Development Method to Estimate Fuel Consumption using Driving Patterns from Probe Data Information

Napon Srisakda; PSK Consultant, Thailand
Atsushi Fukuda & Tetsuhiro Ishizaka; Nihon University, Japan
Sorawit Narupiti; Chulalongkorn University, Thailand

Background

Traffic congestion in developing cities affects high fuel consumption (FC) and green house gas emission

Thus, a new generation of fuel saving and environmentally friendly vehicle or so-called “Hybrid Vehicle (HEV)” has been introduced.

It is expected, for example, that 19 % of CO2 emission can be reduced by introducing HV in Japan (PC;20->83%, ST;10->50%, SPC;0->83%, in 2020)

Background

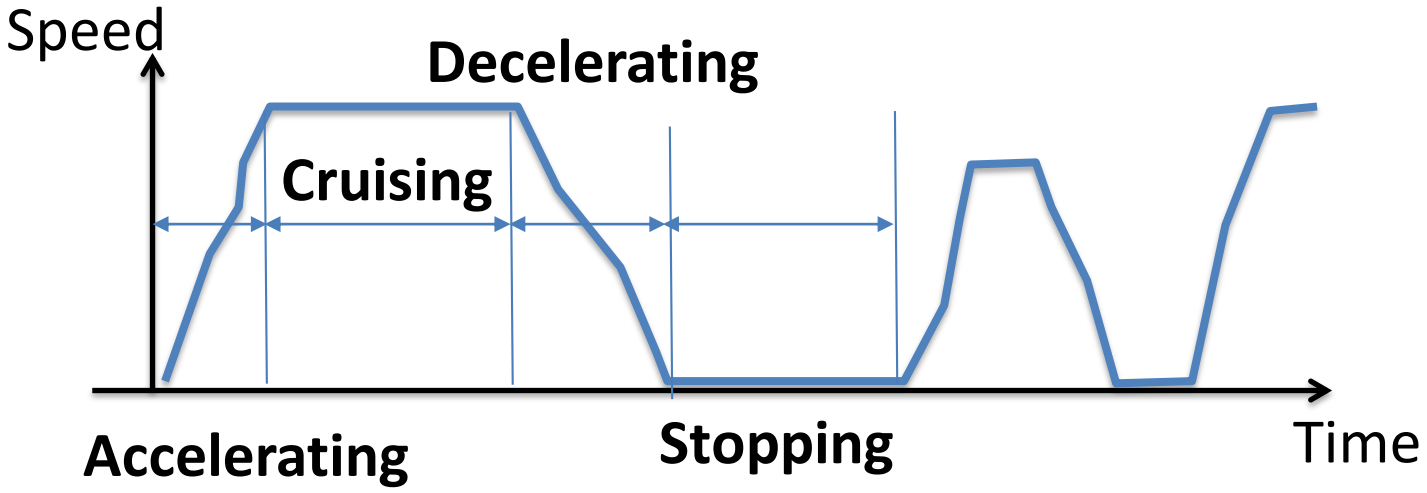
However, because of fluctuate and unstable of driving patterns depending on traffic conditions, FC estimation is difficult

Probe vehicle data, reflecting well traffic conditions, can be used to estimate FC and find the impacts of HEV

How to Use Probe Data in This Study

Probe data, which are one of the real-world data, can be used for fuel consumption estimation using driving patterns which can be seen by speed profiles

- Speed profiles can help to estimate fuel consumption using **the proportion of accumulated time of probe vehicles traveled in different driving modes**
- That can be defined as "**Time Sharing of Driving Modes**"



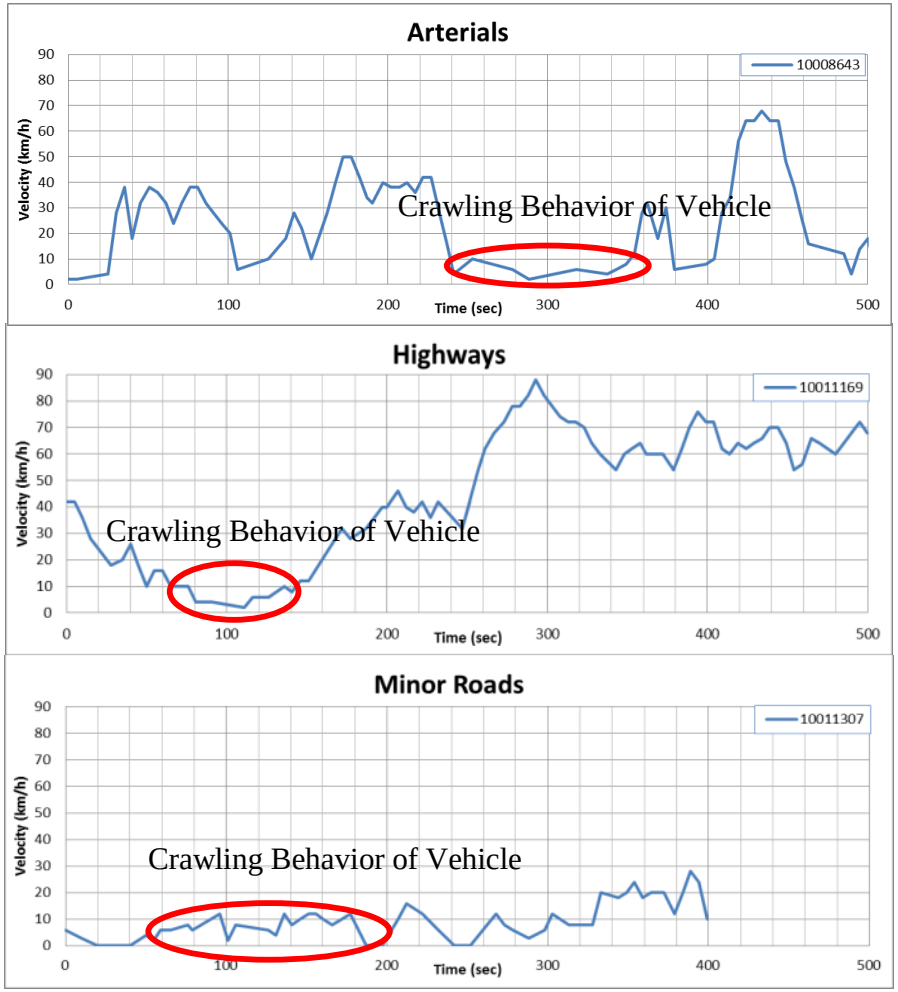
- Time sharing of driving modes can clearly indicate driving patterns better than speed or acceleration data only

Additional Driving Mode (Crawling)

Crawling is a behavior of vehicles in traffic stream, which is the semi-situation between stopping/idling and full moving of vehicles

Occurs in congestion periods, especially during peak hours on weekdays on every road categories

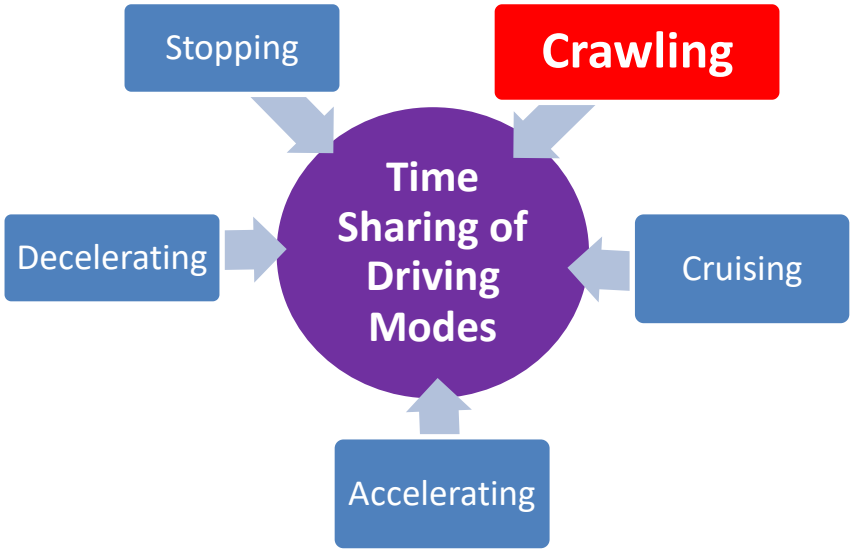
No previous studies considered about this behavior for a more reliable fuel consumption estimation



Crawling of vehicles can be seen around 1-20 km/hr

Objectives

- Determine time sharing of driving modes based on probe data in various conditions for estimating fuel consumption
- Study the impacts of fuel consumption by hybrid car replacing



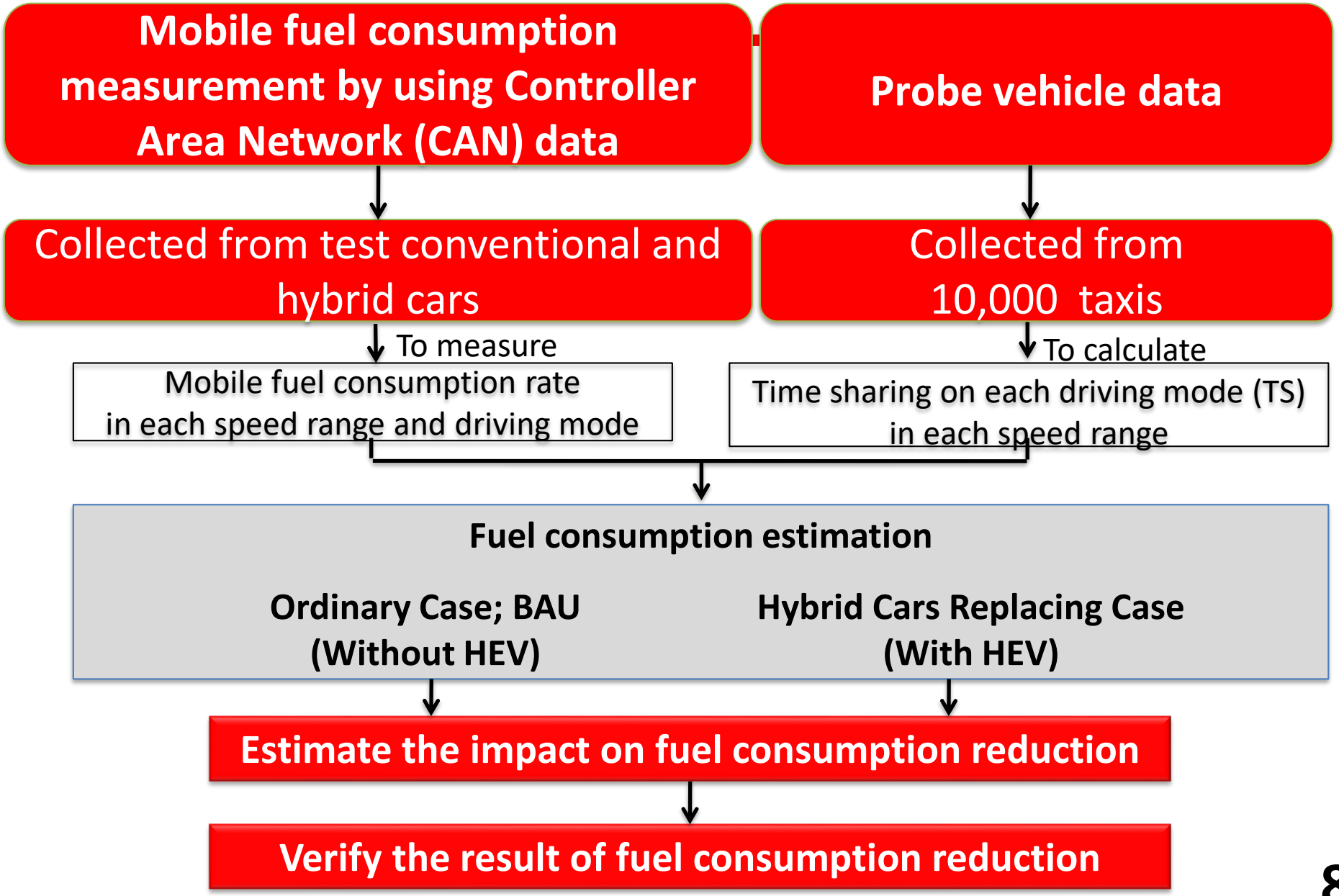
Literature Review

Rakha and Ding (2003) and Rakha et al. (2004) considered only test vehicles in the fields for fuel consumption estimation without sufficient data reflecting activity rates or driving patterns of all traffic system, like probe vehicle data.

Wang et al. (2007), Li et al. (2011), Fukuda et al. (2013), Chang et al. (2013), and Chollacoop et al. (2015) use vehicle kilometer traveled (VKT) to estimate fuel consumption by the principle that more distance traveled of vehicles increases, fuel consumption also increase. However, VKT cannot determine and well reflect driving pattern, which affect fuel consumption directly.

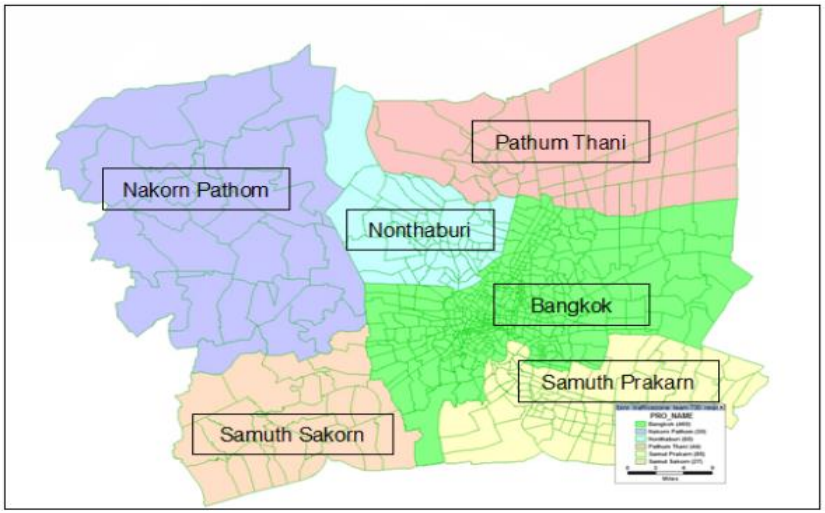
Raykin et al. (2012), Pitanuwat and Sripakagorn (2015), and Wang et al. (2015) used probe data for fuel consumption estimation. However, probe data were used as test vehicles, which could not sufficiently cover all vehicles in traffic system, and were used for identifying only driving pattern/modes, and traffic conditions.

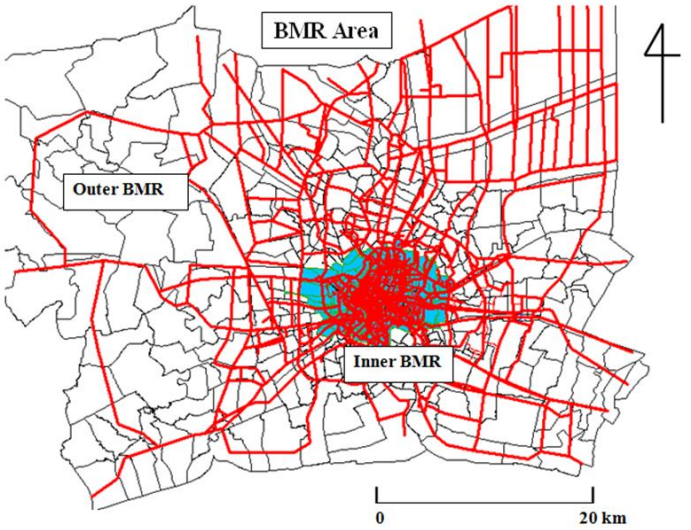
Methodology of Study



Probe Data Collection

- **Study Area**: Bangkok Metropolitan Region (BMR)

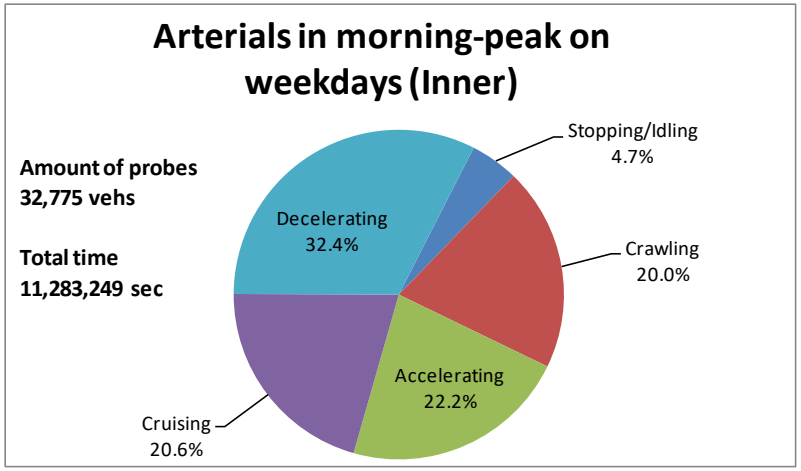


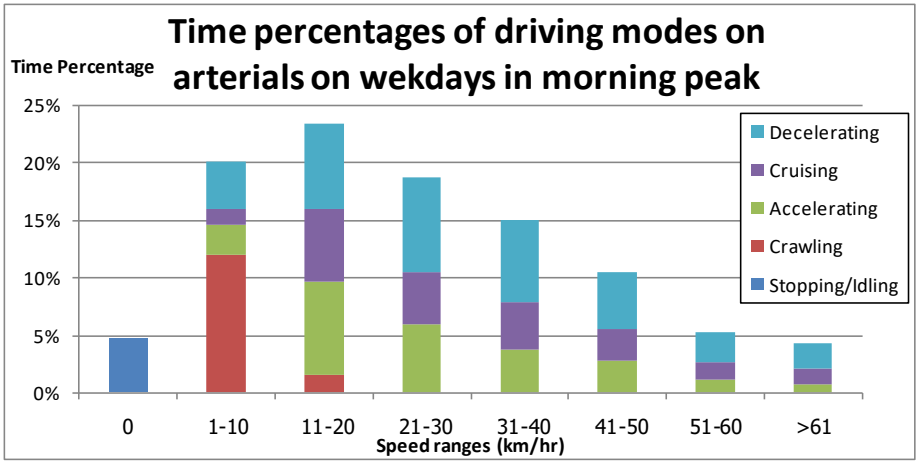


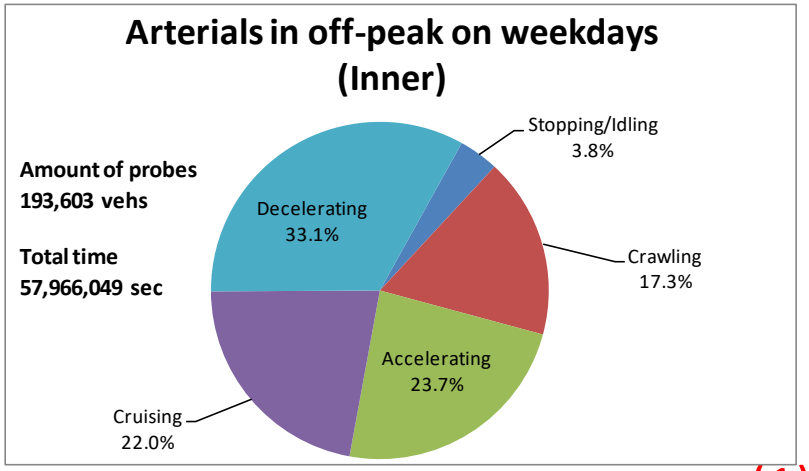
- **Duration**: 30 days (21 weekdays and 9 weekends)
- **Time periods**: Morning peak (7:00 – 8:00), Off peak (12:00 – 13:00), and Evening peak (17:00 – 18:00)
- **Categories of roads**: Highways, Arterials, and Minor roads
- **Speed ranges**: 0, $1 \le v < 10$, $11 \le v < 20$, $21 \le v < 30$, $31 \le v < 40$, $41 \le v < 50$, $51 \le v < 60$, and > 61 km/hr
- **5 driving modes**: Stopping, Accelerating, Cruising, Decelerating, and Crawling

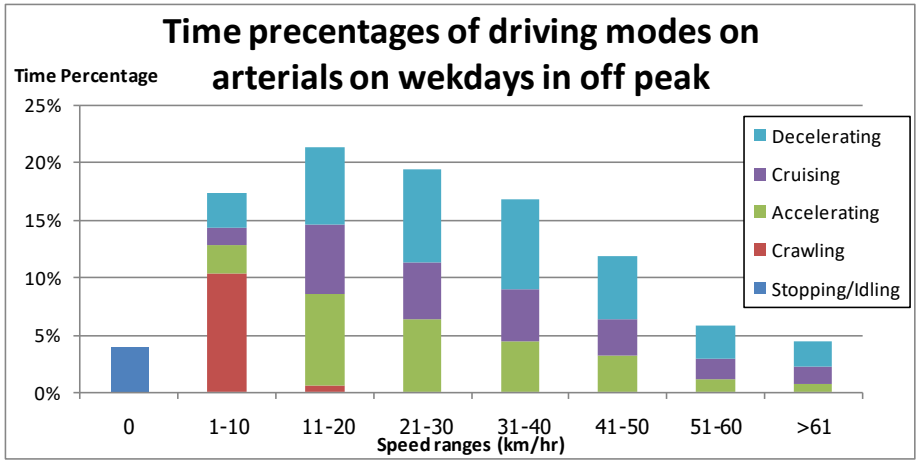
Time Sharing of Driving Modes Results

Time sharing of driving modes diagrams





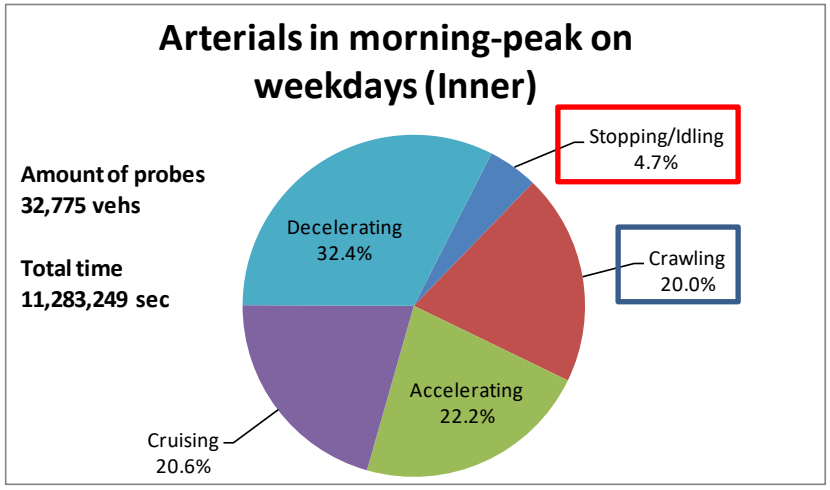


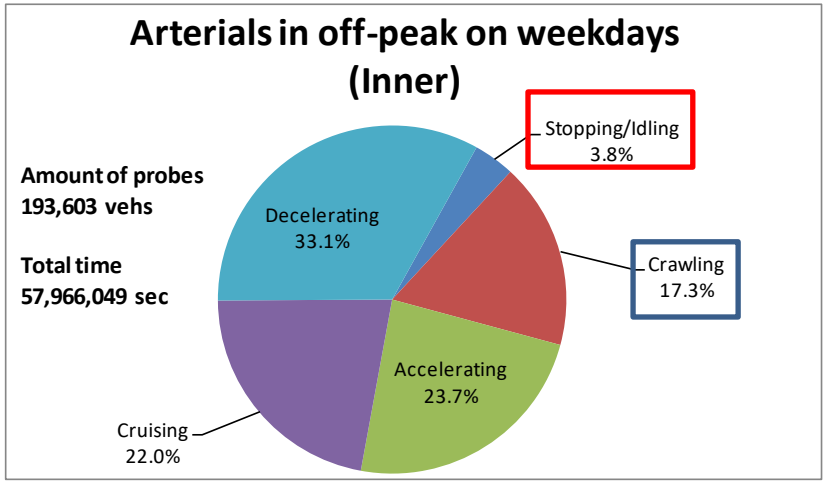


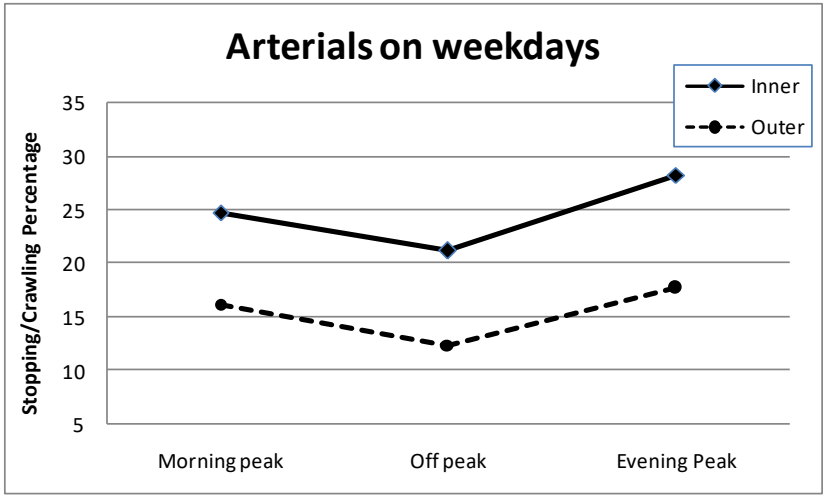
(1) Each driving mode can be distributed by speed range for fuel consumption estimation

Time Sharing of Driving Modes Results

Time sharing of driving modes diagrams





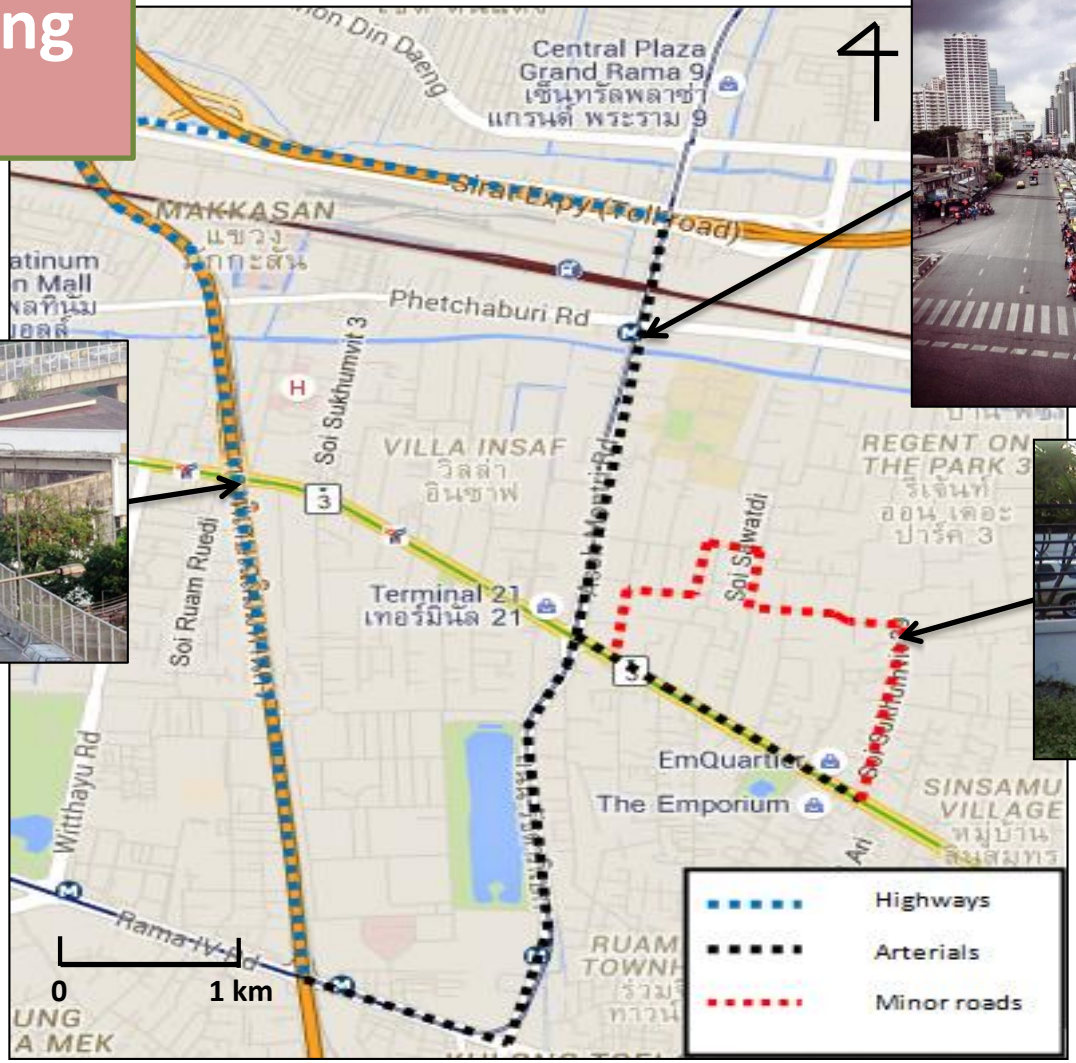


(2) Traffic congestion can be indicated by stopping and crawling mode

Collecting Mobile Fuel Consumption

Real Running Test

Highways
6 km



Arterials
7.6 km

Minor roads
2.6 km

Mobile Fuel Consumption Results

Mobile fuel consumption (CC/sec) of both conventional and hybrid cars can be calculated for different days of week (weekdays and weekends), and periods (peak hours and off-peaks) in each driving mode, speed range, and indicated time frequency (sec) in case of hybrid system operated (OFF) or in-operated (ON)

Mobile fuel consumption (CC/sec) and time frequency (sec) of conventional gasoline car

Driving Modes	Stopping/Idling				Crawling				Accelerating				Cruising				Decelerating			
Speed Range (km/h)	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec
0	0.25	298	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1-10	-	-	-	-	0.53	564	0	0	1.95	155	0	0	0.40	126	0	0	0.35	169	0	0
11-20	-	-	-	-					1.24	169	0	0	0.68	122	0	0	0.46	211	0	0
21-30	-	-	-	-	-	-	-	-	1.39	123	0	0	0.73	108	0	0	0.51	178	0	0
31-40	-	-	-	-	-	-	-	-	1.65	95	0	0	1.23	87	0	0	0.49	142	0	0
41-50	-	-	-	-	-	-	-	-	1.96	78	0	0	1.26	84	0	0	0.62	119	0	0
51-60	-	-	-	-	-	-	-	-	1.58	64	0	0	0.89	73	0	0	0.63	104	0	0
>61	-	-	-	-	-	-	-	-	1.27	21	0	0	0.54	13	0	0	0.59	24	0	0
Total time frequency (sec)	-	298	-	0	-	564	-	0	-	705	-	0	-	613	-	0	-	947	-	0
Avg. Fuel consumption (CC/sec)	0.25	-	-	-	0.53	-	-	-	1.58	-	-	-	0.82	-	-	-	0.52	-	-	-

Mobile fuel consumption (CC/sec) and time frequency (sec) of hybrid car

Driving Modes	Stopping/Idling				Crawling				Accelerating				Cruising				Decelerating			
Speed Range (km/h)	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec
0	0.25	18	0	286	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1-10	-	-	-	-	0.44	283	0	269	1.09	82	0	70	0.39	63	0	72	0.21	76	0	88
11-20	-	-	-	-					0.82	101	0	74	0.51	64	0	64	0.30	98	0	116
21-30	-	-	-	-	-	-	-	-	1.12	86	0	39	0.48	57	0	61	0.30	63	0	109
31-40	-	-	-	-	-	-	-	-	1.16	70	0	35	0.52	45	0	47	0.45	59	0	79
41-50	-	-	-	-	-	-	-	-	1.16	49	0	32	0.61	42	0	38	0.29	53	0	63
51-60	-	-	-	-	-	-	-	-	1.33	33	0	33	0.55	37	0	35	0.29	47	0	58
>61	-	-	-	-	-	-	-	-	1.11	25	0	0	0.51	10	0	0	0.21	21	0	0
Total time frequency (sec)	-	18	-	286	-	283	-	269	-	446		282	-	318	-	317	-	417	-	513
Avg. Fuel consumption (CC/sec)	0.25	-	-	-	0.44	-	-	-	1.11	-	-	-	0.51	-	-	-	0.29	-	-	-

Assumptions for studying the impact on fuel consumption reductions

First Assumption

- All probe vehicles (10,000 taxis) will be replaced by hybrid cars
- The aims to calculate fuel consumption rate for studying the impacts and reductions of hybrid cars for different sub-area, road category, days of week, and periods

Second Assumption

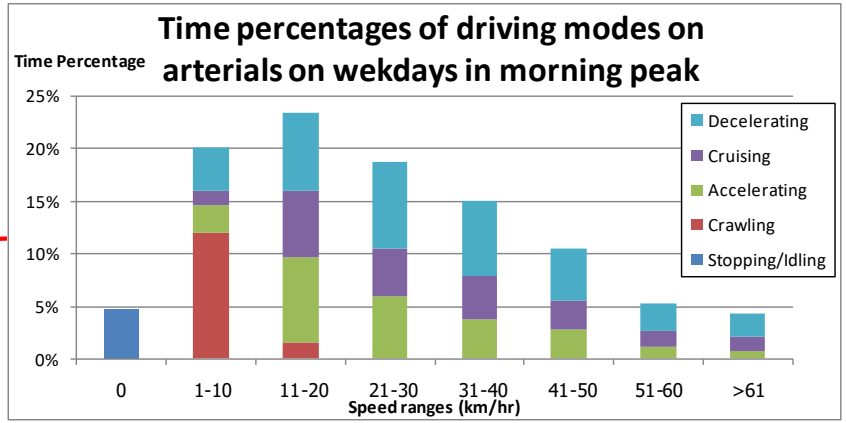
- Private vehicles in BMR will be replaced by hybrid cars
- Specify the policy is hybrid car sales will be 25% of private cars proposed by Energy and Policy office, Ministry of energy of Thailand in 2011 for the 20-year energy efficiency plan (2011 to 2031)
- The aims to estimate fuel consumption for studying reduction impacts if amount of hybrid cars increase from the present year (2016) to 15 years later (2031)

How to estimate fuel consumption (First Assumption)

All probe vehicles (10,000 taxis) will replace by hybrid cars

Ordinary Case; BAU (Without HEV)

$$FC_{WithoutHEV} = \sum_{m,s} \left(FC_{m,s}^{Con} \times TS_{m,s} \right)$$



Where

m = driving mode, s = speed range

$FC_{WithoutHEV}$ = Total fuel consumption for With HEV (CC)

$FC_{m,s}^{Con}$ = Mobile fuel consumption during gasoline engine ON (CC/sec) of hybrid car in each i and j

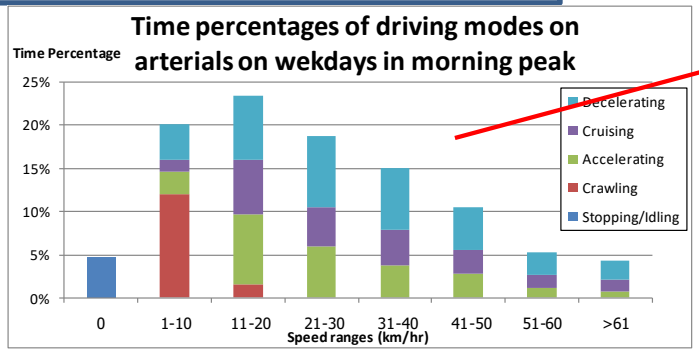
$TS_{i,j}$ = Time sharing in each i and j from probe data (sec)

Driving Modes	Accelerating			
Speed Range (km/h)	ON	sec	OFF	sec
0	-	-	-	-
1-10	1.95	155	0	0
11-20	1.24	169	0	0
21-30	1.39	123	0	0
31-40	1.65	95	0	0
41-50	1.96	78	0	0
51-60	1.58	64	0	0
>61	1.27	21	0	0
Total time frequency (sec)	-	705	-	0
Avg. Fuel consumption (CC/sec)	1.58	-	-	-

How to estimate fuel consumption (First Assumption)

Hybrid System Replacing Case (With HEV)

$$FC_{WithHEV} = \sum_{m,s}\left(FC_{m,s}^{HEV} \times TS_{m,s} \times \frac{Freq_{on,m,s}}{Freq_{on,m,s} + Freq_{off,m,s}}\right)$$



Driving Modes	Accelerating			
Speed Range (km/h)	ON	sec	OFF	sec
0	-	-	-	-
1-10	1.09	82	0	70
11-20	0.82	101	0	74
21-30	1.12	86	0	39
31-40	1.16	70	0	35
41-50	1.16	49	0	32
51-60	1.33	33	0	33
>61	1.11	25	0	0
Total time frequency (sec)	-	446	-	283
Avg. Fuel consumption (CC/sec)	1.11	-	-	-

Where

m = driving mode, s = speed range

$FC_{WithoutHEV}$ =Total fuel consumption for Without HEV (CC)

$FC_{m,s}^{Con}$ = Mobile fuel consumption (CC/sec) of conventional car in each m and s

$TS_{i,j}$ = Time sharing in each i and j from probe data (sec)

$Freq_{on,m,s}$ and $Freq_{off,m,s}$ = Time frequency (sec) of gasoline engine operated (ON) or in-operated (OFF)

For effective finding the impact

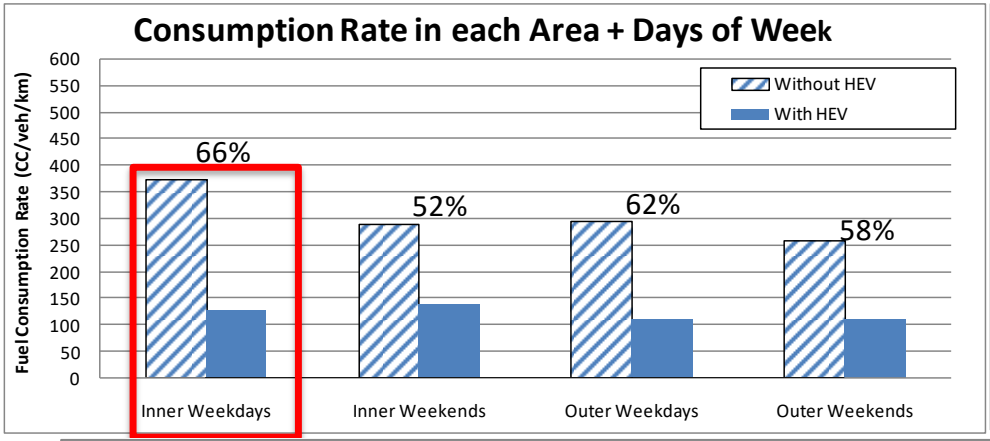
$$Fuel\ Consumption\ Rate = \frac{FC_{With\ or\ WithoutHEV}}{VKT\ from\ probe\ data}$$

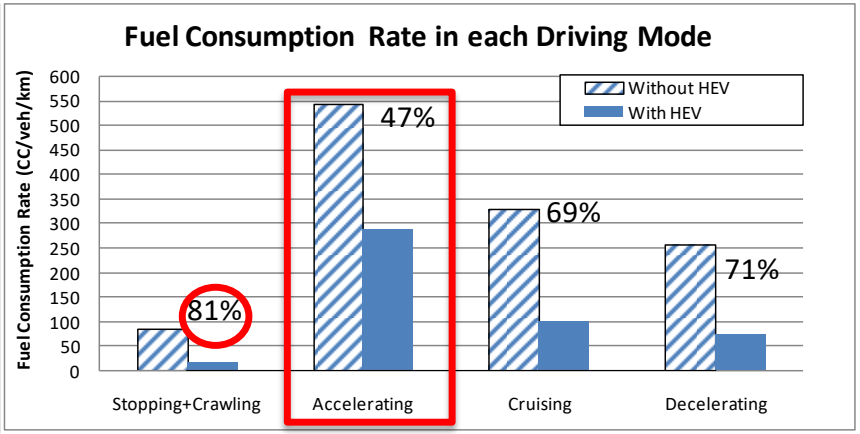
VKT = vehicle kilometer traveled collected from probe data

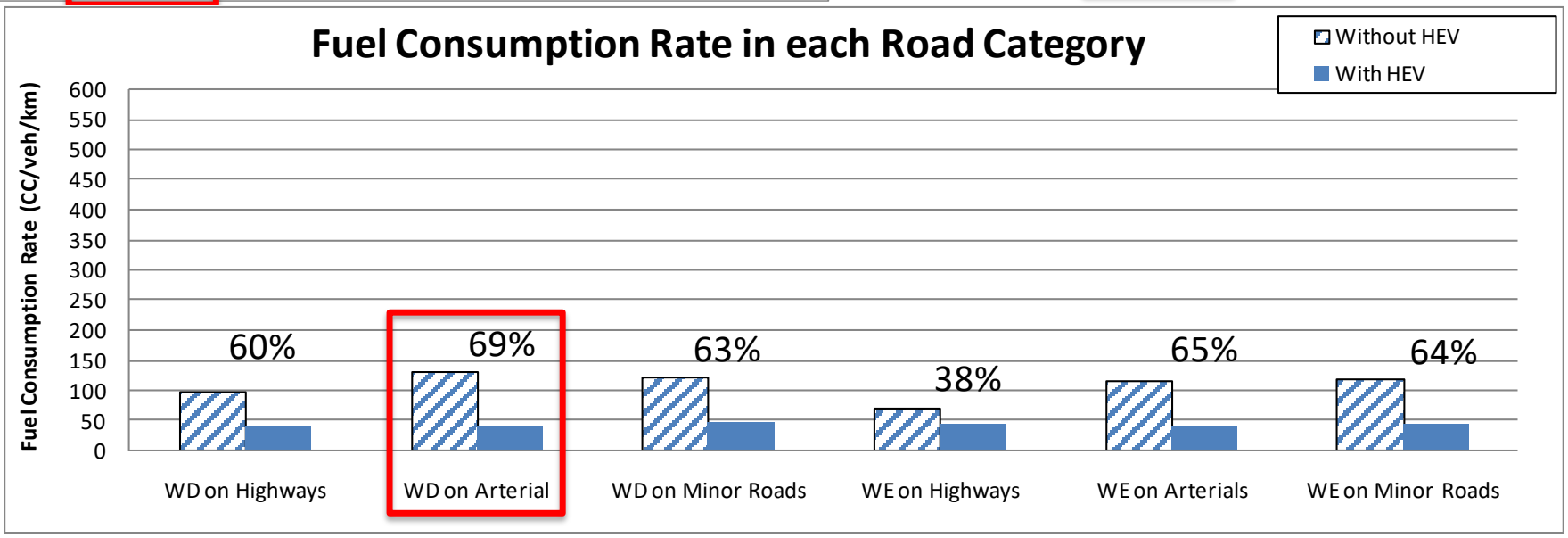
Estimate the impacts on fuel consumption reduction

Impact on Fuel Estimation Reduction (First Assumption)

All probe vehicles (10,000 taxis) will replace by hybrid cars







Note: WD = weekdays, WE = weekends

How to estimate fuel consumption (Second Assumption)

Private cars (PC) will replace by hybrid cars

Ordinary Case; BAU (Without HEV)

Equation

No. of vehicles

Distance (km)

$$FC_{y,k,f,r,d,p} = \sum_{l} \left(Traffic\ volume_{l,y,d,p} \times \left(\frac{V}{3600} \times \frac{\sum_{s,m} TS_{s,m}}{Probes} \right)_{l,r,d,p} \right) \times Veh\ type\%_{y,k} \times Fuel\ share\%_{y,k,f} \times \frac{1}{FE_{k,f}}$$

Fuel economy (km/liter)

Where

y = year, l = link, k = vehicle type, f = fuel share
r = road category, d = days of week, p = period
s = speed range, m = driving modes

$FC_{y,k,f,r,d,p}$ = Fuel consumption in future year (liter per day)

$Traffic\ volume_{l,y,d,p}$ = Link traffic volume in future year (vehicle per day)

V = Link average speed calculated from probe data (km/hr)

$TS_{s,m}$ = Time sharing of driving mode in each speed range and link calculated from probe data (sec)

$FC_{s,m}$ = Mobile fuel consumption (liter/sec) of hybrid cars in each driving mode and speed range

$FE_{k,f}$ = Fuel economy (kilometer-veh /liter)

$Veh\ type\%_{y,k}$ = Percentage of each vehicle type in future year

$Fuel\ share\%_{y,k,f}$ = Percentage of each fuel in each vehicle type in future year

$Probes$ = Amount of probe vehicles detected in each link

How to estimate fuel consumption (Second Assumption)

Hybrid car sales expansion (With HEV)

Equation

No. of vehicles

Time (sec)

Fuel economy (liter/sec)

$$FC_{y,hybrid,r,d,p} = \left[\sum_{l}(Traffic\ volume_{l,y,d,p})\right] \times \left(\frac{\sum_{m,s}(TS \times FC)_{m,s}}{\sum_{l} Probes}\right)_{r,d,p} \times PC\%_y \times Hybrid\ Share\%_y$$

Where

y = year, l = link, r = road category, d = days of week, p = period, s = speed range, m = driving modes

$FC_{y,\ hybrid,r,d,p}$ = Fuel consumption of hybrid cars in future year (liter per day)

$Traffic\ volume_{l,y,d,p}$ = Link traffic volume only in future year (vehicle per day)

V = Link average speed calculated from probe data(km/hr)

$TS_{m,s}$= Time sharing of driving modes in each speed range and link calculated from probe vehicles (sec)

$FC_{m,s}$ = Mobile fuel consumption (liter/sec/veh) of hybrid cars in each driving mode and speed range

$PC\%_y$ = Percentage of private cars in future year

$Hybrid\ share\%_y$ = Percentage of hybrid share in each vehicle type in future year

$Probes$ = Amount of probe vehicles detected in each link

Condition

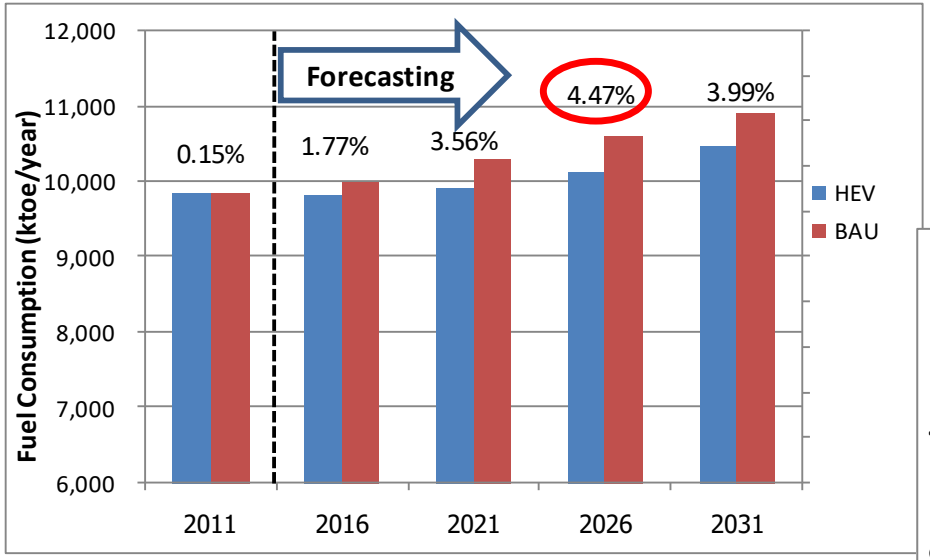
- Growth rates are used for forecasting traffic volume, vehicle type percentage, and fuel share percentage
- Hybrid cars will change fuel share percentage of private cars.

Impact on Fuel Estimation Reduction (Second Assumption)

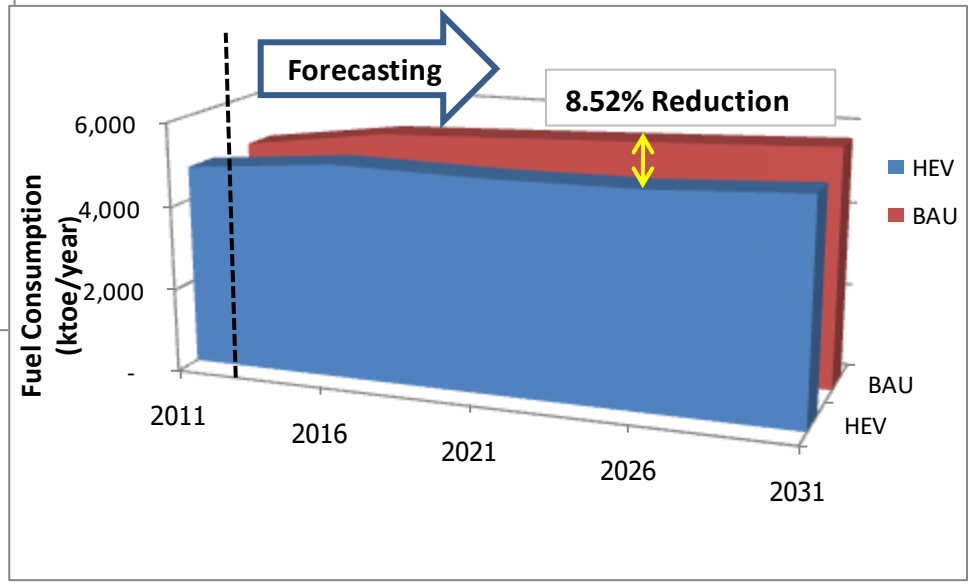
Private cars (PC) will replace by hybrid cars

Share of HEV for private cars for vehicle sales

Year	2010	2015	2025	2025	2030
HEV for PC	0.4	4.6	18.3	24.3	25.0



All vehicles comparison



Within private cars comparison

HEV can reduce 474 ktoe/year in 2026

Verification of Fuel Consumption Reduction

Comparison of fuel consumption rate (cc/veh/km) reduction percentages in each condition between probe data and real running test

Conditions	Probe data			Real running test			% Different between 2 data
	Conventional	Hybrid	% Reduction	Conventional	Hybrid	% Reduction	
WD on Highways	102	40	61%	100	44	56%	5%
WD on Arterial	136	40	70%	161	53	67%	3%
WD on Minor Roads	134	46	65%	156	53	66%	1%
WE on Highways	69	42	39%	65	35	46%	7%
WE on Arterials	119	43	63%	137	44	68%	4%
WE on Minor Roads	94	34	64%	97	35	64%	0%

Note: WD = weekdays, WE = weekends

Different reduction percentages in most conditions between 2 data are not very different from each other (< 10%)

Proving reduction % is reliable

Conclusion

- Time sharing of driving modes, especially stopping and crawling mode, can well reflect traffic congestion
- Inner area of BMR on weekdays on arterials is the conditions that have greatest impacts on fuel consumption corresponding with traffic congestion calculated from time sharing of driving modes
- If hybrid cars replace all probe vehicles, fuel reduction impacts are clearly observed in the inner area on weekdays, on arterials, and on stopping/crawling mode
- If vehicles sales of hybrid cars increases to 25% of PC in 2031, fuel consumption can be reduced up to 4.47% of all road transportation in BMR and 8.52% of all private cars in 2026

Thank you for your attention