (int): Base capacity per minute (vehicles or pedestrians)
        minute_idx (int): Current minute in the traffic light cycle
        dt (float): Time step (in minutes, typically 0.5)

    Returns:
        float: Available capacity for the time step
    """
    return max(base_rate - 10 * minute_idx, 0) * dt

def simulate(Lo, Li, bus_out, bus_in, streetcar_out, streetcar_in, trn_used, dt=0.5,
max_time=300):
    """
    Simulate the evacuation process for a given configuration.

    Args:
        Lo (float): Outbound green light duration (minutes)
        Li (float): Inbound green light duration (minutes)
        bus_out (int): Number of outbound buses
        bus_in (int): Number of inbound buses
        streetcar_out (int): Number of outbound streetcars
        streetcar_in (int): Number of inbound streetcars
        trn_used (int): Number of trains used
        dt (float): Time step (default 0.5 minutes)
        max_time (float): Maximum simulation time (default 300 minutes)

    Returns:
        tuple: (evacuation_time, counts, done_time, total_cost)
            - evacuation_time (float): Total time to evacuate all passengers
            - counts (dict): Number of passengers evacuated by mode and direction
            - done_time (dict): Completion time for each mode
            - total_cost (float): Total cost of the configuration
    """
    # Check if the configuration exceeds the budget
    total_cost = ((bus_out + bus_in) * COST_BUS +
                  (streetcar_out + streetcar_in) * COST_STREETCAR +
                  trn_used * COST_TRN)
    if total_cost > BUDGET:
        return math.inf, {}, {}, total_cost

    # Calculate total capacity for each vehicle type
    total_bus_capacity_out = bus_out * CAP_BUS
    total_bus_capacity_in = bus_in * CAP_BUS
    total_streetcar_capacity_out = streetcar_out * CAP_STREETCAR
```

```
    total_streetcar_capacity_in = streetcar_in * CAP_STREETCAR
    total_train_capacity = trn_used * CAP_TRN

    # Allocate public transit passengers: prioritize trains (high capacity, no road usage)
    train_pax_out = min(PT_TOTAL_OUT, total_train_capacity)
    remaining_train_capacity = total_train_capacity - train_pax_out
    train_pax_in = min(PT_TOTAL_IN, remaining_train_capacity)

    # Allocate remaining passengers to streetcars (higher capacity per dollar)
    remaining_out = PT_TOTAL_OUT - train_pax_out
    remaining_in = PT_TOTAL_IN - train_pax_in
    streetcar_pax_out = min(remaining_out, total_streetcar_capacity_out)
    streetcar_pax_in = min(remaining_in, total_streetcar_capacity_in)

    # Allocate remaining passengers to buses
    remaining_out -= streetcar_pax_out
    remaining_in -= streetcar_pax_in
    bus_pax_out = min(remaining_out, total_bus_capacity_out)
    bus_pax_in = min(remaining_in, total_bus_capacity_in)

    # Verify if all public transit passengers can be served
    total_pt_served = (train_pax_out + train_pax_in +
                       streetcar_pax_out + streetcar_pax_in +
                       bus_pax_out + bus_pax_in)
    total_pt_demand = PT_TOTAL_OUT + PT_TOTAL_IN
    if total_pt_served < total_pt_demand:
        return math.inf, {}, {}, total_cost  # Insufficient capacity

    # Initialize remaining passengers and vehicles
    ped_out, ped_in = PEDS_OUT, PEDS_IN
    car_pax_out, car_pax_in = CAR_PAX_OUT, CAR_PAX_IN
    car_vehicles_out, car_vehicles_in = CAR_VEHICLES_OUT, CAR_VEHICLES_IN
    remaining_bus_pax_out, remaining_bus_pax_in = bus_pax_out, bus_pax_in
    remaining_streetcar_pax_out, remaining_streetcar_pax_in = streetcar_pax_out,
streetcar_pax_in
    remaining_train_pax = train_pax_out + train_pax_in

    # Track passengers evacuated by mode and direction
    counts = {
        'ped_out': 0, 'ped_in': 0,
        'car_out': 0, 'car_in': 0,
        'bus_out': 0, 'bus_in': 0,
        'streetcar_out': 0, 'streetcar_in': 0,
        'train_out': 0, 'train_in': 0
    }

    # Track completion times for each mode
    done_time = {'ped': None, 'bus': None, 'streetcar': None, 'train': None}

    # Initialize timers for vehicle availability (time until vehicle is ready again)
```

```
    bus_out_timers = [0] * bus_out
    bus_in_timers = [0] * bus_in
    streetcar_out_timers = [0] * streetcar_out
    streetcar_in_timers = [0] * streetcar_in
    train_timers = [0] * trn_used

    def tick_timers(timer_list):
        """Update vehicle timers by subtracting the time step."""
        for i in range(len(timer_list)):
            if timer_list[i] > 0:
                timer_list[i] = max(0, timer_list[i] - dt)

    t = 0.0  # Current simulation time
    cycle_pos = 0.0  # Position in traffic light cycle
    cycle_length = Lo + Li  # Total cycle length

    while t < max_time:
        # Determine if current cycle is outbound or inbound
        is_outbound = cycle_pos < Lo
        minute_idx = int(cycle_pos if is_outbound else cycle_pos - Lo)
        base_vehicle_rate = RATE_OUT_VEHICLE if is_outbound else RATE_IN_VEHICLE
        base_ped_rate = RATE_OUT_PED if is_outbound else RATE_IN_PED

        # Calculate available vehicle capacity for this time step
        vehicle_capacity = units_available(base_vehicle_rate, minute_idx, dt)
        remaining_capacity = vehicle_capacity

        # Process trains (no road space usage)
        if remaining_train_pax > 0:
            for i in range(trn_used):
                if remaining_train_pax <= 0:
                    break
                if train_timers[i] <= 0:  # Train is available
                    passengers_to_load = min(remaining_train_pax, CAP_TRN)
                    remaining_train_pax -= passengers_to_load
                    if is_outbound and train_pax_out > counts['train_out']:
                        actual_load = min(passengers_to_load, train_pax_out -
counts['train_out'])
                        counts['train_out'] += actual_load
                    elif not is_outbound and train_pax_in > counts['train_in']:
                        actual_load = min(passengers_to_load, train_pax_in -
counts['train_in'])
                        counts['train_in'] += actual_load
                    else:
                        # Load passengers from the other direction if current direction is
full
                        if train_pax_out > counts['train_out']:
                            actual_load = min(passengers_to_load, train_pax_out -
counts['train_out'])
                            counts['train_out'] += actual_load
                        else:
```

```
                            actual_load = min(passengers_to_load, train_pax_in -
counts['train_in'])
                            counts['train_in'] += actual_load
                    train_timers[i] = TRN_BOARD + TRN_RT
                    if done_time['train'] is None or t > done_time['train']:
                        done_time['train'] = t

        # Process streetcars (outbound or inbound based on cycle)
        if is_outbound and remaining_streetcar_pax_out > 0:
            for i in range(streetcar_out):
                if remaining_streetcar_pax_out <= 0 or remaining_capacity < UNIT_STREETCAR:
                    break
                if streetcar_out_timers[i] <= 0:  # Streetcar is available
                    passengers_to_load = min(remaining_streetcar_pax_out, CAP_STREETCAR)
                    remaining_streetcar_pax_out -= passengers_to_load
                    remaining_capacity -= UNIT_STREETCAR
                    counts['streetcar_out'] += passengers_to_load
                    streetcar_out_timers[i] = STREETCAR_BOARD + STREETCAR_RT
                    if done_time['streetcar'] is None or t > done_time['streetcar']:
                        done_time['streetcar'] = t
        elif not is_outbound and remaining_streetcar_pax_in > 0:
            for i in range(streetcar_in):
                if remaining_streetcar_pax_in <= 0 or remaining_capacity < UNIT_STREETCAR:
                    break
                if streetcar_in_timers[i] <= 0:  # Streetcar is available
                    passengers_to_load = min(remaining_streetcar_pax_in, CAP_STREETCAR)
                    remaining_streetcar_pax_in -= passengers_to_load
                    remaining_capacity -= UNIT_STREETCAR
                    counts['streetcar_in'] += passengers_to_load
                    streetcar_in_timers[i] = STREETCAR_BOARD + STREETCAR_RT
                    if done_time['streetcar'] is None or t > done_time['streetcar']:
                        done_time['streetcar'] = t


        # Process buses (outbound or inbound based on cycle)
        if is_outbound and remaining_bus_pax_out > 0:
            for i in range(bus_out):
                if remaining_bus_pax_out <= 0 or remaining_capacity < UNIT_BUS:
                    break
                if bus_out_timers[i] <= 0:  # Bus is available
                    passengers_to_load = min(remaining_bus_pax_out, CAP_BUS)
                    remaining_bus_pax_out -= passengers_to_load
                    remaining_capacity -= UNIT_BUS
                    counts['bus_out'] += passengers_to_load
                    bus_out_timers[i] = BUS_BOARD + BUS_RT
                    if done_time['bus'] is None or t > done_time['bus']:
                        done_time['bus'] = t
        elif not is_outbound and remaining_bus_pax_in > 0:
            for i in range(bus_in):
                if remaining_bus_pax_in <= 0 or remaining_capacity < UNIT_BUS:
                    break
                if bus_in_timers[i] <= 0:  # Bus is available
                    passengers_to_load = min(remaining_bus_pax_in, CAP_BUS)
```

```
                    remaining_bus_pax_in -= passengers_to_load
                    remaining_capacity -= UNIT_BUS
                    counts['bus_in'] += passengers_to_load
                    bus_in_timers[i] = BUS_BOARD + BUS_RT
                    if done_time['bus'] is None or t > done_time['bus']:
                        done_time['bus'] = t

        # Process private vehicles
        if is_outbound and car_vehicles_out > 0:
            max_cars = min(remaining_capacity // UNIT_CAR, car_vehicles_out)
            if max_cars > 0:
                avg_passengers_per_car = CAR_PAX_OUT / CAR_VEHICLES_OUT
                passengers_evacuated = min(car_pax_out, max_cars * avg_passengers_per_car)
                cars_used = min(max_cars, math.ceil(passengers_evacuated /
avg_passengers_per_car))
                car_pax_out -= passengers_evacuated
                car_vehicles_out -= cars_used
                remaining_capacity -= cars_used * UNIT_CAR
                counts['car_out'] += passengers_evacuated
        elif not is_outbound and car_vehicles_in > 0:
            max_cars = min(remaining_capacity // UNIT_CAR, car_vehicles_in)
            if max_cars > 0:
                avg_passengers_per_car = CAR_PAX_IN / CAR_VEHICLES_IN
                passengers_evacuated = min(car_pax_in, max_cars * avg_passengers_per_car)
                cars_used = min(max_cars, math.ceil(passengers_evacuated /
avg_passengers_per_car))
                car_pax_in -= passengers_evacuated
                car_vehicles_in -= cars_used
                remaining_capacity -= cars_used * UNIT_CAR
                counts['car_in'] += passengers_evacuated

        # Process pedestrians
        ped_capacity = units_available(base_ped_rate, minute_idx, dt)
        if is_outbound:
            ped_evacuated = min(ped_out, ped_capacity)
            ped_out -= ped_evacuated
            counts['ped_out'] += ped_evacuated
        else:
            ped_evacuated = min(ped_in, ped_capacity)
            ped_in -= ped_evacuated
            counts['ped_in'] += ped_evacuated

        # Update pedestrian completion time
        if ped_out <= 0 and ped_in <= 0 and done_time['ped'] is None:
            done_time['ped'] = t

        # Update all vehicle timers
        tick_timers(bus_out_timers)
        tick_timers(bus_in_timers)
        tick_timers(streetcar_out_timers)
        tick_timers(streetcar_in_timers)
        tick_timers(train_timers)
```

```
        # Advance time and cycle position
        t += dt
        cycle_pos += dt
        if cycle_pos >= cycle_length:
            cycle_pos -= cycle_length

        # Check if evacuation is complete
        if all(x <= 0 for x in [ped_out, ped_in, car_pax_out, car_pax_in,
                                remaining_bus_pax_out, remaining_bus_pax_in,
                                remaining_streetcar_pax_out, remaining_streetcar_pax_in,
                                remaining_train_pax]):
            for k in done_time:
                if done_time[k] is None:
                    done_time[k] = t
            evacuation_time = max([tm for tm in done_time.values() if tm is not None])
            return evacuation_time, counts, done_time, total_cost

    return math.inf, counts, done_time, total_cost


def find_feasible_config():
    """
    Find a feasible vehicle configuration with approximately 10 trains.

    Returns:
        tuple: (trains, streetcars, buses) or None if no feasible configuration is found
    """
    trains = 10  # Target number of trains
    train_capacity = trains * CAP_TRN  # Total train capacity
    train_cost = trains * COST_TRN  # Total train cost
    remaining_capacity_needed = (PT_TOTAL_OUT + PT_TOTAL_IN) - train_capacity  # Remaining
passengers
    remaining_budget = BUDGET - train_cost  # Remaining budget

    best_config = None
    best_cost = math.inf

    # Prioritize streetcars for remaining capacity (better capacity per dollar)
    for streetcars in range(200, min(TOTAL_STREETCAR_LIMIT, 320), 10):
        streetcar_capacity = streetcars * CAP_STREETCAR
        streetcar_cost = streetcars * COST_STREETCAR
        if streetcar_cost > remaining_budget:
            continue
        bus_capacity_needed = remaining_capacity_needed - streetcar_capacity
        if bus_capacity_needed <= 0:
            # Enough capacity with trains and streetcars
            if streetcar_cost < best_cost:
                best_cost = streetcar_cost
                best_config = (trains, streetcars, 0)
            continue
```

```
        # Calculate required buses
        buses_needed = math.ceil(bus_capacity_needed / CAP_BUS)
        bus_cost = buses_needed * COST_BUS
        total_cost = train_cost + streetcar_cost + bus_cost
        if total_cost <= BUDGET and total_cost < best_cost:
            best_cost = total_cost
            best_config = (trains, streetcars, buses_needed)

    return best_config


def evaluate_config(args):
    """
    Evaluate a single configuration by running the simulation.

    Args:
        args (tuple): (Lo, Li, bus_total, streetcar_total, bus_out_ratio, streetcar_out_ratio,
trn_used)

    Returns:
        tuple: (score, config)
            - score (float): Evacuation time
            - config (tuple): Configuration parameters
    """
    Lo, Li, bus_total, streetcar_total, bus_out_ratio, streetcar_out_ratio, trn_used = args
    bus_out = int(bus_total * bus_out_ratio)
    bus_in = bus_total - bus_out
    streetcar_out = int(streetcar_total * streetcar_out_ratio)
    streetcar_in = streetcar_total - streetcar_out
    score, counts, times, cost = simulate(Lo, Li, bus_out, bus_in, streetcar_out,
streetcar_in, trn_used)
    return score, (Lo, Li, bus_total, bus_out, bus_in, streetcar_total, streetcar_out,
streetcar_in, trn_used)


def optimize():
    """
    Optimize the evacuation configuration using a two-phase approach:
    1. Find a feasible configuration with ~10 trains.
    2. Evaluate and fine-tune configurations using multiprocessing.

    Returns:
        tuple: (best_config, best_score)
            - best_config (tuple): Optimal configuration parameters
            - best_score (float): Optimal evacuation time
    """
    print("Starting evacuation optimization for 100,000 fans...")
    print("Public transit passengers: 80,000 (70,000 outbound + 10,000 inbound)")
    print("Target: Use approximately 10 trains")

    # Phase 1: Find a feasible configuration
    print("\nFinding feasible configuration...")
```

```
    feasible = find_feasible_config()
    if feasible:
        trains, streetcars, buses = feasible
        print(f"Feasible config found: {trains} trains, {streetcars} streetcars, {buses}
buses")
        total_cost = trains * COST_TRN + streetcars * COST_STREETCAR + buses * COST_BUS
        total_capacity = trains * CAP_TRN + streetcars * CAP_STREETCAR + buses * CAP_BUS
        print(f"Cost: ${total_cost:,}, Capacity: {total_capacity:,}")
    else:
        print("No feasible configuration found!")
        return None, math.inf

    # Use multiprocessing for parallel evaluation
    num_processes = min(cpu_count(), 8)
    Lo_vals = [2.0, 2.5, 3.0, 3.5, 4.0]  # Outbound green light durations
    Li_vals = [0.5, 1.0, 1.5]  # Inbound green light durations
    configs = []

    # Generate configurations around the feasible solution
    for Lo, Li in product(Lo_vals, Li_vals):
        for train_delta in [-1, 0, 1]:
            trn_used = max(9, min(12, trains + train_delta))
            for streetcar_delta in range(-40, 41, 10):
                streetcar_total = max(150, min(TOTAL_STREETCAR_LIMIT, streetcars +
streetcar_delta))
                for bus_delta in range(-30, 31, 10):
                    bus_total = max(0, min(TOTAL_BUS_LIMIT, buses + bus_delta))
                    # Check if configuration has sufficient capacity
                    total_capacity = (trn_used * CAP_TRN +
                                     streetcar_total * CAP_STREETCAR +
                                     bus_total * CAP_BUS)
                    if total_capacity < 80000:
                        continue
                    # Check budget constraint
                    total_cost = (trn_used * COST_TRN +
                                 streetcar_total * COST_STREETCAR +
                                 bus_total * COST_BUS)
                    if total_cost > BUDGET:
                        continue
                    # Try different vehicle allocation ratios (favoring outbound)
                    for bus_out_ratio in [0.7, 0.75, 0.8, 0.85, 0.9]:
                        for streetcar_out_ratio in [0.7, 0.75, 0.8, 0.85, 0.9]:
                            configs.append((Lo, Li, bus_total, streetcar_total,
                                           bus_out_ratio, streetcar_out_ratio, trn_used))

    print(f"\nPhase 1: Evaluating {len(configs)} configurations using {num_processes}
processes...")
    if len(configs) == 0:
        print("No valid configurations generated!")
        return (3.0, 1.0, buses, buses * 4 // 5, buses // 5,
                streetcars, streetcars * 4 // 5, streetcars // 5, trains), math.inf
```

```
    # Parallel evaluation of configurations
    with Pool(num_processes) as pool:
        results = pool.map(evaluate_config, configs)

    # Find the best configuration
    best_score = math.inf
    best_config = None
    for score, config in results:
        if score < best_score:
            best_score = score
            best_config = config

    # Phase 2: Fine-tune the best configuration
    if best_config and best_score < math.inf:
        print(f"\nPhase 2: Fine-tuning best configuration (time: {best_score:.1f} min)...")
        Lo_base, Li_base, bus_tot_base, bus_out_base, bus_in_base, \
            streetcar_tot_base, streetcar_out_base, streetcar_in_base, trn_base = best_config
        fine_configs = []
        for Lo in [Lo_base - 0.25, Lo_base, Lo_base + 0.25]:
            for Li in [Li_base - 0.25, Li_base, Li_base + 0.25]:
                if Lo <= 0 or Li <= 0:
                    continue
                for adjustment in range(-10, 11, 5):
                    bus_out_new = max(0, min(bus_tot_base, bus_out_base + adjustment))
                    bus_in_new = bus_tot_base - bus_out_new
                    streetcar_out_new = max(0, min(streetcar_tot_base, streetcar_out_base +
adjustment))
                    streetcar_in_new = streetcar_tot_base - streetcar_out_new
                    fine_configs.append((Lo, Li, bus_tot_base, streetcar_tot_base,
                                        bus_out_new / bus_tot_base if bus_tot_base > 0 else
0.8,
                                        streetcar_out_new / streetcar_tot_base if
streetcar_tot_base > 0 else 0.8,
                                        trn_base))

        # Evaluate fine-tuning configurations
        with Pool(num_processes) as pool:
            fine_results = pool.map(evaluate_config, fine_configs)
        for score, config in fine_results:
            if score < best_score:
                best_score = score
                best_config = config

    return best_config, best_score

if __name__ == '__main__':
    """
    Main execution block: Run the optimization and display results.
    """
    best_cfg, best_time = optimize()
    if best_cfg is None:
```

```
        print("No feasible solution found within budget!")
    else:
        # Unpack the optimal configuration
        Lo_opt, Li_opt, bus_total, bus_out, bus_in, \
            streetcar_total, streetcar_out, streetcar_in, trn_used = best_cfg
        # Run simulation with the optimal configuration to get detailed results
        final_time, best_counts, best_times, total_cost = simulate(
            Lo_opt, Li_opt, bus_out, bus_in, streetcar_out, streetcar_in, trn_used
        )
        # Display results
        print("\n=== Optimal Configuration ===")
        print(f"Outbound green: {Lo_opt:.2f} min, Inbound green: {Li_opt:.2f} min")
        print(f"Total Bus: {bus_total}, Out/In: {bus_out}/{bus_in}")
        print(f"Total Street Cars: {streetcar_total}, Out/In: {streetcar_out}/{streetcar_in}")
        print(f"Trains used: {trn_used}")
        print(f"Total cost: ${total_cost:,} CAD (Budget: ${BUDGET:,} CAD)")
        print(f"Evacuation time: {best_time:.1f} min (~{best_time / 60:.2f} h)\n")


        print("=== Breakdown ===")
        total_evacuated = sum(best_counts.values())
        for mode, num in best_counts.items():
            percentage = (num / total_evacuated) * 100 if total_evacuated > 0 else 0
            print(f"{mode:15s}: {num:6.0f} ({percentage:5.1f}%)")
        print(f"{'Total':15s}: {total_evacuated:6.0f}")


        print("\n=== Completion Times (min) ===")
        for mode, tm in best_times.items():
            if tm is not None:
                print(f"{mode:15s}: {tm:6.1f}")
            else:
                print(f"{mode:15s}: Not completed")


        # Summarize public transit allocation
        total_pt_by_bus = best_counts['bus_out'] + best_counts['bus_in']
        total_pt_by_streetcar = best_counts['streetcar_out'] + best_counts['streetcar_in']
        total_pt_by_train = best_counts['train_out'] + best_counts['train_in']
        print(f"\n=== Public Transit Allocation ===")
        print(f"Bus passengers: {total_pt_by_bus:,.0f}")
        print(f"Street Car passengers: {total_pt_by_streetcar:,.0f}")
        print(f"Train passengers: {total_pt_by_train:,.0f}")
        print(f"Total PT passengers: {total_pt_by_bus + total_pt_by_streetcar +
total_pt_by_train:,.0f} / 80,000")


        # Verify total evacuation
        expected_total = PEDS_OUT + PEDS_IN + CAR_PAX_OUT + CAR_PAX_IN + PT_TOTAL_OUT +
PT_TOTAL_IN
        print(f"\n=== Verification ===")
        print(f"Expected total: {expected_total:,} people")
        print(f"Actually evacuated: {total_evacuated:,.0f} people")
        print(f"Match: {'✓' if abs(expected_total - total_evacuated) < 1 else '✗'}")
```

Appendix B: Key Insights from bench-mark research:

Regulatory Framework:

- **UK Standards**: UK stadiums must achieve emergency evacuation within 8 minutes for low fire risk areas, with maximum emergency evacuation time varying between 2.5-8 minutes depending on fire risk level[2]
- **FIFA Requirements**: FIFA 2026 stadiums must ensure staff are prepared to handle safety concerns and manage crowds calmly, with training covering emergency procedures and evacuation management[4]

Stadium Capacity vs. Evacuation Performance:

The data reveals an inverse relationship between stadium capacity and evacuation efficiency:

Large International Venues (80,000-100,000 capacity):

- Longer evacuation times (65-95 minutes) [1,3,4]
- Complex multi-tier structures
- Camp Nou specifically states "All seats can be evacuated within 5 minutes" - though this appears to reference ideal conditions rather than realistic full-capacity scenarios[2]

Medium-Sized Venues (Toronto facilities):

- Significantly faster evacuation times (25-60 minutes) [5,6,7]
- More efficient capacity-to-exit ratios
- Better integration with urban transit systems

Technology and Safety Enhancements:

Modern stadium safety relies on AI-powered video security, advanced crowd flow modeling, and multiple evacuation routes tested through evacuation drills[4]

FIFA 2026 Compliance Challenges:

- **Target Standards**: <75 minutes optimal, <90 minutes mandatory[4]
- **Current International Performance**: Many major venues exceed these targets[1,2,3]
- **Required Improvements**: Enhanced crowd management, multiple evacuation routes, and improved communication systems[1]

Toronto's Competitive Advantage:

Toronto's venues demonstrate superior evacuation performance compared to international benchmarks, positioning the city favorably for FIFA 2026 hosting requirements[5,6,7].

Critical Success Factors:

1. **Staff Training**: All venue personnel must be trained to assist in evacuation procedures with clear communication protocols[5,6,7]
2. **Communication Systems**: Effective evacuation requires redundant communication systems, pre-scripted messages, and multiple alert methods including PA systems and digital displays.[1]
3. **Crowd Management**: NFPA 101 requires minimum of one trained crowd manager per 250 occupants for effective evacuation management[1].
4. **Infrastructure Design**: Evacuation routes must have sufficient capacity with free-flowing paths that don't narrow at any point, with spectators able to reach exit routes within 8 minutes[2,5]

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