Thesis Defense for the Degree of Master of Science

AN INTEGRATED BUS-BASED PROGRESSION SYSTEM FOR ARTERIALS HAVING HEAVY TRANSIT FLOWS

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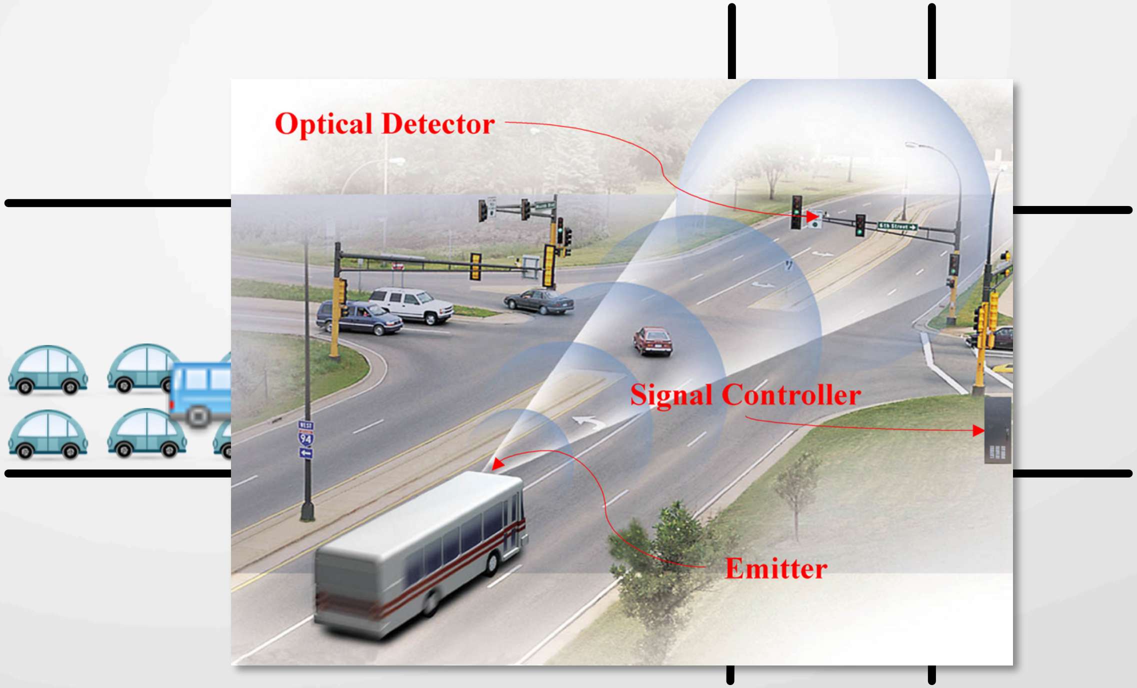
Transit Signal Priority (TSP)

- Transit system
- Active control strategies
- Bus-based progression
- Bus operational features



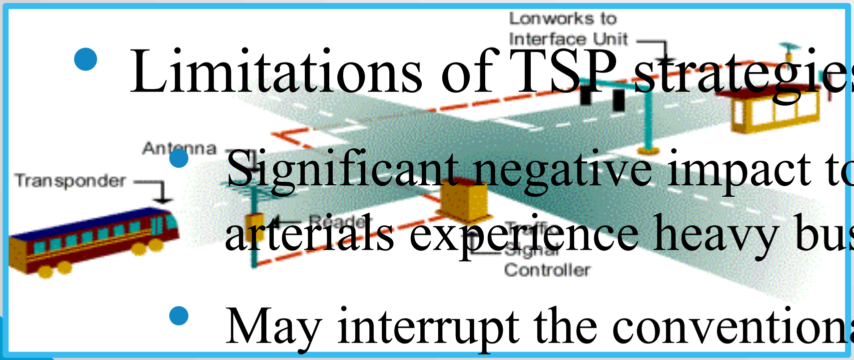
Source: Sustainable Transportation in the Netherlands

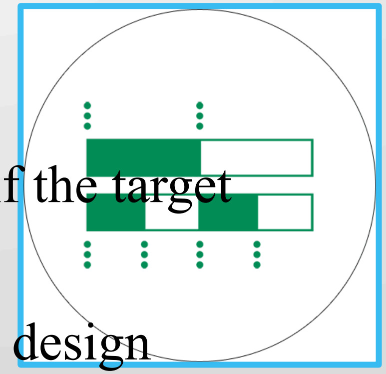
Outline

- Literature Review
- Problem Nature and Modelling Framework
- Methodology
- Case Study
- Conclusions and Future Study

Literature Review

- The concept of TSP has been developed since late 1960s (Smith, 1968).
  - Active strategies detect the arrival of buses and grant a priority to them. (Ludwick & John, 1974; Dion & Hesham, 2005)
  - Passive strategies do not recognize the presence of buses, but predetermine the signal timings to facilitate bus movements. (Urbanik, 1977)

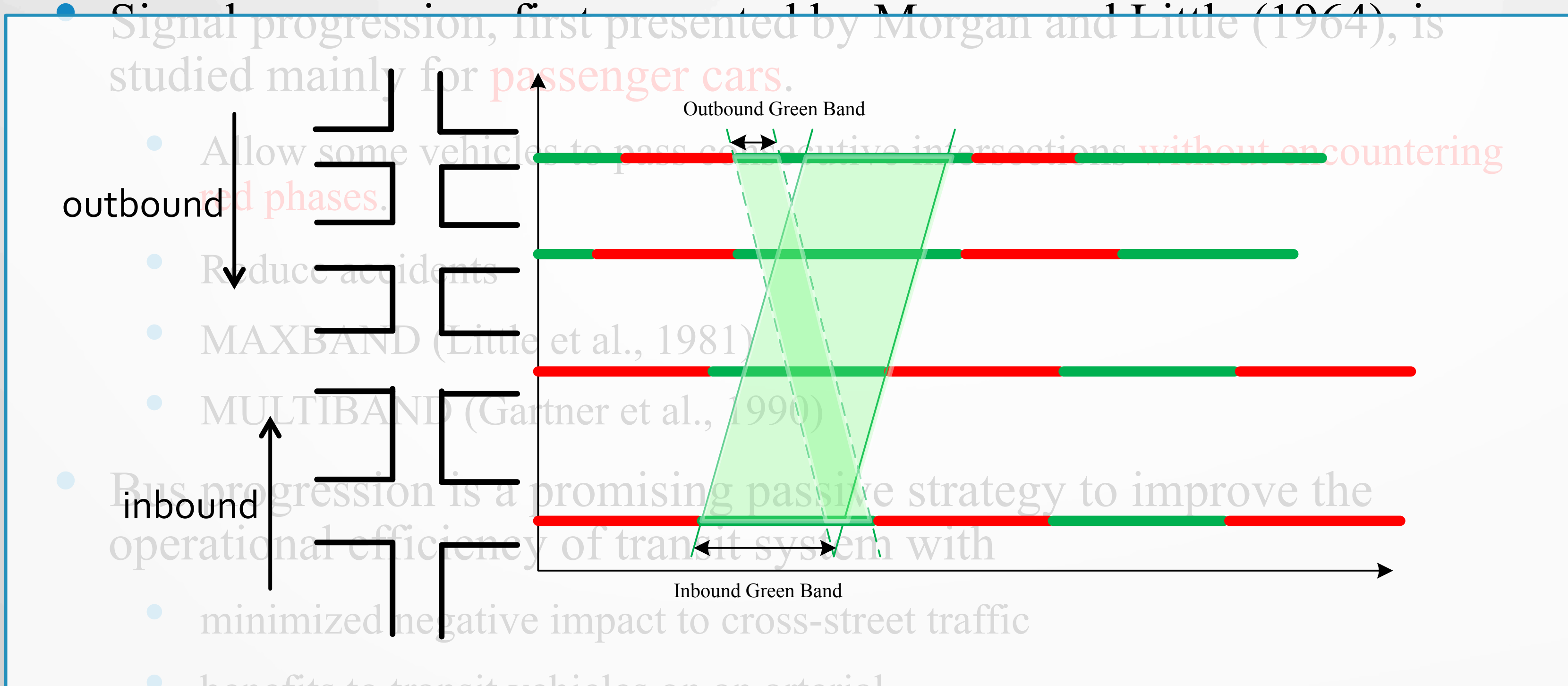




- Limitations of TSP strategies
  - Significant negative impact to cross-street traffic if the target arterials experience heavy bus volumes
  - May interrupt the conventional signal progression design

Literature Review

- Signal progression, first presented by Morgan and Little (1964), is studied mainly for passenger cars.
  - Allow some vehicles to pass consecutive intersections without encountering red phases.
  - Reduce accidents
  - MAXBAND (Little et al., 1981)
  - MULTIBAND (Gartner et al., 1990)
- Bus progression is a promising passive strategy to improve the operational efficiency of transit system with
  - minimized negative impact to cross-street traffic
  - benefits to transit vehicles on an arterial



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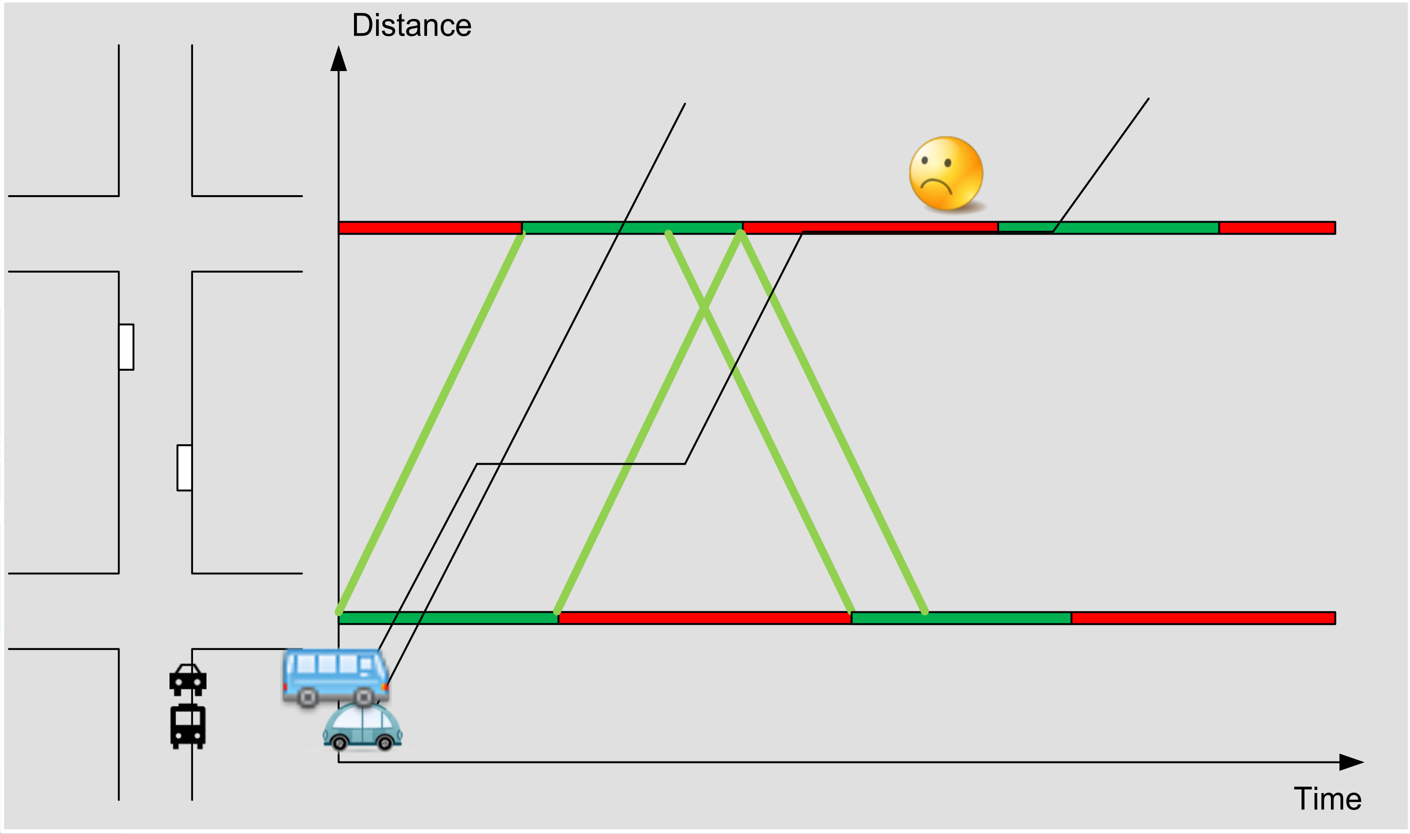
Critical issues

- Dwell time at bus stops
- Dwell time uncertainty
- Bus stop capacity
- Competition between buses and PCs

Critical issues

Dwell time at bus stop

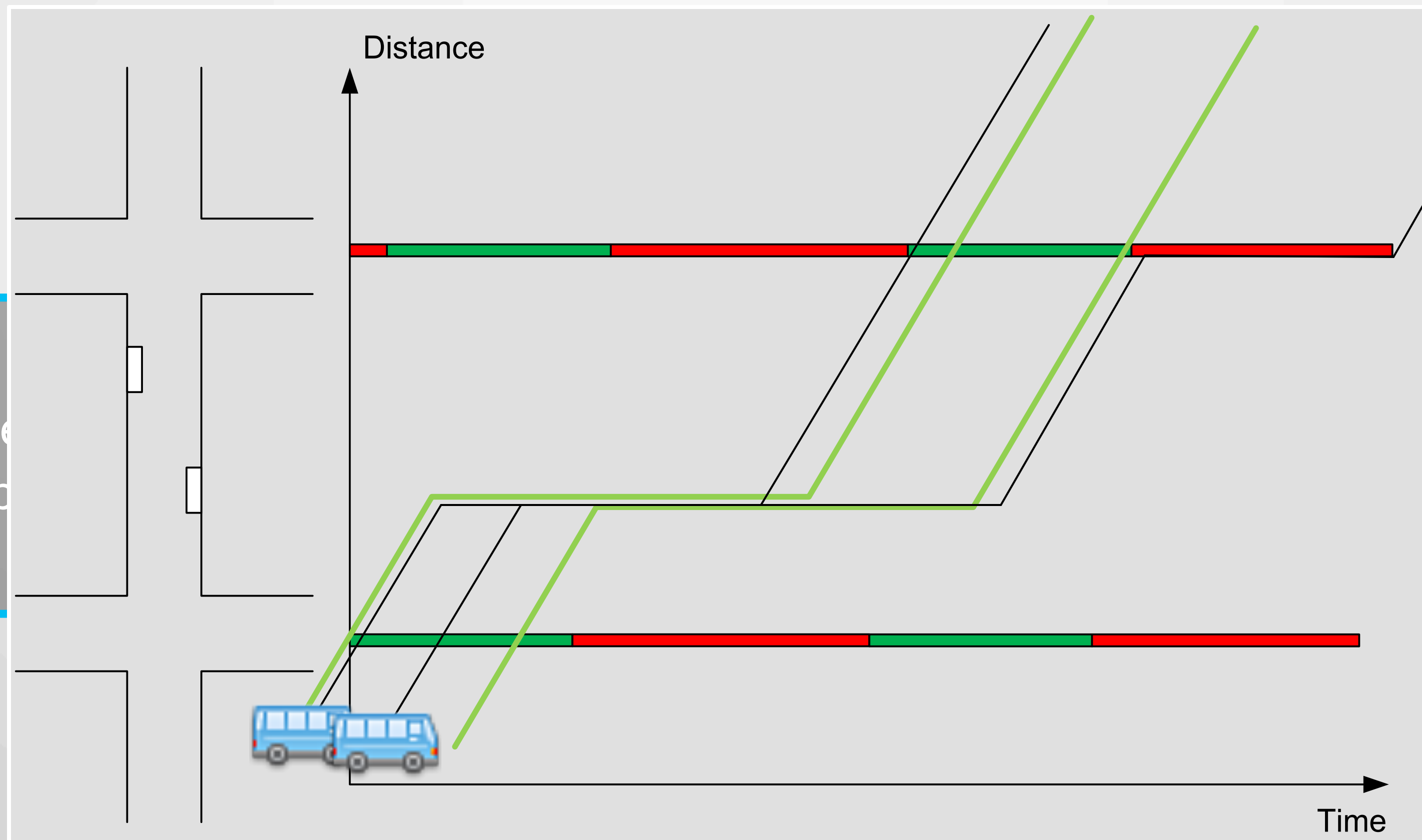


Transit vehicles, impacted by the dwell time at stops, may not stay in the green band designed for passenger cars.

Critical issues

Deterministic dwell time VS. Stochastic dwell time

Dwell tim
bus stop

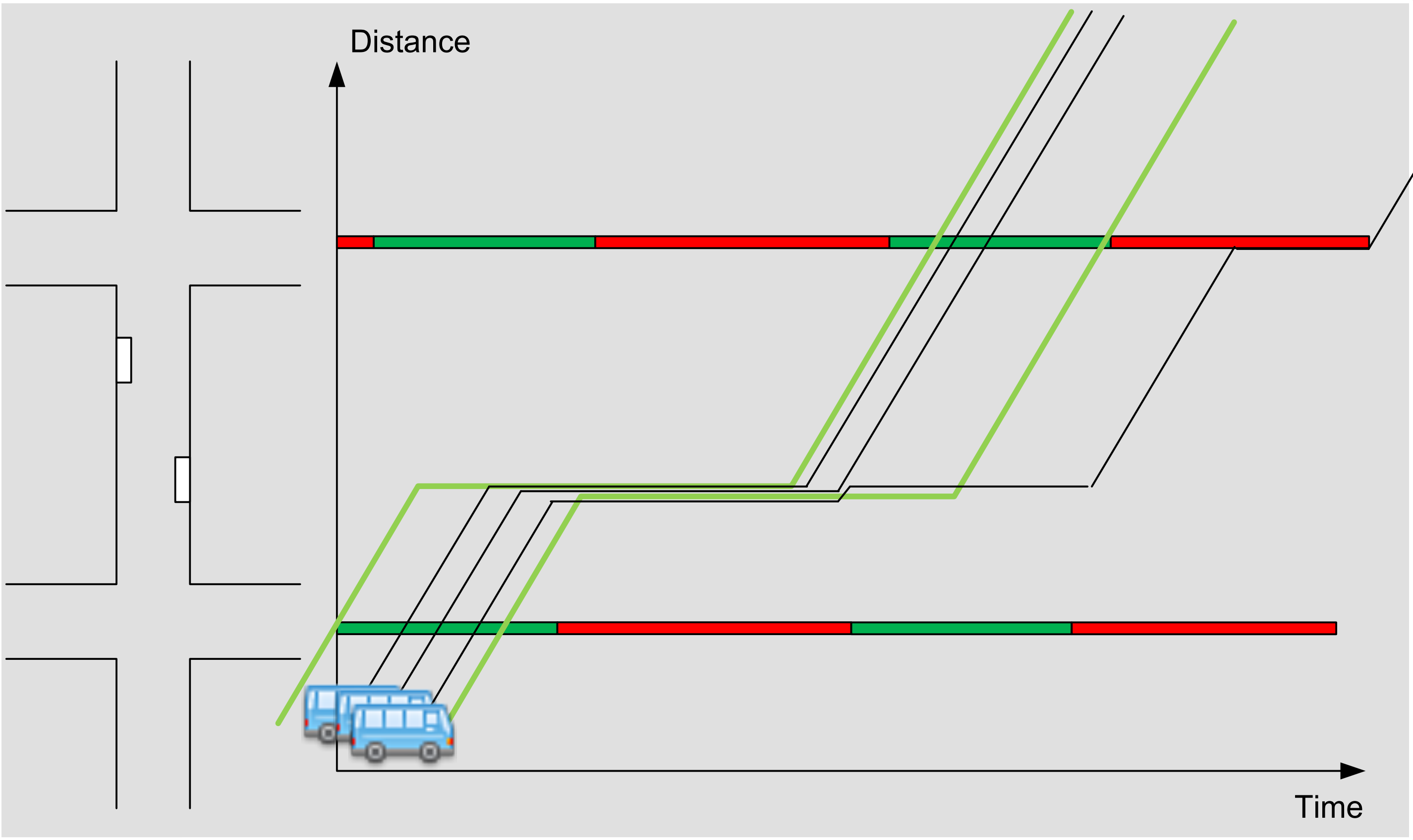


The stochastic nature of bus dwell time should be considered when studying bus progression.

Critical issues

Is the wider band always better?

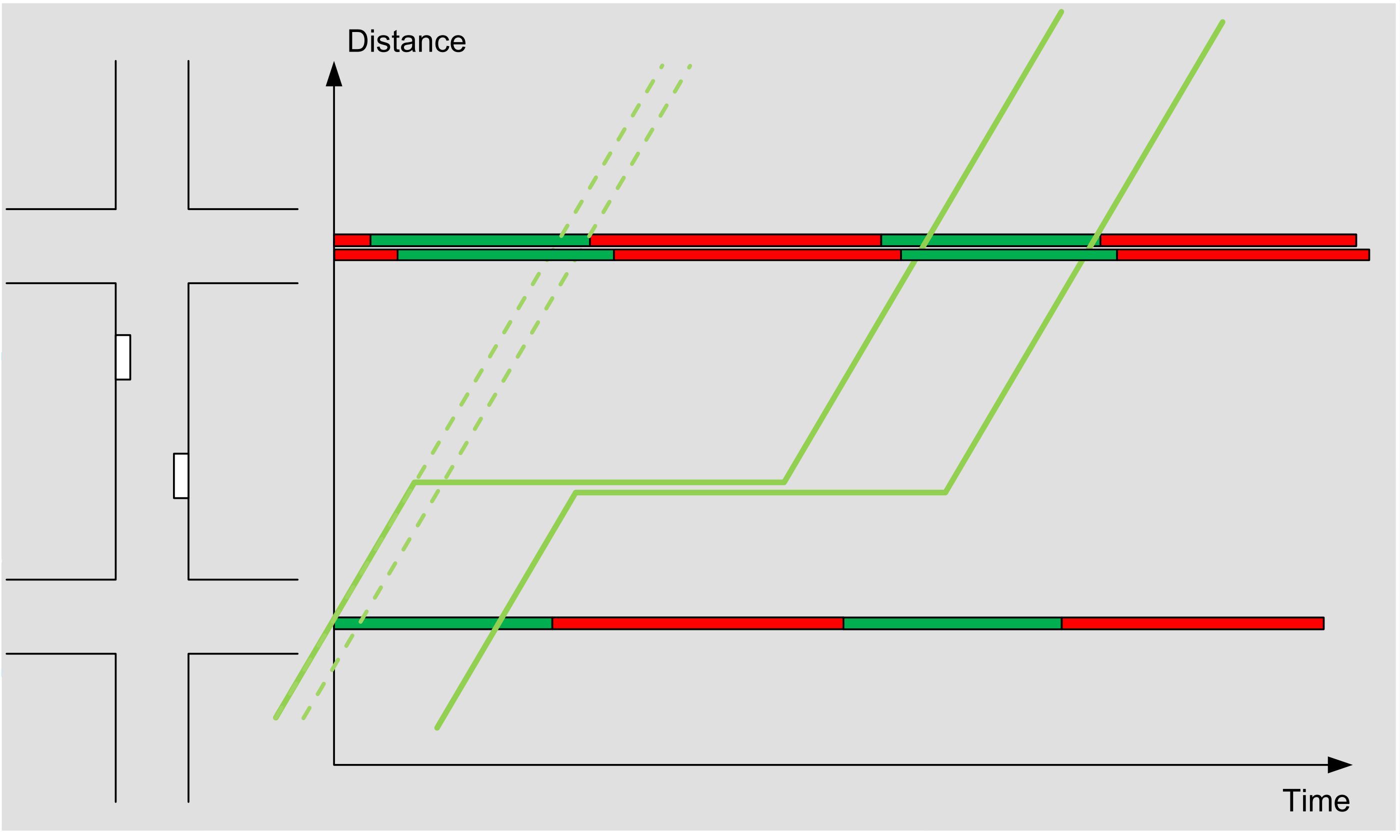
Dwell time bus stop



The number of buses in a band shall not exceed the capacity of the bus stop to prevent the formation of bus queues.

Critical issues

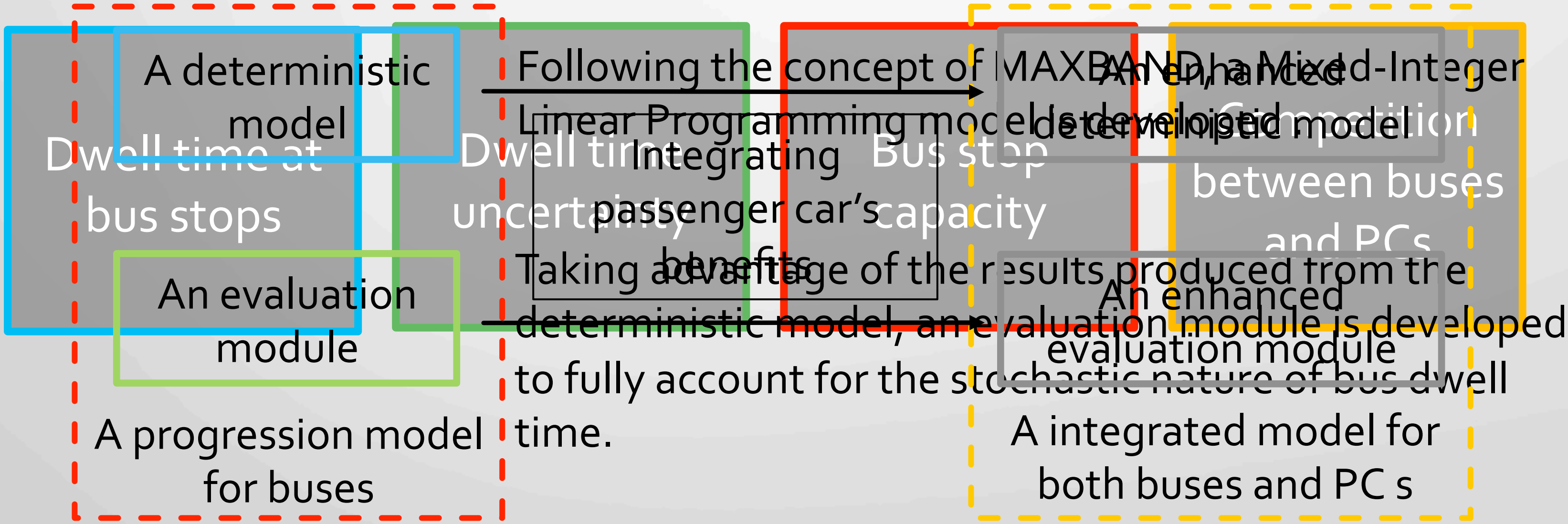
Dwell time
bus stops



The bus band and passenger-car band may need to be optimized concurrently.

Critical issues

Modelling Framework



Outline

- Literature Review
- Problem Nature and Modelling Framework
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- Case Study
- Conclusions and Future Study

A deterministic model

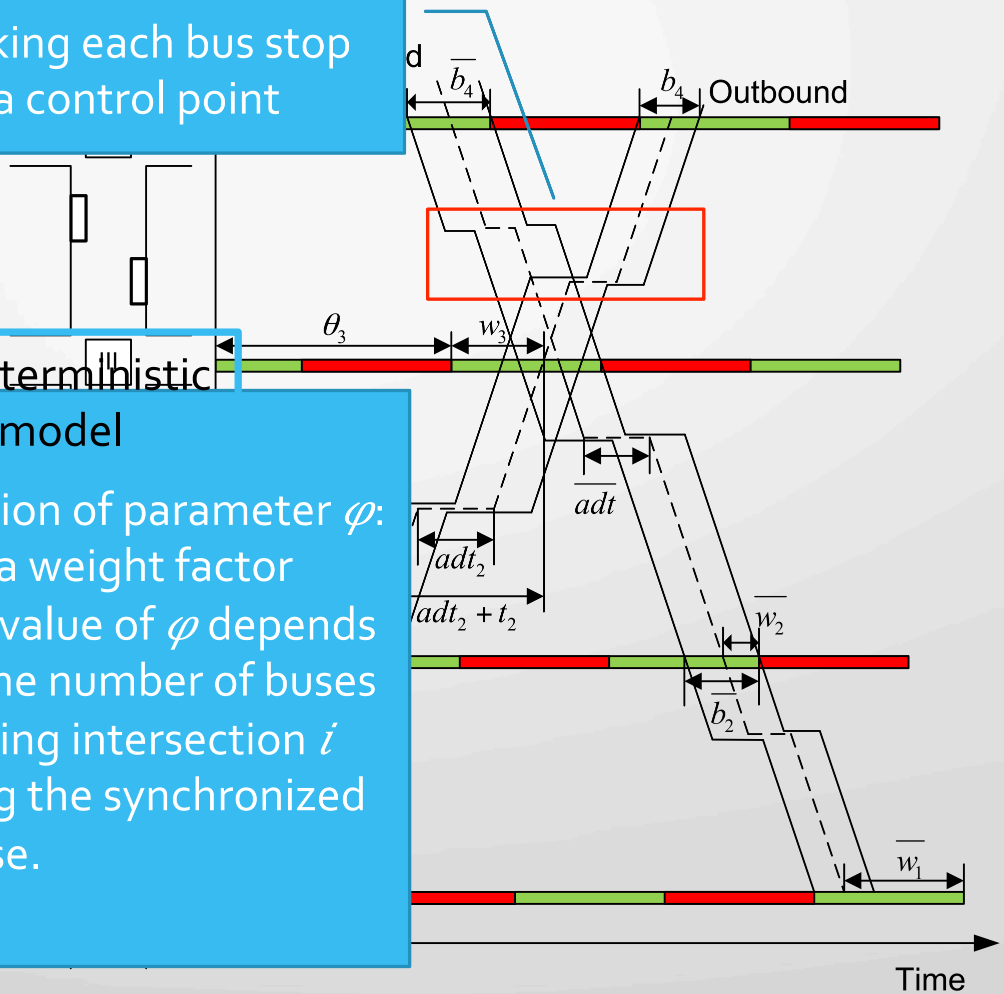
An evaluation module

An integrated model

Methodology

- Mixed Integer Linear Programming
- Objective function
  - $Max \sum_i \varphi_i b_i + \sum_i \overline{\varphi_i}\,\overline{b_i}$
- Constraints
  - Interference constra
  - $w_i - 0.5b_i \geq 0 \quad \forall i$
  - $w_i + 0.5b_i \leq g_i \quad \forall i$
  - $\overline{w_i} - 0.5\overline{b_i} \geq 0 \quad \forall i$
  - $\overline{w_i} + 0.5\overline{b_i} \leq g_i \quad \forall i$

Taking each bus stop as a control point



A deterministic model

Discussion of parameter φ:

- φ is a weight factor
- The value of φ depends on the number of buses passing intersection i using the synchronized phase.

Methodology

A deterministic model

- Constraints
  - Progression constraints
    - For links with bus stops

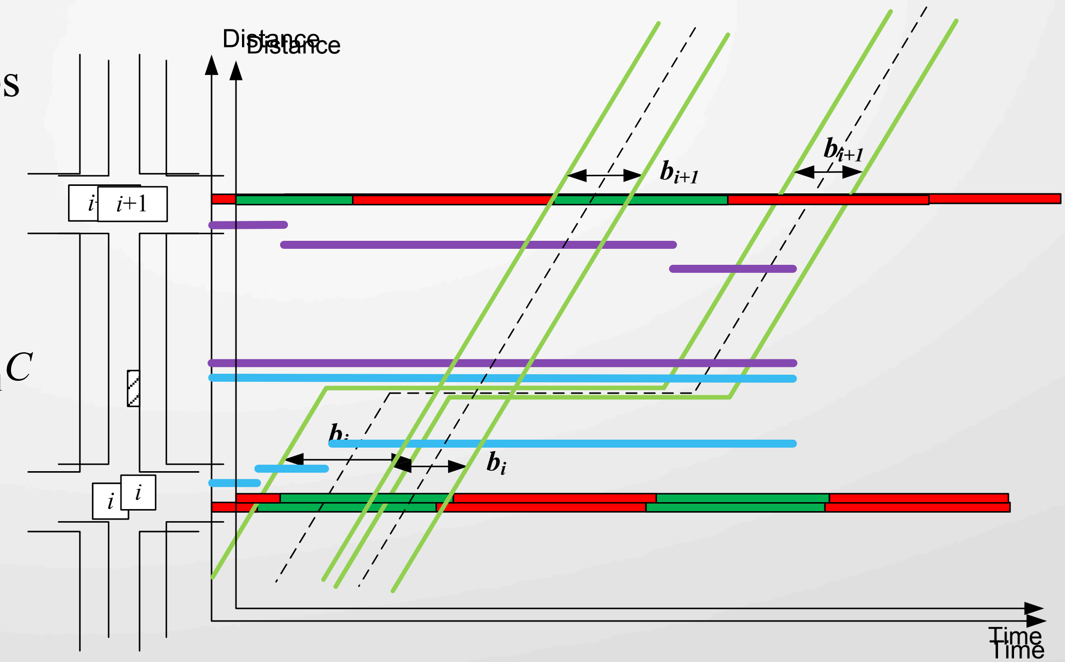
Average dwell time

$$\theta_i + w_i + t_i + adt_i = \theta_{i+1} + w_{i+1} + n_{i+1} C$$

Dwell time at bus stops

- Inbound

$$-\theta_i - \bar{r}_i + \bar{w}_i + \bar{t}_i + \overline{adt}_i = -\theta_{i+1} - \bar{r}_{i+1} + \bar{w}_{i-1} + \bar{n}_{i+1} C$$



- For other intersections
  - Outbound

$$\theta_i + w_i + t_i = \theta_{i+1} + w_{i+1} + n_{i+1} C$$

  - Inbound

$$-\theta_k - \bar{r}_i + \bar{w}_i + \bar{t}_i = -\theta_{i+1} - \bar{r}_{i+1} + \bar{w}_{i+1} + \bar{n}_{i+1} C$$

Methodology

A deterministic model

b_i^{max} : a predetermined maximum bandwidth

M: a big number

x_i : a binary variable

- Constraints (bus stop capacity)
  - Bandwidth limit
    - Outbound

$$w_i - 0.5 \times b_i^{max} \le M \times x_i$$

$$w_i + 0.5 \times b_i^{max} \ge g_i - M \times (1 - x_i)$$

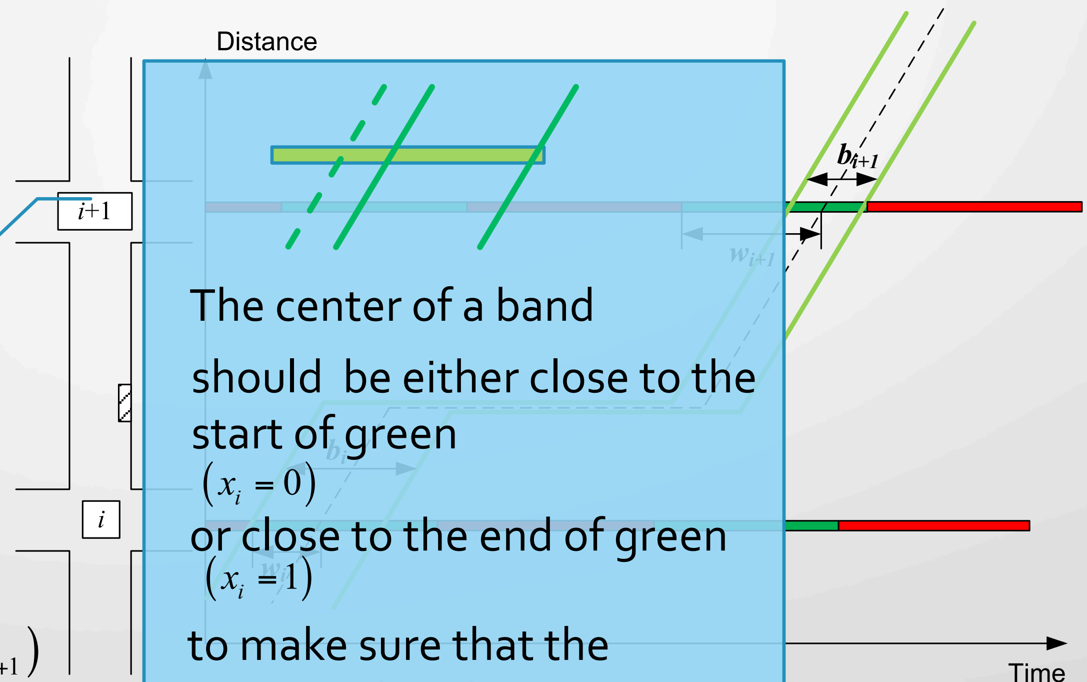
    - Inbound

$$\bar{w}_{i+1} - 0.5 \times b_i^{max} \le M \times \bar{x}_{i+1}$$

$$\bar{w}_{i+1} + 0.5 \times b_i^{max} \ge g_{i+1} - M \times (1 - \bar{x}_{i+1})$$

    - These constraints are only for upstream intersections of bus stops

Bus stop capacity



The center of a band should be either close to the start of green $(x_i = 0)$ or close to the end of green $(x_i = 1)$ to make sure that the potential band is realistic.

Methodology

A deterministic model

- Other Con
  - Bandwi
    - For

      b

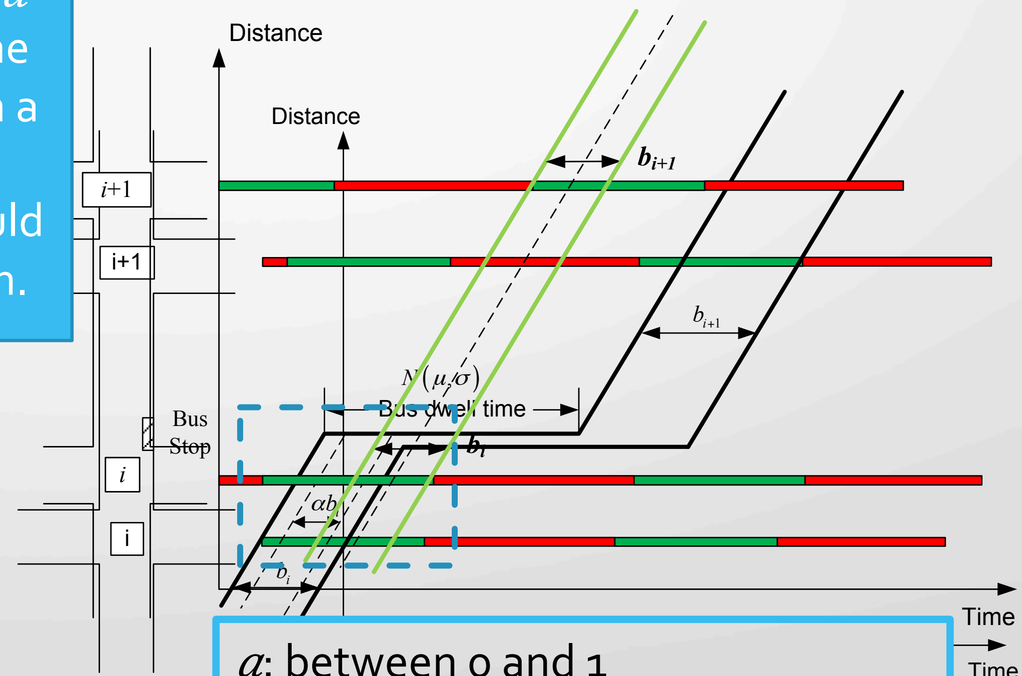
      $\bar{b}$

For those buses passing the upstream intersection during $a\, b_i$, if the dwell time uncertainty is within a specific range, the departing band should accommodate them.

  - Dwell time uncertainty
    - For links with bus stops

$$b_{i+1} \geq a \times b_i + \beta \times \sigma_i$$

$$\bar{b}_i \geq a \times \bar{b}_{i+1} + \beta \times \bar{\sigma}_{i+1}$$



a: between 0 and 1

β: indicating the tolerance of dwell time uncertainty

Methodology

A deterministic model

- Objective Function $Max \sum_i \varphi_i b_i + \sum_i \overline{\varphi_i}\,\overline{b_i}$
- Constraints

$$w_i - 0.5b_i \geq 0,\ w_i + 0.5b_i \leq g_i \quad \overline{w_i} - 0.5\overline{b_i} \geq 0,\ \overline{w_i} + 0.5\overline{b_i} \leq g_i \quad \forall i$$

Interference constraints

For adjacent intersections between which that a stop is located

$$\theta_k + w_k + t_k + adt_k = \theta_{k+1} + w_{k+1} + n_{k+1}C \quad -\theta_k + \overline{r_k} + \overline{w_k} + \overline{t_k} + \overline{adt_k} = -\theta_{k+1} + \overline{r_{k+1}} + \overline{w_{k+1}} + \overline{n_{k+1}}C$$

Progression constraints

$$w_k - 0.5 \times b_k^{\max} \leq M \times x_k \quad w_k + 0.5 \times b_k^{\max} \geq g_k - M \times \left(1 - x_k\right)$$

$$\overline{w_{k+1}} - 0.5 \times b_k^{\max} \leq M \times \overline{x_{k+1}} \quad \overline{w_{k+1}} + 0.5 \times b_k^{\max} \geq g_{k+1} - M \times \left(1 - \overline{x_{k+1}}\right)$$

Bandwidth constraints

$$b_{k+1} \geq a \times b_k + \beta \times \sigma_k \quad \overline{b_k} \geq a \times \overline{b_{k+1}} + \beta \times \overline{\sigma_{k+1}}$$

Dwell time uncertainty

For other intersections

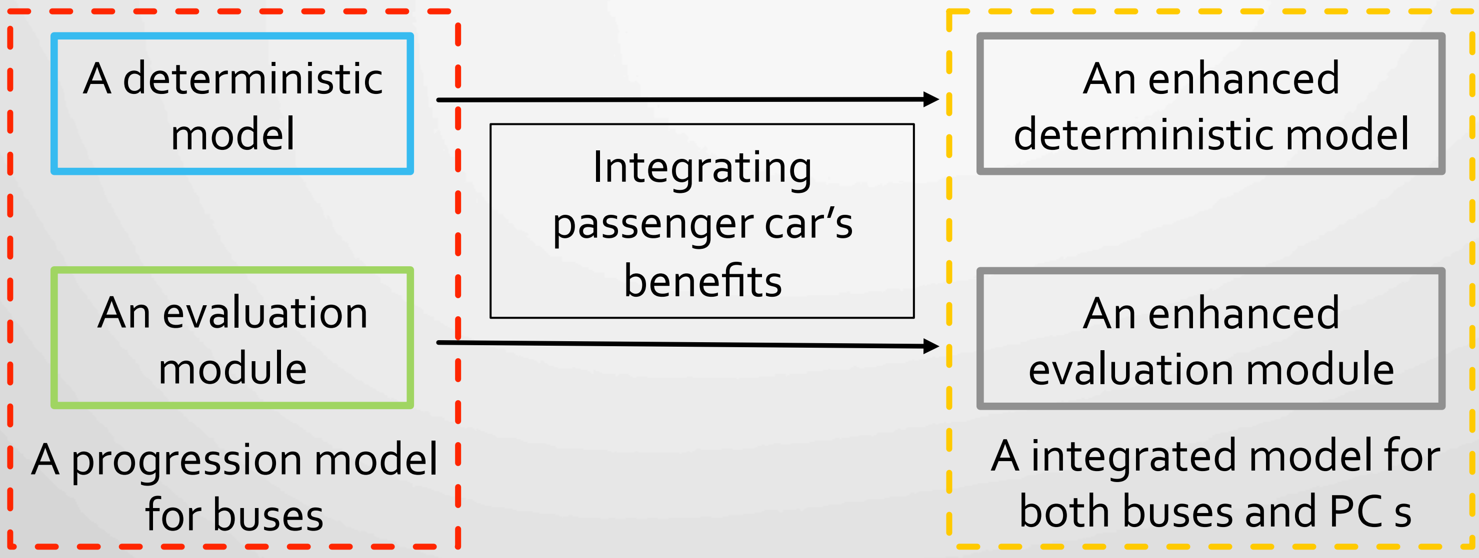
$$\theta_k + w_k + t_k = \theta_{k+1} + w_{k+1} + n_{k+1}C \quad -\theta_k + \overline{r_k} + \overline{w_k} + \overline{t_k} = -\theta_{k+1} + \overline{r_{k+1}} + \overline{w_{k+1}} + \overline{n_{k+1}}C$$

Progression constraints

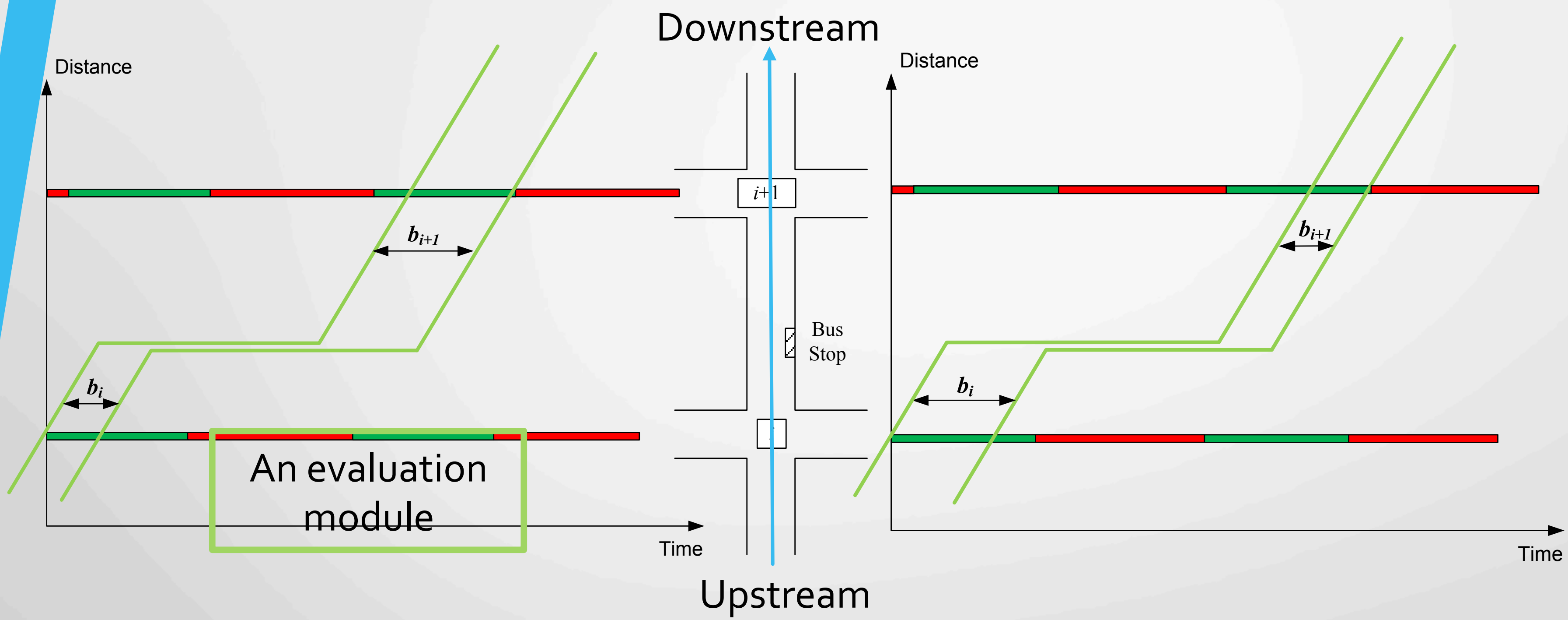
$$b_k = b_{k+1} \quad \overline{b_k} = \overline{b_{k+1}}$$

Bandwidth equality

Methodology



Methodology



$$b_{i+1} \geq \color{red}{a} \times b_i + \color{red}{\beta} \times \sigma_i$$

By adjusting parameters in this critical constraint, one may have multiple sub-optimal solutions.

They will be evaluated and ranked, fully taking the stochastic nature of bus dwell time into consideration.

Methodology

An evaluation module

$$b_{i+1} \geq a' \times b_i$$

- Computational complexity
- Still describing the relation between the arriving bandwidth and the departing bandwidth
- Still ensuring a relatively large departing bandwidth based on its arriving bandwidth
- Although the dwell time variance is no longer considered in the constraints, the analysis to sub-optimal solutions applies a more rigorous method to assess the impact of dwell time variance

$$b_{i+1} \geq a \times b_i + \beta \times \sigma_i$$

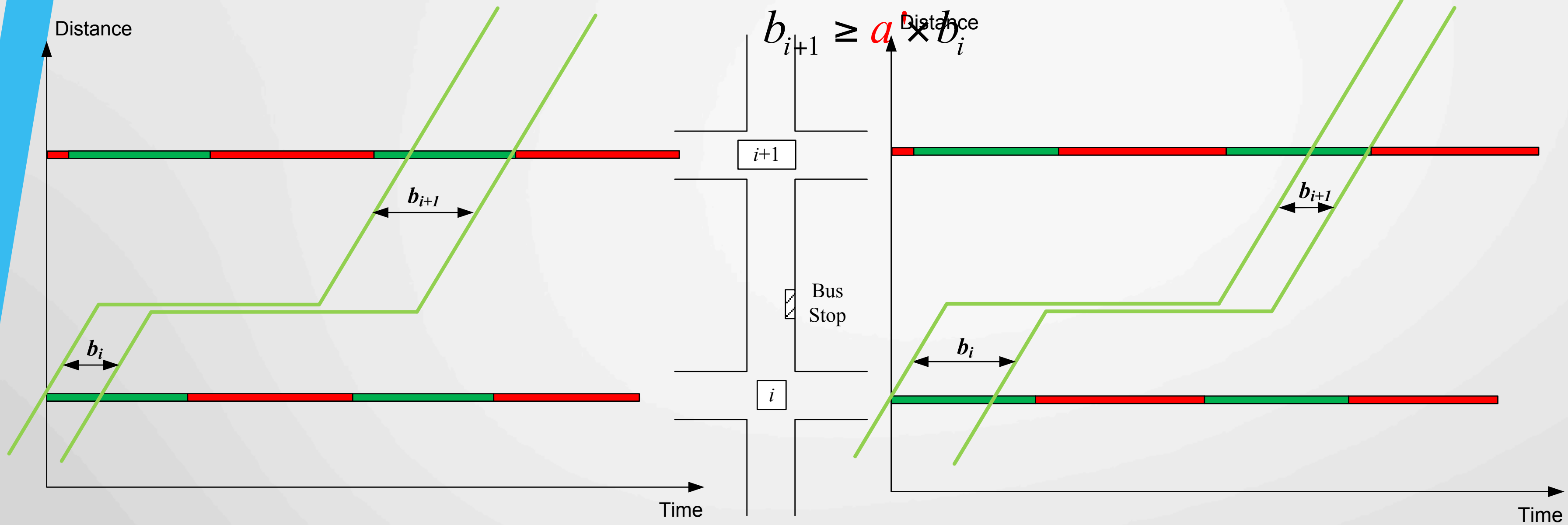
Discussion of parameter a':

- Different values lead to different "optimal" solution
- A Greater value for a' ensures a higher probability of a bus to keep in the band
- A Smaller value for a' allows a larger arriving bandwidth
- A too Large value for a' leads to meaningless upstream bands.

Methodology

An evaluation module

$$b_{i+1} \geq a^{i} \times b_i$$

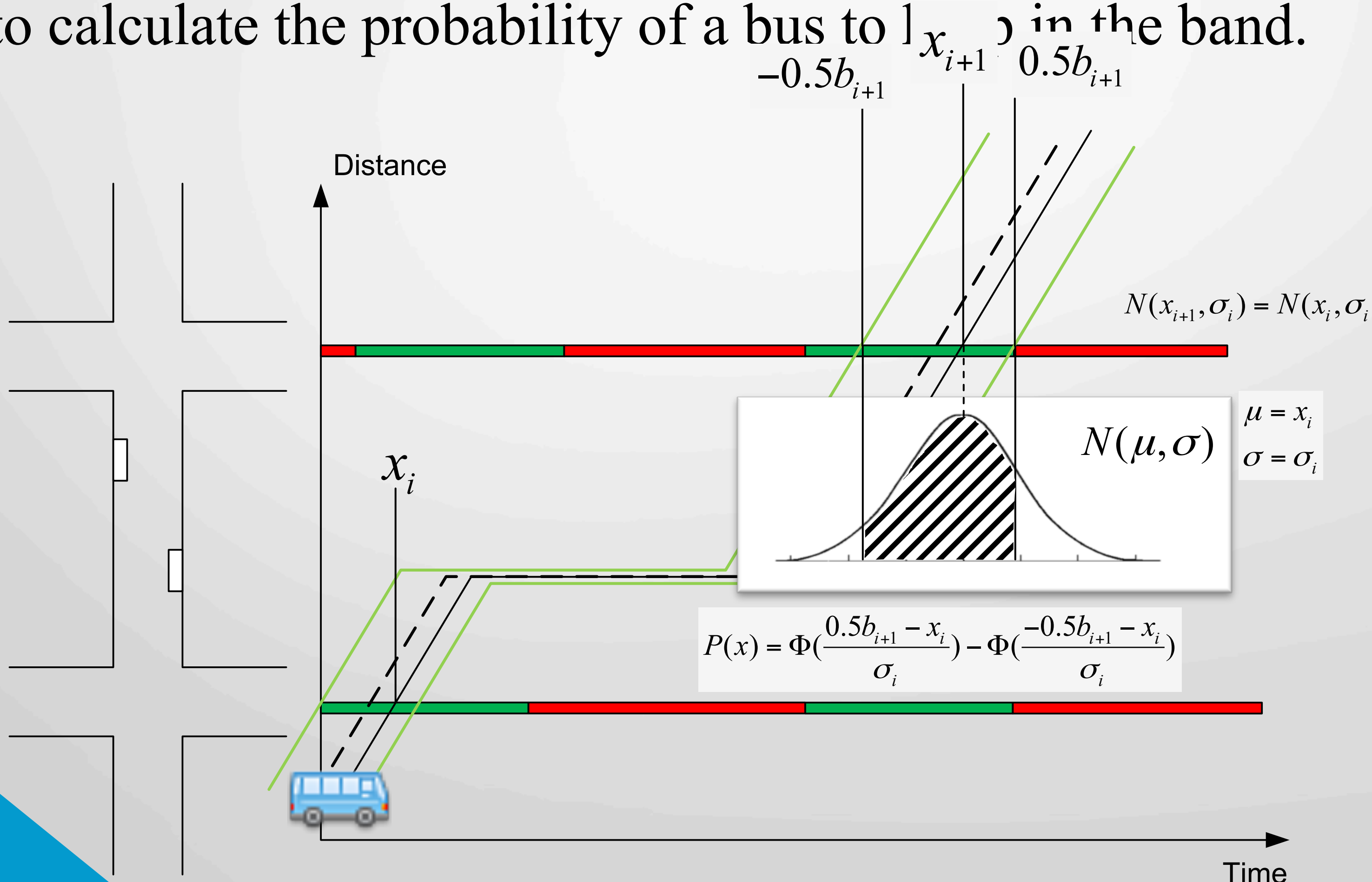


- How effective a signal plan is highly depends on the relation between each pair of bands arriving to and departing from a bus stop.
- To evaluate the sub-optimal solutions, this module computes the expectation of the fraction of the arriving bandwidth which can be effectively utilized.
- This expectation is called "effective bandwidth".

Methodology

An evaluation module

- In order to compute the effective bandwidths, one first needs to calculate the probability of a bus to l… in the band.



Methodology

An evaluation module

- Probability for the bus coming at time x to stay in the downstream band
  - For outbound

$$P(x) = \Phi(\frac{0.5b_{i+1} - x}{\sigma_i}) - \Phi(\frac{-0.5b_{i+1} - x}{\sigma_i})$$

  - For inbound

$$\overline{P(x)} = \Phi(\frac{0.5\overline{b_k} - x}{\sigma_k}) - \Phi(\frac{-0.5\overline{b_k} - x}{\sigma_k})$$

Dwell time uncertainty

- Calculate the "effective bandwidth"
  - $P(x)dx$ is the "effective" part among a short period of time dx
  - The "effective bandwidth" can be calculated by
    - For outbound

$$b_i^e = \int_{-0.5b_i}^{0.5b_i} P_i(x)dx$$

    - For inbound

$$\overline{b}_{i+1}^e = \int_{-0.5b_{i+1}}^{0.5b_{i+1}} \overline{P_{i+1}(x)}dx$$

For an intersection that is not at upstream of a bus stop:

$$b_i^e = b_i, \overline{b}_{i+1}^e = \overline{b}_{i+1}$$

Methodology

An evaluation module

- A larger "effective bandwidth" indicates a higher fraction of the buses which can stay in both the arriving and departing bands.
- Each solution from the deterministic model will generate $2m$ effective bandwidths, an outbound one and an inbound one for each intersection, where m is the number of intersections.
- The solution giving the maximum sum of effective bandwidths can be considered as the optimal solution for the model.

Methodology

An evaluation module

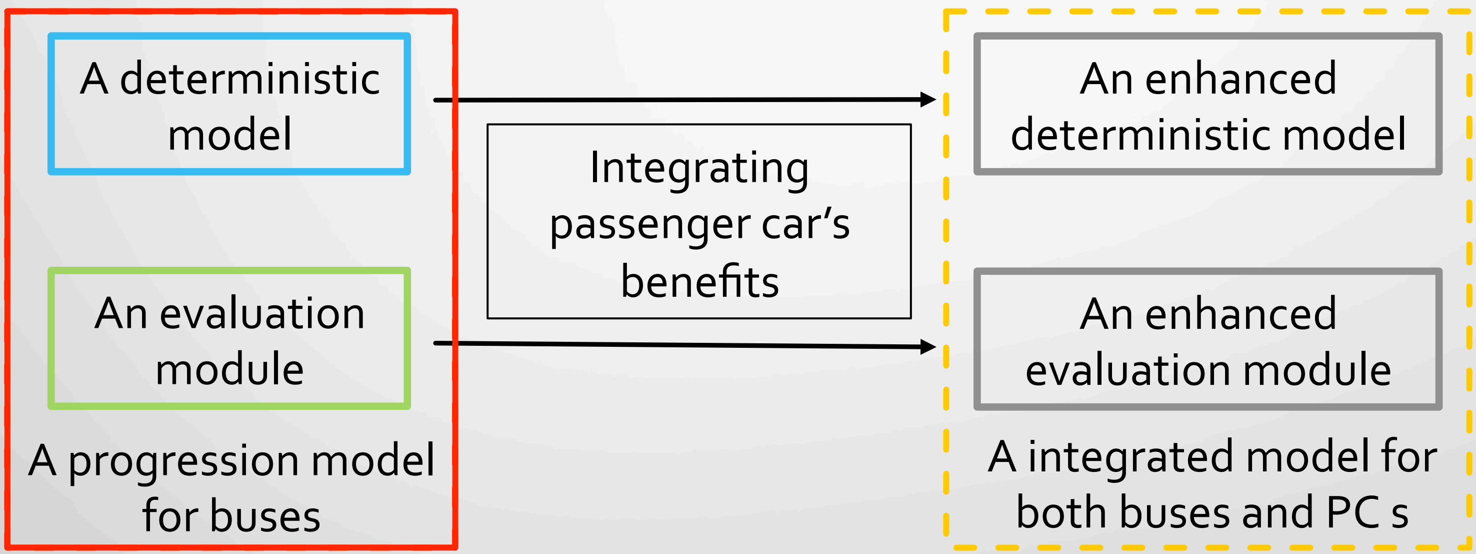
Cycle length, green split, travel time, estimated bus dwell time….

$$b_{i+1} \geq a' \times b_i$$

Each solution has a set of bandwidths and offsets

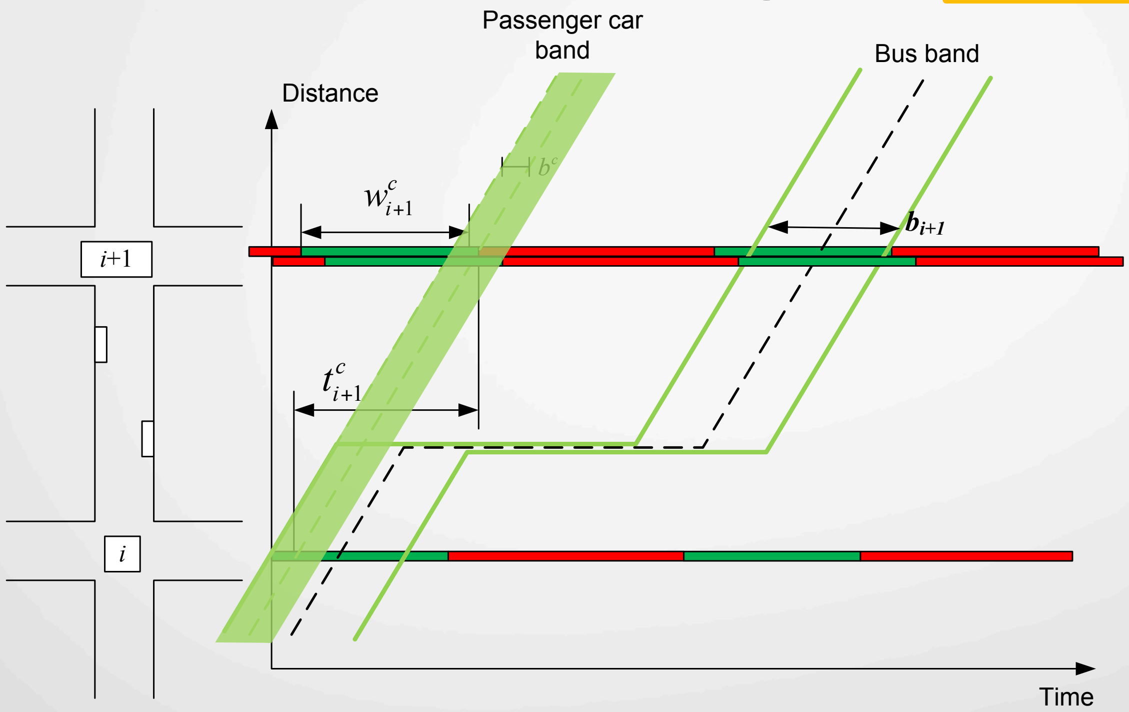
Find the solution with the maximum total effective bandwidths

Methodology



Methodology

An integrated model



- Designing bus bands causes potential interruption for passenger car movements.
- Even with the same bus bands, the benefit for passenger cars can be different among signal plans.

Methodology

An integrated model

- Therefore, the bus bands and the passenger car bands need to be optimized concurrently.

An enhanced deterministic model

- Revising the objective function to include bands for both types of vehicles.
- Revising the constraints to express passenger car bands.

An enhanced evaluation module

- When comparing the sub-optimal solutions, both effective bandwidths for buses and passenger car bandwidths are considered.

Methodology

An integrated model

- Objective function

Ratio between numbers of passengers on two types of vehicles

Competition between buses and PCs

$$Max \quad k\left(\sum_i \varphi_i b_i + \sum_i \bar{\varphi}_i \bar{b}_i\right) + n\left(b^c + \bar{b}^c\right)$$

- Additional constraints
  - T... ds ar... id one dominating the other,

An enhanced deterministic model

k<1: Passengers on PCs are less
k>1: Passengers on buses are less

$$(1-k)\left(\sum_i \varphi_i b_i + \sum_i \bar{\varphi}_i \bar{b}_i\right) \geq k(1-k)n\left(b^c + \bar{b}^c\right)$$

  - Constraints to express passenger-car bands

$$w_i^c - 0.5b^c \geq 0 \quad w_i^c + 0.5b^c \leq g_i \qquad \bar{w}_i^c - 0.5\bar{b}^c \geq 0 \quad \bar{w}_i^c + 0.5\bar{b}^c \leq g_i$$

$$\theta_i + w_i^c + t_i^c + n_i^c C = \theta_{i+1} + w_{i+1}^c + n_{i+1}^c C$$

$$-\theta_i - r_i + \bar{w}_i^c + \bar{t}_i^c + \bar{n}_i^c C = -\theta_{i+1} - r_{i+1} + \bar{w}_{i+1}^c + \bar{n}_{i+1}^c C$$

Methodology

An enhanced evaluation module

- Enhancement to the stochastic analysis
  - The ranking index of a sub-optimal solution includes both effective bandwidth of bus bands and passenger-car bands

$$R = k\left(\sum_{i=1}^{n-1} b_i^e + \sum_{i=2}^{n} \bar{b}_i^e\right) + (n-1)\left(b^c + \bar{b}^c\right)$$

Total effective bandwidths

Total passenger-car bandwidths

Methodology

An integrated model

Cycle length, green split, travel time, estimated bus dwell time….

$$b_{i+1} \geq a' \times b_i$$

Each solution has a set of bandwidths and offsets

Find the solution with the maximum ranking index

Methodology

A deterministic model

An evaluation module

A progression model for buses

Following the concept of MAXBAND, a Mixed-Integer Linear Programming model is developed.

By adjusting a parameter in the MILP, multiple sub-optimal solutions will be produced and evaluated, accounting for the stochastic nature of bus dwell time.

Integrating passenger car s benefits

An enhanced deterministic model

An enhanced evaluation module

An integrated model for both buses and PC s

Dwell time at bus stops

Bus stop capacity

Dwell time uncertainty

Competition between buses and PCs

Benefits of both buses and passenger cars are considered.

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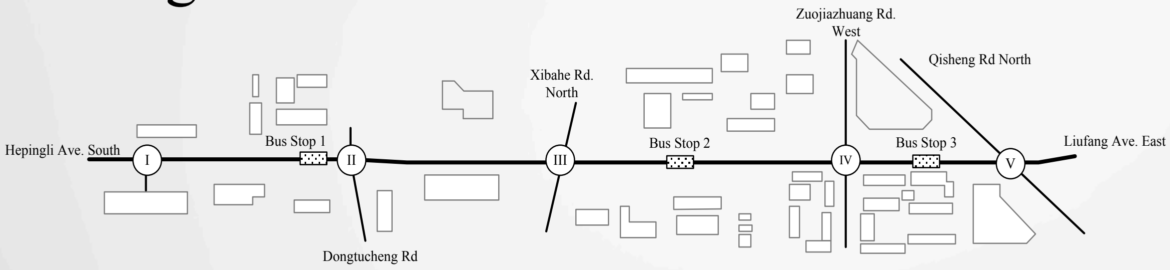
Case Study

- Case Design



Link	Link length (ft)	travel time	With bus stop?
I↔II	906	20	Yes
II↔III	948	21	No
III↔IV	1250	28	Yes
IV↔V	725	16	Yes

- Cycle length is 150 seconds;
- Green times at intersections are 99 , 77 , 66, 75, and 60 seconds, respectively;
- The dwell time: bus stop 1: N(30,9); bus stop 2: N(27,7); bus stop 3: (24,9);
- The bus stop capacity is 2 buses at each direction, and the confidence parameter *p* equals 0.95; then the maximal bus bandwidth could be computed as 50 seconds
- For each direction along the arterial, the bus volume is 60 veh/h, with an average headway of 1.0 minute and the passenger car volume is 750 veh/h;

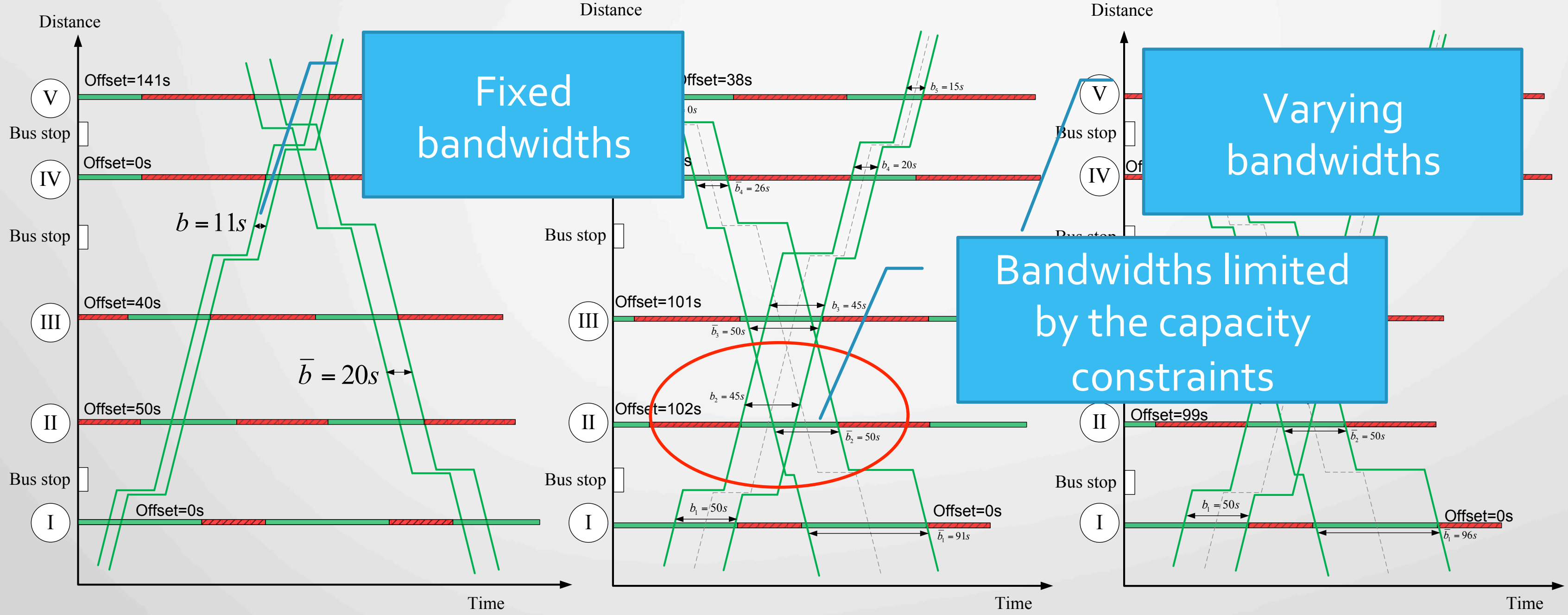
Case Study

- Models to be evaluated
  - Model-1: MAXBAND with fixed phase sequences
  - Model-2: A direct extension of MAXBAND by adding the average bus dwell time to the travel time on the links having a bus stop.
  - Model-3: The proposed deterministic model
  - Model-4: The proposed deterministic model with the evaluation module
  - Model-5: The proposed integrated model
- The MILP is solved with LINGO. The evaluation module is conducted with R studio.

Case Study

- Task 1: Bandwidths and performance measures generated by bus progression models will first be compared to verify the necessity of the evaluation module.
- Task 2: Then the signal plans generated by all Models will be applied in the simulation software, VISSIM, and will be evaluated based on the average delays and number of stops.
- Task 3: Sensitivity Analysis will then be conducted with respect to the number of passengers on buses to assess the stability of the proposed integrated model.

Case Study



MAXBAND with extension

The deterministic model

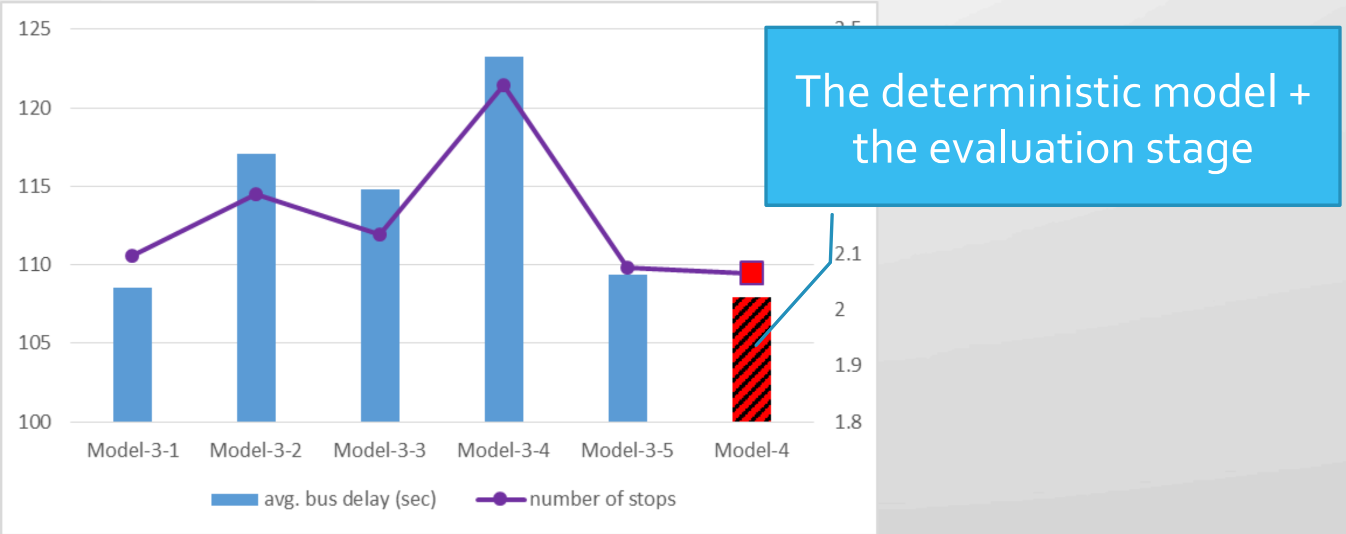
The deterministic model + the evaluation stage

Case Study

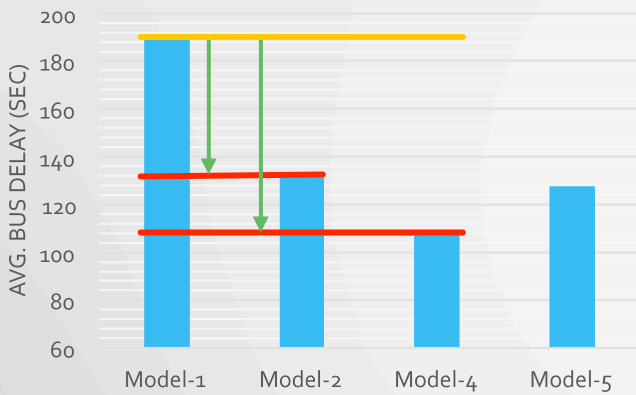
To verify the necessity of the evaluation module, several sets of parameters for Model-3 are tested.

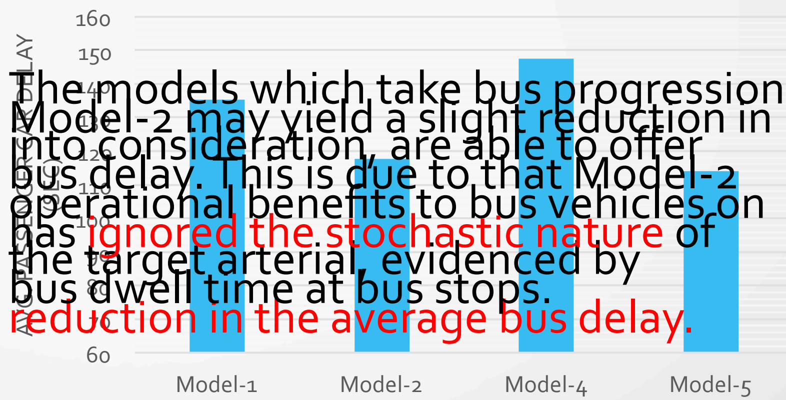
$$b_{i+1} \geq a \times b_i + \beta \times \sigma_i$$

			Offsets (s) at Intersection No.				
	α	β	1	2	3	4	5
Model-3-1	0.3	1	0	102	101	40	38
Model-3-2	0.3	2	0	107	104	38	43
Model-3-3	0.5	1	0	105	98	37	41
Model-3-4	0	1	0	99	104	25	35
Model-3-5	0.1	2	0	104	99	41	40



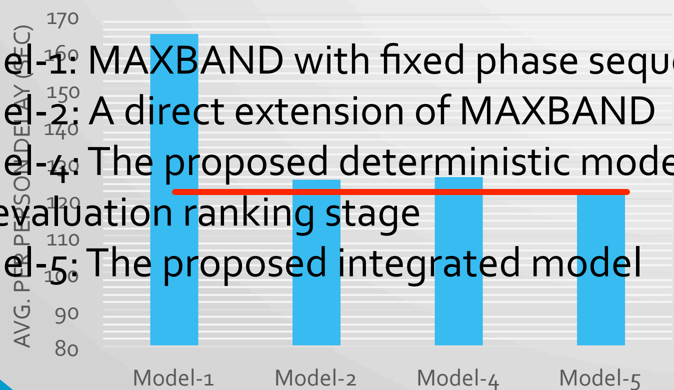
Case study



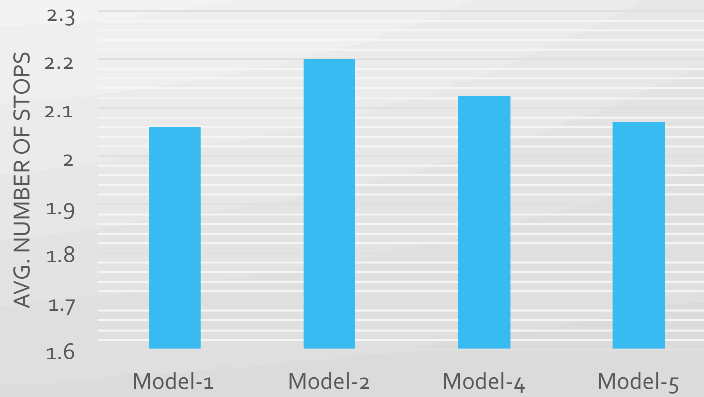


The models which take bus progression into consideration, are able to offer operational benefits to bus vehicles on the target arterial, evidenced by reduction in the average bus delay.

Model-2 may yield a slight reduction in bus delay. This is due to that Model-2 has ignored the stochastic nature of bus dwell time at bus stops.



Model-1: MAXBAND with fixed phase sequences
Model-2: A direct extension of MAXBAND
Model-4: The proposed deterministic model with the evaluation ranking stage
Model-5: The proposed integrated model



Model-2 and 4 outperform Model-1, and Model-5 outperforms both Model-2 and Model-4

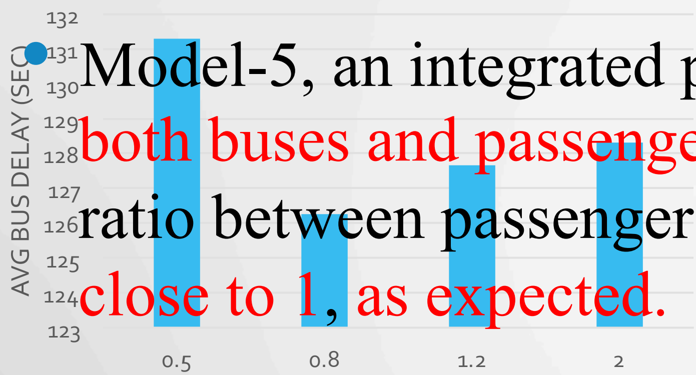
Case Study

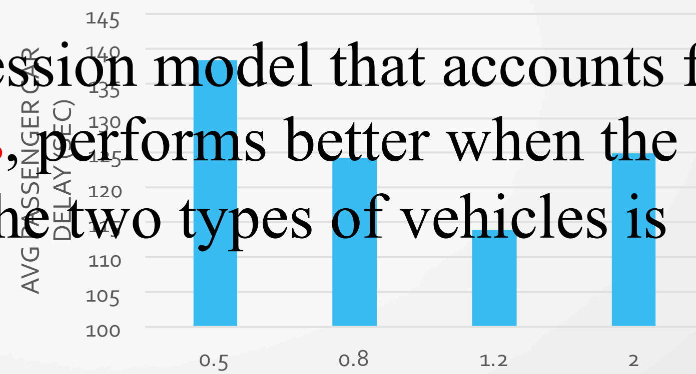
- It can be expected that the integrated model should be only applied when the difference between numbers passengers on two types of vehicles is small
- When the number of passengers on buses dominates that on passenger cars, bus progression model may be preferred, and vice versa.
- The system performance is quite sensitivity to the preference factor *k*

$$Max\ \ k(\sum_i \varphi_i b_i + \sum_i \bar{\varphi}_i \bar{b}_i) + n\left(b^c + \bar{b}^c\right)$$

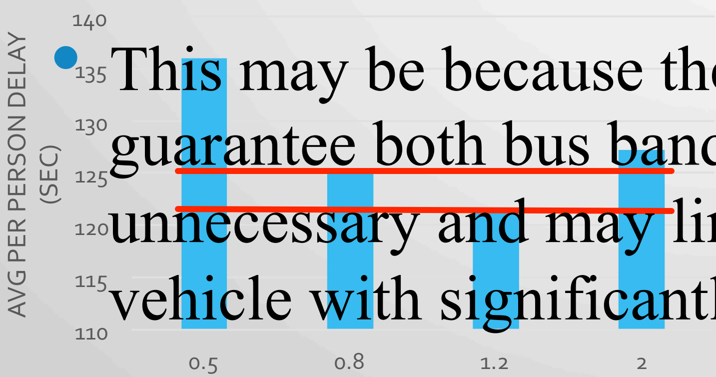
Loading factor on buses	Passenger ratio k
12	0.8
18	1.2
30	2
7.5	0.5

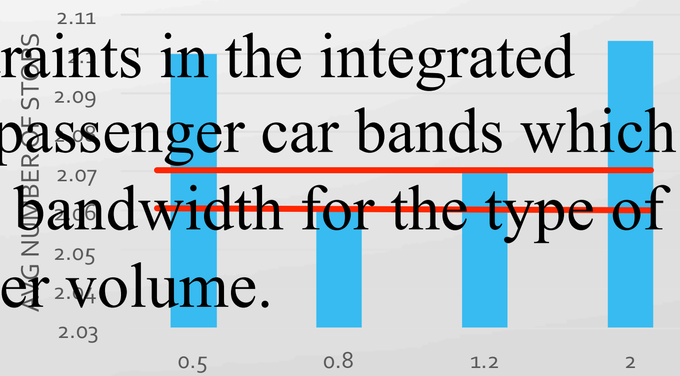
Case Study





- Model-5, an integrated progression model that accounts for both buses and passenger cars, performs better when the ratio between passengers on the two types of vehicles is close to 1, as expected.





- This may be because the constraints in the integrated guarantee both bus bands and passenger car bands which is unnecessary and may limit the bandwidth for the type of vehicle with significantly higher volume.

Outline

- Literature Review
- Problem Nature and Modelling Framework
- Methodology
- Case Study
- Conclusions and Future Study

Conclusions

- Due to the limited functions of the active transit signal priority control and the strengths of arterial signal progression, this study has developed a bus progression system to facilitate bus movements on an arterial.
- The key features of the developed model include:
  - 1) the impact of bus dwell time at a bus stop between intersections on the progression design;
  - 2) the stochastic nature of bus dwell time;
  - 3) the capacity of bus stops; and
  - 4) the competition on the green band between buses and passenger cars
- The simulation results demonstrate that the proposed model can reduce both bus passenger delays and average person delays for vehicles in the entire network, compared to the conventional progression models.

Future Research

- Developing a set of rigorous criteria that can compute the trade-off between bus based and passenger-car-based progression models and select the proper one in real time based on the detected traffic conditions
- An extensive sensitivity analysis with field data and simulation experiments

Thank you

- Questions and Comments

Methodology

A deterministic model

- How to determine b_{max}?
- Probability of k buses being in a band i is

$$f(k) = (\lambda b_i)^k \times e^{-\lambda b_i} / k!$$

  - Where, λ is bus arrival rate and b_i is bandwidth of band i
- The probability that the number of buses in a band does not exceed the capacity should be greater than a predetermined α, which can be expressed as,

$$\sum_{k=0}^{C_s} f(k) \geq \alpha$$

  - Where, C_s is the bus stop capacity
- Then b_{max} can be determined by

$$\sum_{k=0}^{C_s} (\lambda b_i)^k \times e^{-\lambda b_i} / k! \geq \alpha$$

Methodology

An evaluation module

- How to determine a?
- 1) set a minimum band b_{min} and $b_{max,k}$
- 2) $a^u = \min_k \left(\sqrt{b \ldots} \ldots \sqrt{b \ldots} \right)$

upper bound

- 3) $a^l = \min_k \left(\ldots \right)$, b_{min}, $\min \left\{ \frac{b_{max,2}}{l}, \ldots \right\}$, $\sqrt{b_{max,3} \ldots}$

lower bound

- 4) $a'^{min} = \max_k \left(\frac{b_{max,1}}{b_{max,k}}, \frac{b_{max,2}}{\ldots}, b_m \ldots \right)$, $\min \left\{ \frac{b_{min}}{\ldots}, \ldots \right\}$

Minimum interval

- 5) the number of different values of a is $a^u - a^l / a'^{min}$

- The smaller one among b_{max} and the green time

- A band smaller than that is meaningless operationally.

Based on the bandwidth resolution of 1 second