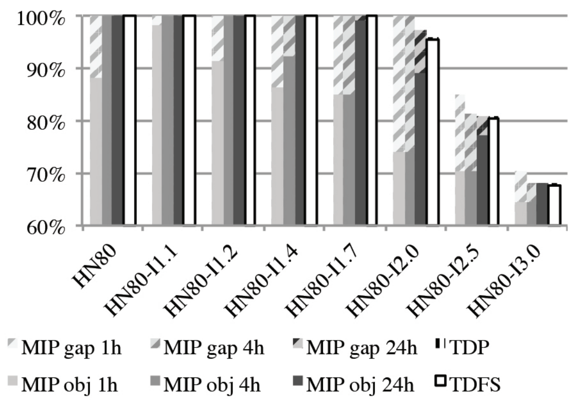


Figure 2: Primal Bounds as a Function of Solving Time.

| Instance | FF-CT | TDP-CT | | TDFS-CT | | |
|---|---|---|---|---|---|---|
| | CT (min) | CPU (s) | CT (min) | CPU (s) | CT (min) | Gap (min) |
| **HN80-I1.0** | 260 | 105 | 300 | 115 | 345 | 48 |
| **HN80-I1.1** | 280 | 30 | 330 | 39 | 375 | 48 |
| **HN80-I1.2** | 300 | 108 | 360 | 122 | 410 | 53 |
| **HN80-I1.4** | 340 | 30 | 420 | 47 | 470 | 54 |
| **HN80-I1.7** | 405 | 220 | 510 | 233 | 575 | 69 |
| **HN80-I2.0** | 465 | 35 | 595 | 63 | 645 | 50 |
| **HN80-I2.5** | 570 | 63 | 745 | 92 | 820 | 76 |
| **HN80-I3.0** | 670 | 120 | 895 | 171 | 935 | 43 |

Table 3: Clearance Time on the HN80-I Instances.

of about 90s is spent solving the TDP-CT model, and an average of about 20s is devoted to performing the dichotomic search to find the minimum clearance time.

### Benefits of Convergent Evacuation Plans

Figure 3 illustrates the benefits of convergent evacuation plans. The chart compares the clearance times of TDFS-CT with an instrumented mesoscopic simulation of the evacuation plans produced by the CPG algorithm (Pillac, Van Hentenryck, and Even 2014). CPG assigns a single evacuation path to every evacuation node but allows for divergent paths. The simulation instrumentation adds a delay at each fork for each vehicle, capturing the driver hesitation. The chart shows the effect of this delay on clearance times. The results show that TDFS-CT starts outperforming CPG for an average delay as small as 0.75s. The benefits of TDFS becomes substantial even for delays as small as 2s.

Figure 3: The Effect of Fork Delays on Clearance Times (HN80).

## Conclusion

This paper introduced the concept of convergent evacuation plans to produce fully controllable evacuations avoiding forks. Forks lead to congestions in practice as drivers slow down to consider the alternatives ahead of them. Additionally, the presence of forks makes it harder to guarantee that evacuees will actually follow the evacuation plan.

The paper formalized the Convergent Evacuation Planning Problem (CEPP) and presented a MIP model for finding a convergent evacuation plan maximizing the number of people evacuated. To remedy its scalability issues, the paper proposed a two-stage approach, separating the design of the convergent evacuation routes from the scheduling of evacuees along these routes. The first stage is a Tree Design Problem (TDP) which aggregates arc capacities over time and avoid discretizing time. The second stage is a flow scheduling problem (FDP) that chooses when to evacuate a residential area along a path. Optimal solutions to the TDP are upper bounds to the optimal solutions to the CEPP. The paper also presented results on minimizing the clearance times using a variant of the two-stage approach.

Experimental results on a real case study validate the benefits of the approach. In particular, they show that: (1) The TDP provides stronger dual bounds than the linear relaxation of the MIP model; (2) The two-stage approach provides high-quality solutions with average and worst-case optimality gaps of 0.2% and 0.7% in less than a minute of CPU Time. In contrast, the MIP model provides solutions with average and worst-case optimality gaps of 1.7% and 7.9% even with a time limit set to 24 hours; (3) The benefits of the two-stage approach materialize as soon as a delay of 0.75s is introduced at a fork when simulating the results of state-of-the-art evacuation planning tools on a mesoscopic simulator. The benefits become subtantial when the delay increases: The clearance time doubles when the delay is about 4s.

Future work will focus on extending the models to integrate contraflow decisions and lane separation, build accurate behavioral models of evacuees when responding to evacuation orders, and exploit these models inside the evacuation planning algorithms. Contraflows and lane separations would give more flexibility to the optimisation algorithm to exploit routes that would not be convergent otherwise. Finally, observe that our algorithms can be generalized to allow forks where the resulting increased capacity is beneficial regardless of the slowdown produced.

## Acknowledgments

NICTA is funded by the Australian Government through the Department of Communications and the Australian Research Council through the ICT Centre of Excellence Program.

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