TP 15213E

Maximizing the Benefit of Hybrid Buses

March 2010

Final Report

Prepared for
Transportation Development Centre
Of Transport Canada

By
CrossChasm Technologies Inc.

CrossChasm

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By
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DISCLAIMER

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Since some of the accepted measures in the industry are imperial, metric units are not always used in this report.

Un sommaire français se trouve avant la table de matières.

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16. Abstract

This project combined data acquisition and advanced vehicle simulation to evaluate methods, tools, and technologies to maximize the benefit of hybrid buses. Specifically, the project sought to:

- evaluate the current state of hybrid bus operation,
- generate tools to assist transit operators in the procurement and deployment of hybrid buses, and
- quantify and compare various energy storage technologies for next-generation hybrid vehicles.

Using the high-fidelity simulations that were developed as a result of the data-acquisition phase of the project, fuel consumption and resulting hybrid bus fuel savings were obtained for a number of routes. These routes included both Toronto Transit Commission (TTC) routes, standardized test routes such as the Heavy-Duty UDDS, and routes from other transit authorities such as New York City. The results showed the fuel savings varied widely based upon drive cycle, varying from less than 3 L/100km in savings to more than 75 L/100km in savings. The 75 L/100km result was observed on a New York City drive cycle, and represented a 44% reduction in fuel use. The results underscored the need to evaluate the savings based upon the transit authorities own route data rather than utilize another transit authority's experience and data.

The comparison of energy storage technologies included high-fidelity models using battery, battery-ultracapacitor, ultracapacitor, and flywheel systems. All systems were modeled on the Series hybrid topology, similar to that of the Nova/Allison hybrid bus. Based upon the results it is recommended that hybrid flywheel and ultracapacitor powertrains be built and evaluated.

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16. Résumé

Le présent projet a combiné la collecte de données et la simulation de véhicules avancée pour évaluer les méthodes, les outils et les technologies visant à maximiser les avantages des autobus hybrides. Plus précisément, le projet cherchait à :

- évaluer l'état actuel de l'exploitation des autobus hybrides;
- produire des outils pour aider les exploitants du transport en commun à acheter et à déployer les autobus hybrides;
- quantifier et comparer diverses technologies de stockage de l'énergie pour les véhicules hybrides de la prochaine génération.

À l'aide des simulations hautement fiables élaborées lors de la phase de collecte de données du projet, on a obtenu la consommation de carburant et les économies résultantes de carburant par les autobus hybrides pour un certain nombre de trajets. Ces trajets incluaient des trajets de la Toronto Transit Commission (TTC), des trajets d'essai standardisés comme le Heavy-Duty UDDS, et des trajets d'autres commissions de transport comme celle de la ville de New York. Les résultats ont montré que les économies de carburant variaient largement selon le cycle de conduite, allant de moins de 3 L/100 km à plus de 75 L/100 km. Le résultat de 75 L/100 km a été observé dans un cycle de conduite de la ville de New York, et il représentait une réduction de 44 % de la consommation de carburant. Les résultats ont souligné l'importance d'évaluer les économies selon les données sur les trajets de sa propre commission de transport, plutôt que d'utiliser l'expérience et les données d'une autre commission de transport.

La comparaison des technologies de stockage de l'énergie incluait des modèles hautement fiables utilisant des systèmes de batteries, de batteries-supercondensateurs, de supercondensateurs et de volants. Tous les systèmes sont fondés sur la topologie hybride à configuration en série, semblable à celle des autobus hybrides Nova/Allison. Selon les résultats, on recommande de construire et d'évaluer les volants et les supercondensateurs hybrides.

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EXECUTIVE SUMMARY

This project combined data acquisition and advanced vehicle simulation to evaluate methods, tools, and technologies to maximize the benefit of hybrid buses. Specifically, the project sought to:

- evaluate the current state of hybrid bus operation,
- generate tools to assist transit operators in the procurement and deployment of hybrid buses, and
- quantify and compare various energy storage technologies for next-generation hybrid vehicles.

Based upon data captured on an operational Toronto Transit Commission (TTC) hybrid Orion VII bus, the drive cycle sensitivity of hybrid buses was quantified. The variance in drive cycles observed in TTC operation resulted in fuel consumptions ranging from 43.4 to 61.5 L/100 km. An analytic model was developed to enable fleet operators to estimate fuel consumption based upon drive cycle characteristics. The resulting model provided initial fuel consumption estimates that were generally within 5 L/100 km but could be off by as much as 15 L/100 km. A simulation-based approach was also used to develop fuel consumption estimates and was found to provide a high level of accuracy predicting fuel consumption based upon drive cycle data. By comparison, the simulation-based approach was generally within 2 L/100 km, compared to 5.

Using the high-fidelity simulations that were developed as a result of the data-acquisition phase of the project, fuel consumption and resulting hybrid bus fuel savings were obtained for a number of routes. These routes included both TTC routes, standardized test routes such as the Heavy-Duty UDDS, and routes from other transit authorities such as New York City. The results showed the fuel savings varied widely based upon drive cycle, varying from less than 3 L/100 km in savings to more than 75 L/100 km in savings. The 75 L/100 km result was observed on a New York City drive cycle, and represented a 44% reduction in fuel use. The results underscored the need to evaluate the savings based upon the transit authorities own route data rather than utilize another transit authority's experience and data.

The comparison of energy storage technologies included high-fidelity models using battery, battery-ultracapacitor, ultracapacitor, and flywheel systems. All systems were modeled on the Series hybrid topology, similar to that of the Nova/Allison hybrid bus. The results demonstrated that the battery-hybrid or ultracapacitor-hybrid systems had the lowest fuel consumption, depending on drive cycle characteristics. However, considering the degradation considerations of batteries, the fuel consumption results suggested that ultracapacitor and/or flywheel energy storage technologies could be ideally suited for transit bus operations. The results clearly indicate that substantial improvement remains achievable and that ultracap and flywheel systems should be considered for these hybrid powertrains.

The results obtained herein were combined with feedback provided from the TTC based upon their experience to date with hybrid buses. These were compiled into a best-practices summary that is included herein and in a separate summary marketing document.

Based upon the results it is recommended that hybrid flywheel and ultracapacitor powertrains be built and evaluated. This can be achieved efficiently through the development of a modular testbed that is capable of demonstrating and evaluating the performance of both technologies over various cycles, validating the simulation results and establishing the commercial viability/benefit of these hybrids.

SOMMAIRE

Le présent projet a combiné la collecte de données et la simulation de véhicules avancée pour évaluer les méthodes, les outils et les technologies visant à maximiser les avantages des autobus hybrides. Plus précisément, le projet cherchait à :

- évaluer l'état actuel de l'exploitation des autobus hybrides;
- produire des outils pour aider les exploitants du transport en commun à acheter et à déployer les autobus hybrides;
- quantifier et comparer diverses technologies de stockage de l'énergie pour les véhicules hybrides de la prochaine génération.

On a utilisé les données relatives à un autobus hybride Orion VII utilisé par la Toronto Transit Commission (TTC) pour quantifier la sensibilité aux cycles de conduite des autobus hybrides. La variance des cycles de conduite observée à la TTC a donné des consommations de carburant allant de 43,4 à 61,5 L /100 km. On a élaboré un modèle analytique pour permettre aux exploitants de flottes d'estimer la consommation de carburant d'après les caractéristiques du cycle de conduite. Le modèle résultant a fourni des estimations de la consommation initiale de carburant, généralement à 5 L/100 km près, mais qui pouvaient parfois être à 15 L/100 km près. On a également utilisé des simulations pour estimer la consommation de carburant, et cette méthode, prédisant la consommation de carburant d'après les données sur le cycle de conduite, s'est avérée très exacte. À titre de comparaison, la méthode par simulation a donné des résultats précis à 2 L/100 km près, par rapport à 5 L/100 km.

À l'aide des simulations hautement fiables élaborées lors de la phase de collecte de données du projet, on a obtenu la consommation de carburant et les économies résultantes grâce aux autobus hybrides pour un certain nombre de trajets. Ces trajets incluaient des trajets de la Toronto Transit Commission (TTC), des trajets d'essai standardisés comme le Heavy-Duty UDDS et des trajets d'autres commissions de transport comme celle de la ville de New York. Les résultats ont montré que les économies de carburant variaient largement selon le cycle de conduite, allant de moins de 3 L/100 km à plus de 75 L/100 km. Le résultat de 75 L/100 km a été observé dans un cycle de conduite de la ville de New York, et il représentait une réduction de 44 % de la consommation de carburant. Les résultats ont souligné l'importance d'évaluer les économies selon les données sur les trajets de sa propre commission de transport, plutôt que d'utiliser l'expérience et les données d'une autre commission de transport.

La comparaison des technologies de stockage de l'énergie incluait des modèles hautement fiables utilisant des systèmes de batteries, de batteries-supercondensateurs, de supercondensateurs et de volants. Tous les systèmes sont fondés sur la topologie hybride à configuration en série, semblable à celle des autobus hybrides Nova/Allison. Les résultats ont démontré que les systèmes hybrides à batteries ou à supercondensateurs étaient associés à la plus faible consommation de carburant, selon les caractéristiques du cycle de conduite. Toutefois, si l'on tient compte de la dégradation des batteries, les résultats de la consommation de carburant suggèrent que les technologies de supercondensateur ou de stockage de l'énergie des volants pourraient parfaitement convenir aux autobus des commissions de transport. Les résultats indiquent clairement que des améliorations substantielles restent possibles et que les systèmes de supercondensateurs et de volants devraient être envisagés pour ces groupes motopropulseurs hybrides.

Les résultats obtenus ici ont été combinés avec ceux obtenus par les intervenants de la TTC, d'après leur expérience des autobus hybrides jusqu'à ce jour. Tous ces résultats ont été compilés dans un sommaire des pratiques exemplaires inclus dans le présent document et dans un document sommaire de commercialisation.

Les résultats nous amènent à recommander la construction et l'évaluation de groupes motopropulseurs hybrides à volants et à supercondensateurs. On peut y arriver efficacement grâce à l'élaboration d'un banc d'essai modulaire capable de démontrer et d'évaluer le rendement des deux technologies pour divers cycles, ce qui validera les résultats de la simulation et établira la viabilité et les avantages commerciaux de ces véhicules hybrides.

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UNITS AND CONVENTIONS

The following unit conventions are used:

Velocity	km/h	or	m/s
Mass	kg		
Distance	km	or	m
Power	kW	or	W
Energy	kWh	or	J
Rotational Velocity	Rpm		

GLOSSARY

PSAT	Powertrain System Analysis Toolkit
ESS	Energy Storage System
ECU	Engine Control Unit
UC	Ultracapacitor
GVWR	Gross Vehicle Weight Rating
HD_UDDS	Heavy-Duty Urban Dynamometer Driving Schedule
ADEME	Agence de l'environnement et de la maîtrise de l'énergie (agency from which French Drive Cycle was obtained)
WTVC	World-wide Transient Vehicle Cycle
CBD	Central business District cycle
OCTA	Orange Country Transit Authority cycle
TTC	Toronto Transit Commission
GPS	Global Positioning System
GSM	Global System for Mobile Communications

1. Introduction

As introduced in the project contract:

> *The transport of people and merchandise represents over 30% of all energy consumed in Canada. At present almost all transport fuels are derived from fossil fuels raising serious concerns about energy security, climate change, and price instability in the short to medium term.*
>
> *Transport Canada supports effective action to reduce climate change and requires a widespread shift to new or improved technologies in the transportation sector. Hybrid technology offers a vector to utilize electric drive and decrease fuel requirements for a wide range of vehicle applications such as hybrid buses. The reduction in petroleum fuel use translates directly into reduced greenhouse gas and criteria air contaminant emissions, improved energy security, decreased operating costs and improved air quality in cities in Canada and around the world.*

Since 2005, urban buses equipped with parallel electric hybrid drive systems have slowly been introduced into circulation in Canadian cities with mixed results. While the majority of the press coverage has been positive, some negative exposure has surrounded some of the hybrid buses that have shown limited fuel consumption reductions and poor battery life. As a result there has been some doubt cast in the public eye as to the ability of hybrid buses to successfully reduce fuel consumption and greenhouse gas emissions. Additionally, the substantial incremental cost of hybrid bus powertrains makes purchase decisions all the more difficult to justify on a cost / benefit basis especially when there is evidence, history and even published press articles of less than expected performance. Currently, the incremental cost of the hybrid option exceeds $200,000 with studies demonstrating fuel reduction benefits as low as 10%.

Some of the reasons for reports of poor performance have been due to the fact that buses have not been deployed on routes that would most benefit from the use of hybrid drive. Higher frequency of stop and start events are more suited to maximize the benefits of hybrid drive as opposed to higher constant speed suburban driving. Long-term reliability of hybrid powertrains also plays a key role in the cost / benefit calculation. There has been evidence to show that early and current battery technology can play a significant role in underperformance of hybrid buses and therefore potentially negating some or all of the cost reductions provided from reduced fuel consumption.

Heavy vehicle applications such as buses (and refuse trucks) are in the fortunate situation of having the potential to reap the most benefit from hybrid powertrains because of their duty cycle characteristics. Deployment of hybrid buses to the appropriate routes can affect the adoption rates of this technology if vehicle technology is not properly utilized for maximum benefit. While this is a simple theory in concept, to actually compare and evaluate bus routes on this basis is not a simple straightforward task that can be accomplished by fleet managers. The driving characteristics of heavy vehicle urban routes call upon high acceleration and high deceleration events where hybrid powertrains see high amounts of electrical motor power demands as well as generation. The ability for the electrical energy storage device to deliver and absorb the required energy in an efficient and long-time durable manner can make or break the business case for any vehicle.

Sub-optimal efficiency in the energy storage system results in lost opportunity for operating cost reductions and longer payback periods. Likewise, any lack of durability or life time for any hybrid drivetrain component, especially the relatively new application of energy storage devices has a first order effect on payback for hybrid powertrain premiums.

Battery technology has progressed substantially in recent years however the combination of duty cycle and vehicle weight of an urban bus demands extremely high power input and output events from the battery. Such demanding operating requirements ultimately result in reduced battery life as well as reduced ability of the battery to absorb and deliver energy efficiently due to internal resistance losses and increased parasitic energy consumption for thermal management systems.

Ultracapacitors represent an ideal energy storage option for hybrid powertrains that require high power capability and cycle life. High cycle life refers to the ability of the energy storage system to maintain performance for a high number of operational cycles. The high-power/low-energy pulse profile of refuse trucks have resulted in the recent introduction of ultracapacitor-based refuse trucks. Based upon duty cycle characterization, a logical subsequent step in the technology adoption of ultracapacitor hybrids could be urban buses. Currently, early versions of these powertrains have been released by ISE Corporation and Voith Turbo.

Flywheel energy storage is another promising alternative for hybrid powertrains. Initial results have suggested that flywheels maintain performance over a number of years and thousands of cycles, have high power capability, and exhibit high efficiency. Flywheel energy storage merits further investigation for high-power urban trucks and buses.

2. Objectives

As defined in the contract, the objective of the project is to utilize a three-phase approach at helping hybrid powertrains deliver the most benefit to fleet operators. These objectives include:

1. Address the best way to decide where to apply hybrid technology in one's bus fleet by the development of a simple map-based decision-making tool.
2. Investigate combining real-world operational data with the newest vehicle energy simulation software to evaluate ultracapacitor-hybrid, ultracapacitor-battery-hybrid, flywheel-hybrid and battery-hybrid urban buses and compare to existing conventional and current hybrid buses.
3. Maximize the utility of the results. A condensed highly targeted document and webpage will be created for quick reference by Canadian urban fleet managers when considering technology-route combinations and new vehicle purchases.

3. Project Process and Phases

To obtain the objectives listed above, a three-phase approach is undertaken. The first phase consists of obtaining performance data from existing vehicle operation. The second phase is split into two parallel streams; with one stream developing and evaluating a method for estimating relative fuel consumption of the existing vehicles and the second stream developing next-generation vehicle models and evaluating their fuel consumption on the drive cycles captured in the first phase. The third phase focuses on the reporting of these results and summarizing the best-practices of hybrid bus procurement and deployment based upon a large fleet's experience.

As introduced, **Phase 1** includes data-acquisition from an operational Toronto Transit Commission (TTC) hybrid bus. **Phase 2a** develops and evaluates an estimation tool that could assist in identifying the optimal routes for a given powertrain technology. To achieve this, key drive cycle parameters that could be determined from fleet metrics or map data would be identified. Correlations between those parameters and actual energy consumption will be developed. The estimation tool will then predict in relative terms which routes would most likely provide the most benefit to hybrid drives. Direct estimation of fuel consumption from fleet metrics or map data in order to develop a decision making tool is investigated. The results highlight the level of accuracy achievable in the initial system. Additionally, methods for improving the estimation accuracy will be identified. The intent of this phase is to develop a simple tool that could be used by a bus fleet operations team to identify route-technology pairings.

Phase 2b focuses on the fuel consumption of various advanced powertrains based upon real-world duty cycles. The intent of this phase is to identify both the sensitivity of these technologies to drive cycles and to compare their relative fuel consumption to identify what technology is best suited for urban bus applications by providing fuel consumption estimates across all of the routes captured in the first task.

To achieve those answers, advanced powertrain models are developed in the Powertrain System Analysis Toolkit (PSAT) framework, based upon the MATLAB/SIMULINK modeling software. The process covered in CrossChasm Technologies' provisional patent entitled "System, method, and computer program for simulating vehicle energy use" will be used to complete this phase.

Phase 3, not shown in graphic, focuses on the generation of a marketing document, covering the best-practices identified throughout the project that could be used by other Canadian urban bus fleet managers. The objective of this document is to maximize the utility of the results by creating a concise, but highly targeted document and webpage for quick reference by fleet managers when considering technology-route combinations and new vehicle purchases.

A detailed description of the individual tasks and timing for the three month project is provided in Figure 3-1. In summary, the project is structured with the following phases, with associated primary and secondary objectives:

Phase 1 – Real-World Operational Data

Primary Objectives

- Obtain real-world drive cycles at 5Hz for a large Canadian transit operator in operation, capturing the widest range, as possible, of drive cycles experienced within that fleet.

Secondary Objectives

- Capture operational data to asses real-world hybrid bus fuel consumption (for Phase 2a)
- Gain operational hybrid bus data to understand baseline control logic (for Phase 2a)
- Capture operational data to develop component models for both hybrid and conventional powertrains (Phase 2a and 2b)

Phase 2a – Analytic Decision-Making Tool

Primary Objectives

- Quantify the real-world fuel consumption of a current hybrid bus in operation.
- Analyze route data to identify key route metrics
- Correlate route metrics to fuel performance and assess accuracy

Secondary Objectives

- Compare prediction accuracy of the analytic decision model to a PSAT simulation model

Phase 2b – Model-Based Design of Hybrid Bus Powertrain for Various Energy Storage Technologies

Primary Objectives

- Develop hybrid bus models using various energy storage technologies
- Utilize drive cycle data captured in Phase 1 to evaluate and compare the various energy storage technologies for beginning of life performance

Secondary Objectives

- Develop preliminary hybrid control logic that is customized for each energy storage technology

Phase 3 – Final Report and Best-Practices Document

Primary Objectives

- Generate a final report including all key technical results
- Generate a marketing document and associated webpage content as a quick-reference guide for transit operators in Canada considering hybrid bus procurement

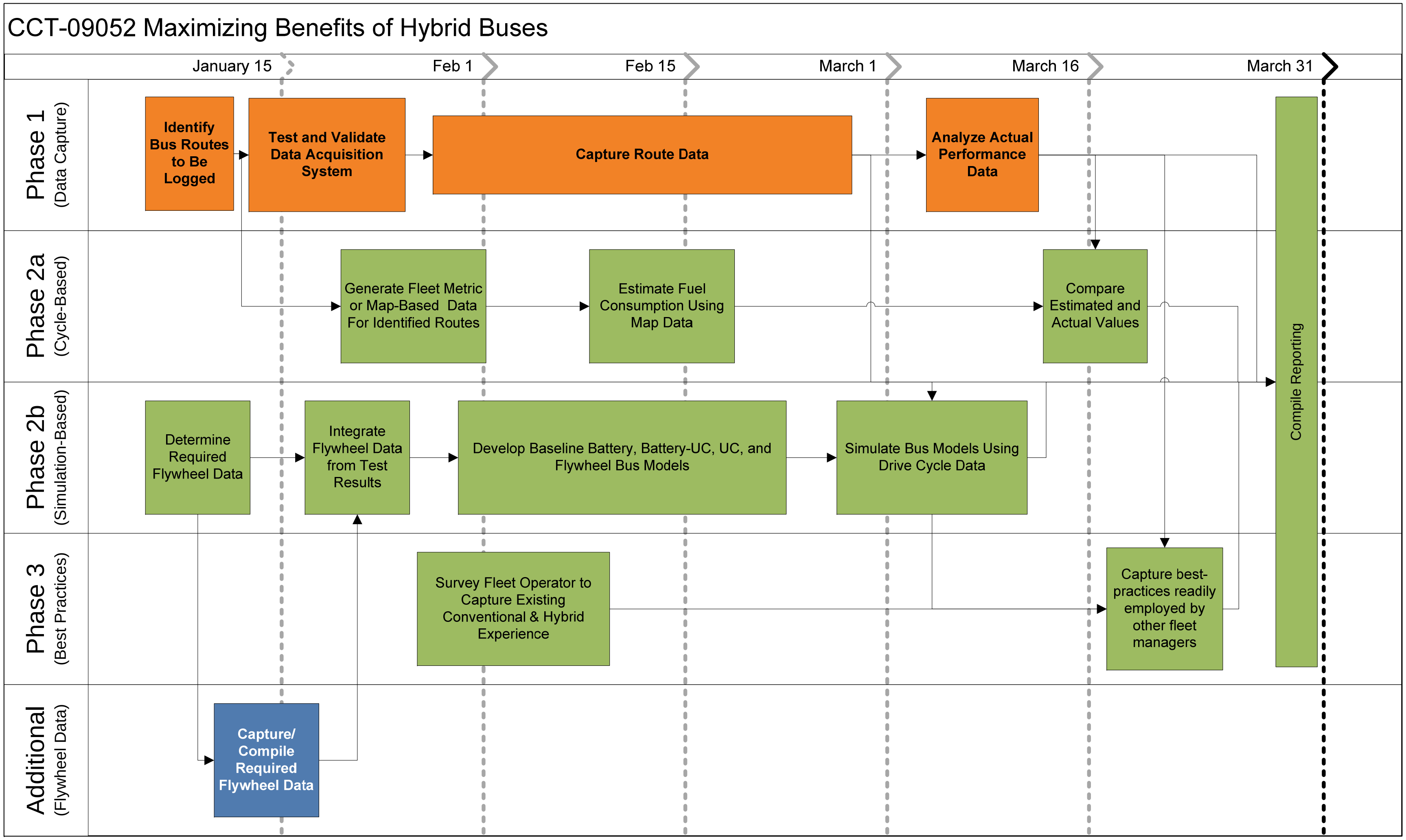


Figure 3-1: Project Process

4. Phase 1 – Real-World Drive Cycles & Operational Data

4.1 Service Facility Identification

The transit partner, TTC, operates five large service facilities throughout the Greater Toronto Area (GTA). Each service facility operates independently with their own fleet of buses, route responsibilities, and service personnel. Based upon TTC's guidance, the project was required to engage only one service facility. As a result, in order to achieve the overall project objective it was important that the service facility with the largest variance of drive cycles (low speed, high speed, rapid stop-start, etc) be selected.

To identify the service facility, the routes by service facility were analyzed, which quickly identified the Wilson and Arrow facilities as having the widest variation of route types. Key routes from the two facilities were then compared based upon average speed. The values are shown in the figure below. The results showed that Arrow's key routes had higher average speeds, with only two routes that had average speeds of less than 20 km/h. Wilson; however, had both average route speeds ranging from 13 to 27 km/h. From this analyis the Wilson facility was selected for the project.

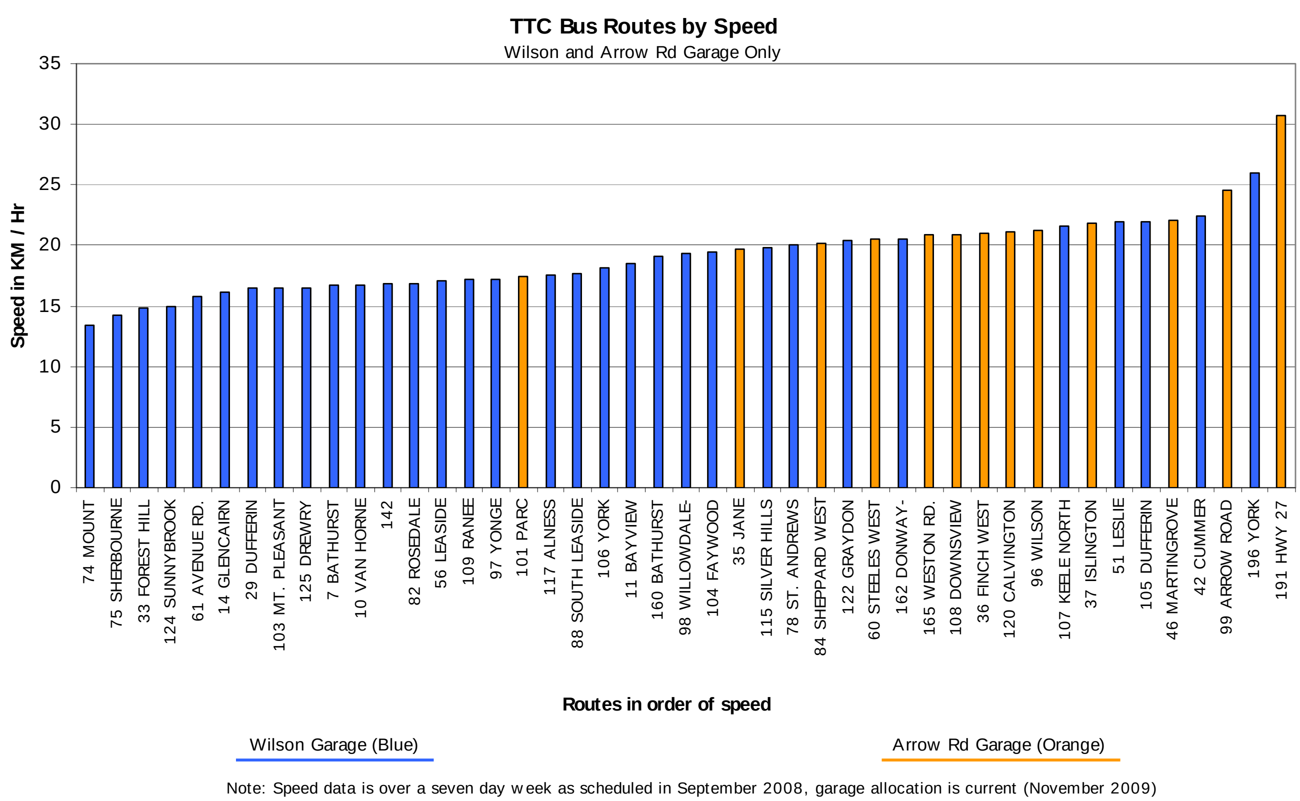


Figure 4-1: Average Route Speed for Toronto Transit Commission's (TTC's) Wilson and Arrow Rd Garages

4.2 Route & Bus Identification

Due to accessibility planning, only certain buses will be used for certain routes. Given the objectives of the project, the Orion VII "Next-Gen" hybrid platform was data-logged to assist in baseline model validation.

Since the Orion VII "Next-Gen" buses only operate on certain routes within the Wilson facility, the routes list had to be shortened by bus type. The route breakdown with accessibility requirements are shown below in Table 4-1 – with Orion VII "Next-Gen" buses being accessible buses with no lift capability.

Table 4-1: Wilson Garage Routes with Accessibility Requirements and Ranked by Average Speed

Route Number	Direction	Accessible/No Lift	Average Speed Rank (lower score = lower ave speed)
74	Mount	YES	1
75	Sherbourne	YES	2
33	Forest Hill	NO	3
124	Sunnybrook	YES	4
61	Avenue Rd	YES	5
14	Glencairn	YES	6
29	Dufferin	NO	7
103	Mt. Pleasant	YES	8
125	Drewry	YES	9
7	Bathurst	YES	10
10	Van Horne	YES	11
142	Downtown/Avenue Rd Express	NO	12
82	Rosedale	YES	13
56	Leaside	YES	14
109	Ranee	YES	15
97	Yonge	YES	16
117	Alness	NO	17
88	South Leaside	YES	18
106	York	YES	19
11	Bayview	YES	20
160	Bathurst	NO	21
98	Willowdale	YES	22
104	Faywood	YES	23
115	Silver Hills	YES	24
78	St. Andrews	YES	25
122	Graydon	YES	26
162	Donway	YES	27
107	Keele North	NO	28
51	Leslie	YES	29
105	Dufferin	YES	30
42	Cummer	YES	31
196	York	NO	32

Based upon the bus type requirements and drive cycle data obtained from TTC, ten desired routes were identified. Given that there are multiple bus runs that operate throughout a day, the next step was to identify the specific runs on those routes to be data-logged.

4.3Run Identification

From the routes listed in Table 4-1, ten routes were selected and submitted to TTC for the identification of ideal runs, which represent bus deployments. The run selection is important as a number of runs are "shoulder runs" meaning they only operate at peak morning and afternoon times; transitioning to other routes mid-day or returning to the service facility. Ideal runs repeated the same route throughout the day, thereby providing peak and non-peak repeats of the same route for project analysis.

Consequently, the following Route/Run combinations were identified and are summarized below. Where two runs are listed, either run is satisfactory. These routes represent a diverse set of drive cycles that the TTC services from the Wilson facility, which will provide a rich data set for the project.

Table 4-2: Route and Run Combinations Requiring an Orion VII Style Bus

Route	Direction	Accessible/ No Lift	Speed Rank	Priority Runs
74	Mount Pleasant	YES	1	Run 1 5.44am-1.48am
75	Sherbourne	YES	2	Run 92 4.49am-2.55am Run 1 4.34am-7.56pm
124	Sunnybrook	YES	4	Run 1 5.44am-7.09pm Run 2 5.56am-6.48am
103	Mt. Pleasant	YES	8	Run 1 5.38am-1.49am Run 2 5.43am-10.17pm
97	Yonge	YES	16	Run 2 5.10am-1.28am Run 3 5.30am-1.39am
11	Bayview	YES	20	Run 5 5.56am-1.45am Run 80 4.12am-2.07am
104	Faywood	YES	23	Run 2 5.49am-1.22am Run 3 6.26am-10.08pm
122	Graydon	YES	26	Run 1 5.42am-7.41pm Run 3 6.04am-8.06pm
105	Dufferin	YES	30	Run 2 5.35am-1.38am Run 1 5.07am-7.53pm
42	Cummer	YES	31	Run 2 5.38am-1.40am Run 3 5.49am-1.53am

From the above parameters, the following cycles were targeted as primary routes:

1) High-Speed "Least-Urban" Route: Route 42 - Cummer
2) "Average" Speed Route: Route 11 – Bayview
3) Low-Speed "Most-Urban" Route: Route 74 – Mount Pleasant

4.4 Desired J1939 Parameters

Data-acquisition was achieved by installing an ISAAC data-logger on the J1939 diagnostics port of an operational hybrid bus. The J1939 has a list for standard/suggested signals also known as PGNs. From the suggested PGN list, a set of messages that would assist in model development and validation was identified. This list represents a "wish-list" as vehicle manufacturers do not have to comply with the suggested message list so not all of the desired messages may be broadcast.

Based upon previous experience developing vehicle models from data-logged information, a recording frequency of 5 Hz (0.2s) was selected by Inertia and CrossChasm.

Table 4-3: J1939 Message IDs logged from the Hybrid Orion VII Bus

CAN Signal Name	CAN Message ID (PGN)	Frequency [Hz]
Vehicle ID	64957	Static
Vehicle speed (navigation based)	65256	5
Vehicle speed (wheel based)	65265	5
Latitude	65267	5
Longitude	65267	5
Engine Speed	61444	5
Actual Engine Per Torque	61444	5
Engine Demand - Percent Torque	61444	5
Drivers Demand Eng Percent Torque	61444	5
Reference Engine Torque	65251	Static
Engine Gas Mass Flow Rate 1	65170	5
Engine Coolant Temperature	65262	5

4.5 Data-Logger Integration

The data-acquisition unit was installed and operational as of January 15th, 2010. Figure 4-2 and Figure 4-3 show the integration into the bus. As evident in the bus information plate image, the bus model was 07.501 B/A having been built in August 2009. The bus was equipped with the newest lithium ion battery pack, as opposed to the early lead-acid variant.

A global positioning system (GPS) antenna and GSM modem were integrated into the data-acquisition system to provide location data to enable route identification and remote data harvesting, respectively. The first day of full operation with the data-acquisition system installed was January 19th, 2010.

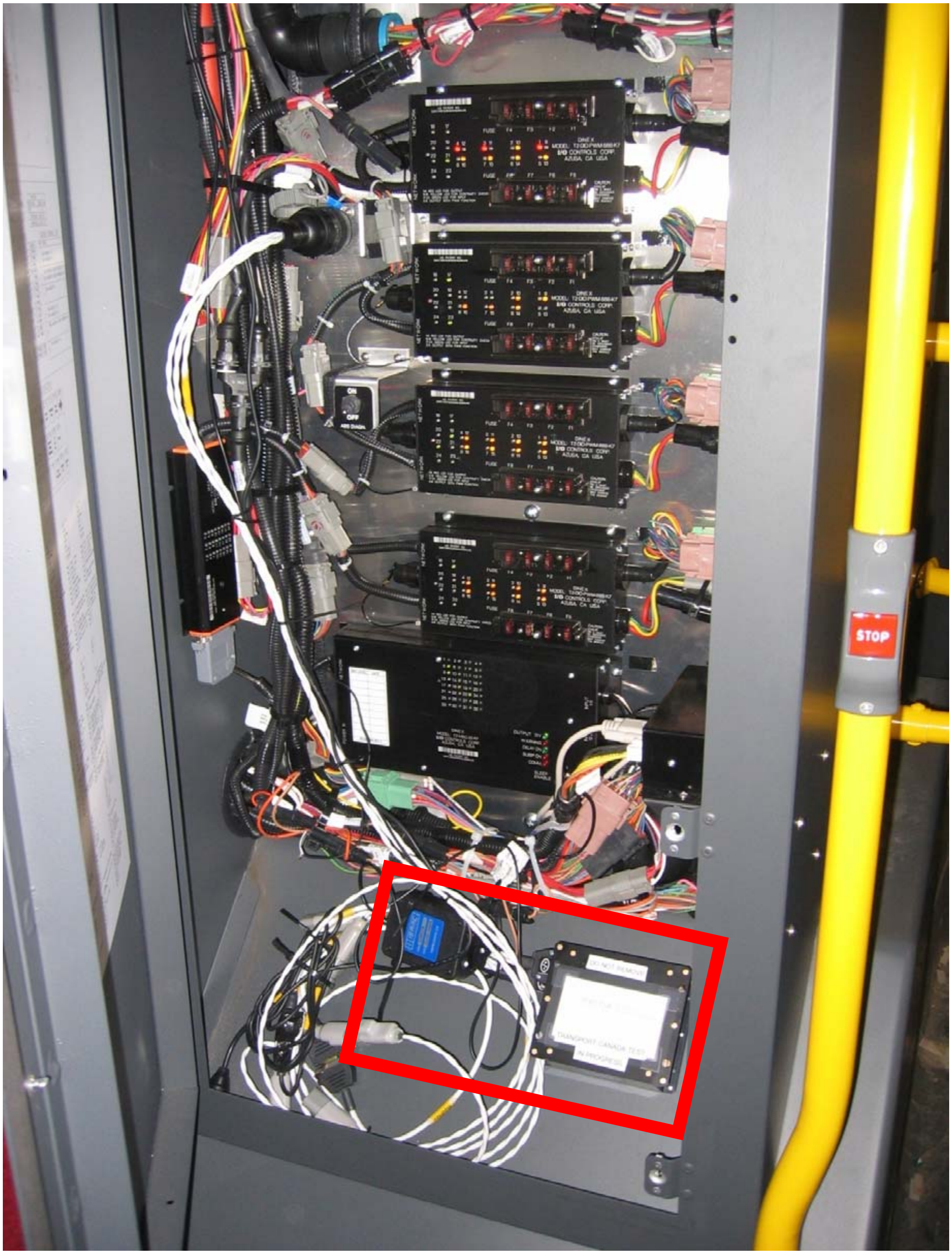


Figure 4-2: Data-logger Installation in Orion VII Hybrid Primary Access Panel (loggers and modem shown in red box)

Figure 4-3: Data-logged Bus, TTC #1825, Information Plate

Data-acquisition was continued until March 5th, 2010. The system was kept on the hybrid bus for the duration of the data-logging period. The decision to keep the logger on the hybrid bus as opposed to only capturing real-world fuel consumption on the hybrid for half of the period and a conventional bus for the remainder was due to Phase 1 objectives. Given that the objectives were to obtain drive cycle information, real-world vehicle fuel consumption for the less-understood hybrid powertrain, and capture operational data for model development the priority was given to capturing data on the hybrid bus. Additionally, given that both the conventional and hybrid Orion VII variants use a common bus glider and similar Cummins engines (ISB vs. ISL models), parameters and performance for the conventional vehicle could be accurately estimated based upon hybrid vehicle data.

4.6 Route Identification and GPS Data Summary

Section 4.3 identified the priority routes. These routes were identified in order to ensure that the 'extreme' drive cycles representing the full range of normal weekday routes are logged. The purpose of extracting fuel consumption data for these specific routes is to provide information usable to the **fleet dispatcher** who is responsible for bus/route assignments on a daily basis. The results are intended to be used as training information for the dispatcher by quantifying the impact and cost of optimal and non-optimal vehicle/route assignments.

The daily performance data was reviewed along with the associated GPS data. The GPS coordinates were mapped and associated Route assignments were identified. The 'stem to' and 'stem from' sections were removed from the analysis. The 'stem to' and 'stem from' sections represent the non-operational portion of the drive cycle related to the travel from the garage facility to the route's starting location and from the route's ending location respectively. The daily route assignments for the first twenty-five (25) days of data-acquisition are shown in **Table 4-4**. Generally a bus was assigned one route for the entire day, meaning that it continually repeated that route throughout the day. The few days where the bus was assigned to multiple routes are shown with two routes in the table below. The three priority routes were captured on January 20th, January 25th, and January 26th.

Table 4-4: Daily Route Assignments for Bus #1825 as Determined from GPS Data

Segment Start	Route
01-19 6:12AM	88
01-20 4:05AM	11
01-21 5:49AM	75
01-21 3:51PM	162
01-22 6:11AM	162
01:23 5:24AM	88
01-24 8:02AM	74
01-25 5:36AM	74/29
01-26 2:59PM	42
01-27 2:58AM	109
01-28 6:49AM	61
01-28 5:39AM	106
01-30 6:22PM	196
01-31 8:23AM	97
02-01 6:12AM	106
02-01 1:58PM	61
02-02 5:45AM	106
02-03 4:43AM	75
02-03 4:23PM	75/97
02-04 6:50AM	125
02-05 5:55AM	125
02-05 2:42PM	29
02-06 8:05AM	162
02-06 3:46PM	162
02-07 3:48AM	162

A sample of the summary data provided by Inertia, which included route assignment, basic summary data such as total hours of operation and distance, and route metrics including average speed and stop frequency is provided below. Additionally, map data with GPS data-points is provided. Summary and GPS route data is provided for a number of Routes in **Appendix A**.

Table 4-5: Summary Data for January 29, 2010 Operating on Route 106

Date	2010-01-29
TTC Route Travelled	106 York University
Time of Record(hour)	16.5
Distance Travelled(km)	317.8
Total Number of Stop	2478.0
Total Travel Time (hour)	11.4
Total Stop Time(hour)	5.0
Average Speed (kph)	19.3
Average Number of Stop (/km)	7.8

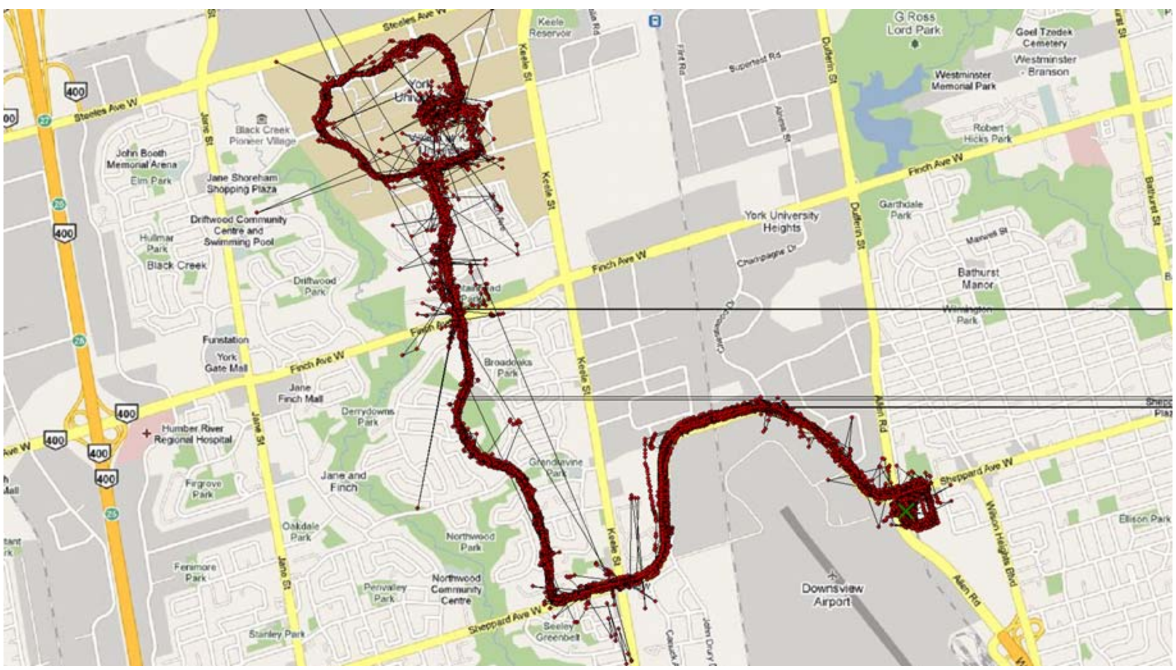


Figure 4-4: GPS Data Obtained from Bus #1825 on January 29, 2010

Subsequent to the initial phase of route identification and the successful capture of weekday operation of the three priority routes, the method of data analysis was modified. Whereas the route identification with ‘stem_to’ and ‘stem_from’ removal provided readily usable results for the fleet dispatcher, the second phase of data-acquisition analysis was tailored towards the interests of the **fleet manager**. In the second phase of analysis the routes were not identified and the drive cycles were observed as full-day cycles, with no consideration of route assignment. The purpose of this analysis is to provide total fuel consumption values over the course of normal daily operations and general variations in route assignments.

4.7Component Operational Data

As previously mentioned, a secondary objective of Phase 1 was capturing data to enable the development of components models. These component models will then be integrated into high-fidelity bus models to be used in Phases 2a and 2b. A representative sample is shown in Figure 4-5 below. The particular result provides the engine and vehicle speeds for a 700 second period. As was observed in reviewing all of the data, the engine in the Orion VII hybrid is not turned off during operation and operates in both load-leveling and load-following hybrid strategies depending on the state of the system. In the section shown, the engine is oscillating between load-following and load-leveling during the 89080 to 89230 section, whereas the engine is operating in exclusively load-following mode during the three subsequent launch events. Using the operational data, the primary control logic and engine efficiency maps were inferred and integrated into a baseline hybrid vehicle model that will be discussed in a following section.

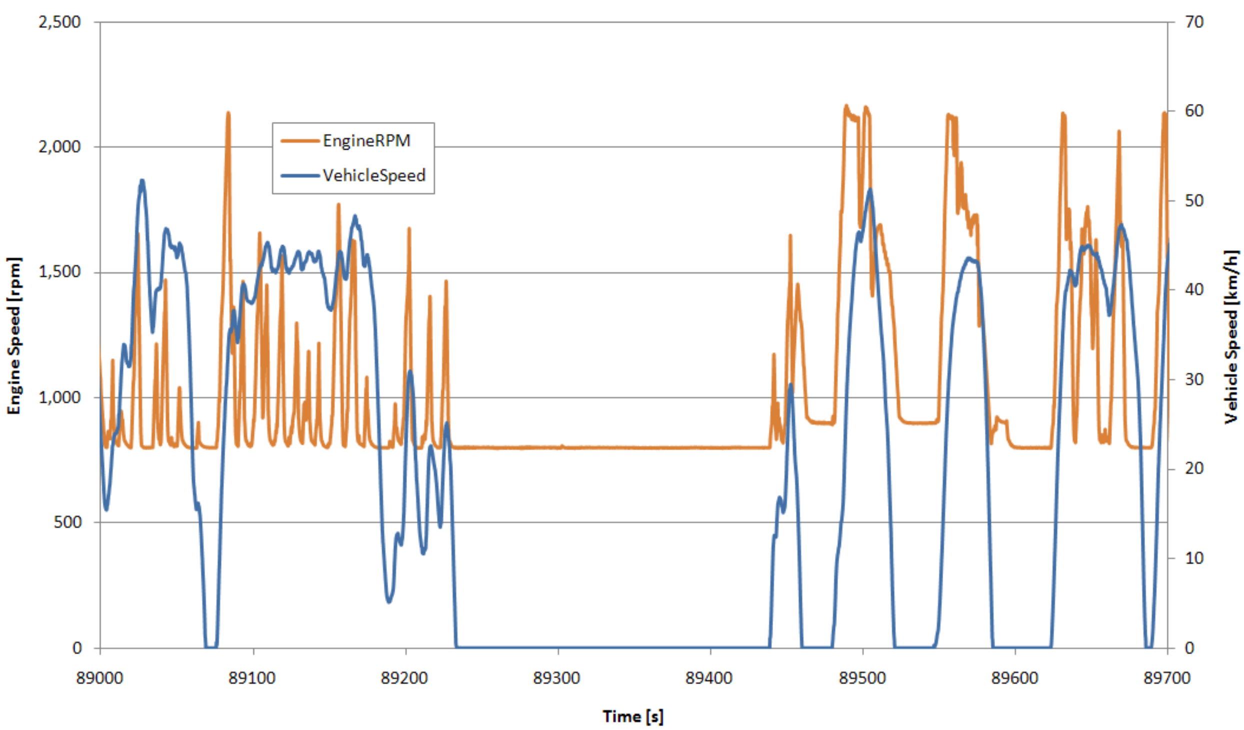


Figure 4-5: Engine and Vehicle Speed for a 700 Second Section Captured on January 26, 2010

4.8 Drive Cycle Inventory Additions

During a conference call with members from Transport Canada, Environment Canada, and Natural Resources Canada, it was identified that it would be beneficial to add nine (9) drive cycles to the simulation inventory. Those cycles are described below:

1. Central Business District
2. Manhattan
3. Orange County Bus Cycle
4. New York Bus Cycle
5. Braunschweig City Driving Cycle
6. ADEME (a drive cycle from an agency in France)
7. Heavy-Duty Urban Dynamometer Driving Schedule
8. Japanese Transit Mode (JE05)
9. World-Wide Transient Vehicle Cycle

Although dynamometer testing is not a component of the bus testing in this project, these cycles will be included in the simulations that will be presented in Phase 2b. These cycles are introduced here as they supplement the primary objective of Phase 1 of obtaining drive cycles to be used in Phases 2a and 2b.

4.9 Phase 1 Summary Results

The following primary results were obtained from the Phase 1 work:

1. The Wilson garage was identified as the ideal garage/facility to provide widest range of route types,
2. From the available routes related to the garage selected, routes representing the 'extremes' of normal weekday operation were identified and prioritized,
3. An ISAAC logger was successfully integrated onto a new Orion VII hybrid bus, connected to the J1939 diagnostic port and equipped with both a GPS and GSM modem,
4. Operational data was acquired from January 19^{th}, to March 5^{th}, and
5. Operational data provided insight into the hybrid control strategy for the current hybrid vehicles and component data to be used in component model development in Phase 2b.

5. Phase 2a – Fuel Consumption & Decision-Making Tool

As outlined in the project plan, the objectives of Phase 2a included the calculation of the real-world fuel consumption of a current hybrid bus in operation and the attempt to correlate that fuel consumption to route metrics and to access the accuracy of that estimation. The purpose of the tool would be to assist fleets in assessing procurement and route assignment/dispatch based upon anticipated fuel consumption values.

5.1 Real-World Hybrid Bus Fuel Consumption

The data obtained from vehicle operation as part of Phase 1 included fuel rate consumption for the engine. Based upon both TTC's guidance and CrossChasm's previous experience in using Engine Control Unit (ECU) reported fuel consumption values, these values were assumed to be accurate estimates of real-world diesel fuel consumption.

For hybrids, total instantaneous fuel consumption analysis requires consideration of changes in the state-of-charge (SOC) for the energy storage system. For longer drive cycles, the energy associated to a change in SOC becomes negligible as compared to the total energy from the engine's diesel consumption. As a result, longer duration studies do not require consideration of changes in SOC. Given that the drive cycles involved in this study consisted of a minimum of four (4) hours of operation with most cycles exceeding sixteen (16) hours, only engine consumption data was required for fuel consumption calculations. The resulting fuel consumption for a series of fifteen (15) days of operation and four (4) priority routes are provided in Figure 5-1. The resulting fuel consumption for the hybrid buses during normal TTC operation ranges from 43.4 to 61.5 L/100 km; resulting in an observed difference of 18.1 L/100 km between the highest and lowest observed fuel consumption values, representing a substantial variance of 42%. For these drive cycles, the shortest distance travelled was 30.4 km, the longest drive cycle was 325 km, and the average distance was 176 km.

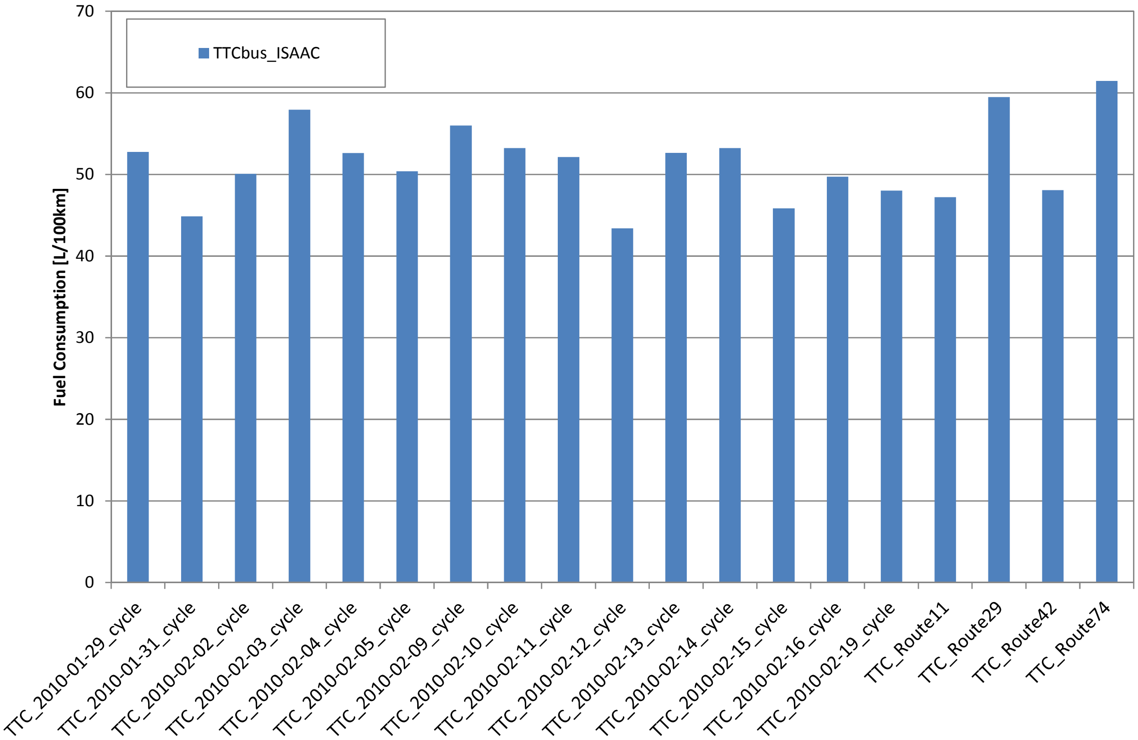


Figure 5-1: Real-World Fuel Consumption of Hybrid Orion VII Buses in TTC Operations

In reviewing the priority routes, the most 'urban' route (Route 74) resulted in the highest fuel consumption value of 61.5 L/100 km. The least 'urban' route (Route 42) posted a fuel consumption of 48 L/100 km, whereas the 'average' route (Route 11) corresponded to a fuel consumption of 53 L/100 km.

5.2 Decision-Making Tool Development and Evaluation

While the results presented above would enable a TTC dispatcher working at the Wilson garage facility to optimize route assignments based upon hybrid bus performance, a primary objective of this work is to provide a tool that could be used by a different fleet to improve their hybrid procurement and dispatching processes. As a result, a decision making tool is sought that would enable other fleets to predict hybrid vehicle performance without a substantial data-acquisition project. The specific objective is to develop and evaluate a decision-making tool utilizing fleet metrics and/or map-data.

Upon working with the TTC, it was quickly identified that the transit operator had a substantial amount of fleet metric data on each route in operation. As a result, initial effort was focused on route metric correlations to fuel consumption. Subsequently, a simulation-based decision-making tool based upon CrossChasm's patent-pending simulation system was deployed and compared to the analytic model.

5.2.1 Analytic Decision-Making Tool

To develop an analytic decision-making tool, a three-step approach was undertaken:

1) Identify key route metrics that correlate to fuel consumption using single-factor scatter plots,
2) Generate an analytic model using the key route metrics identified above, and
3) Evaluate the tool by comparing predicted and actual fuel consumption values.

The data obtained from the Phase 1 work represents hundreds and hundreds of hours of operation. To provide a substantial number of data points upon which scatter plots could be created and correlations observed, the daily duty cycles were parsed into sections of a maximum of four hours. From the set of routes used in the parsing, the result was 257 route segments. The fuel consumption was calculated for each route segment. Additionally, the drive cycle for each route segment was analyzed to generate a number of route metrics including, but not limited to, average speed, stop frequency, average acceleration, and aggressiveness factors. The fuel consumption for each route segment was then plotted against the associated route metric, providing scatter plots consisting of 257 data points. In total, over thirty scatter plots were created are provided in **Appendix B**. These plots were reviewed to identify which route metrics showed a strong correlation to fuel consumption. The scatter plots showing correlations are provided in Figure 5-2, Figure 5–3, and Figure 5-4.

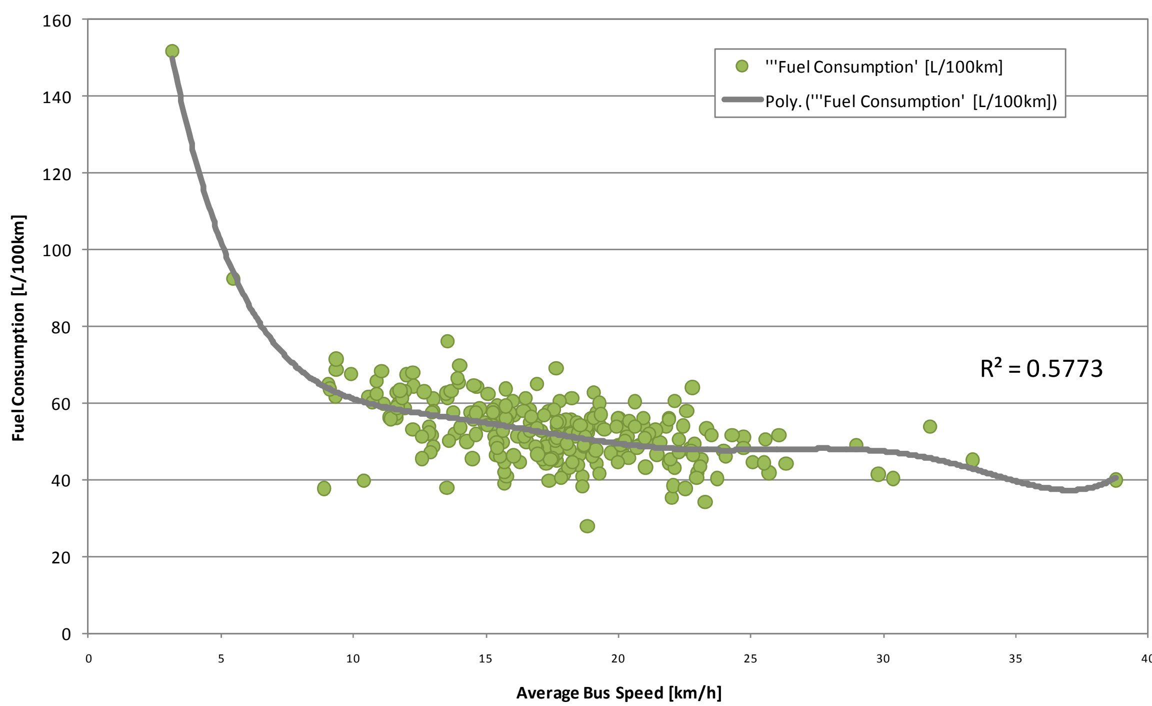


Figure 5-2: Fuel Consumption Correlation to Average Route Speed for 257 Route Segments

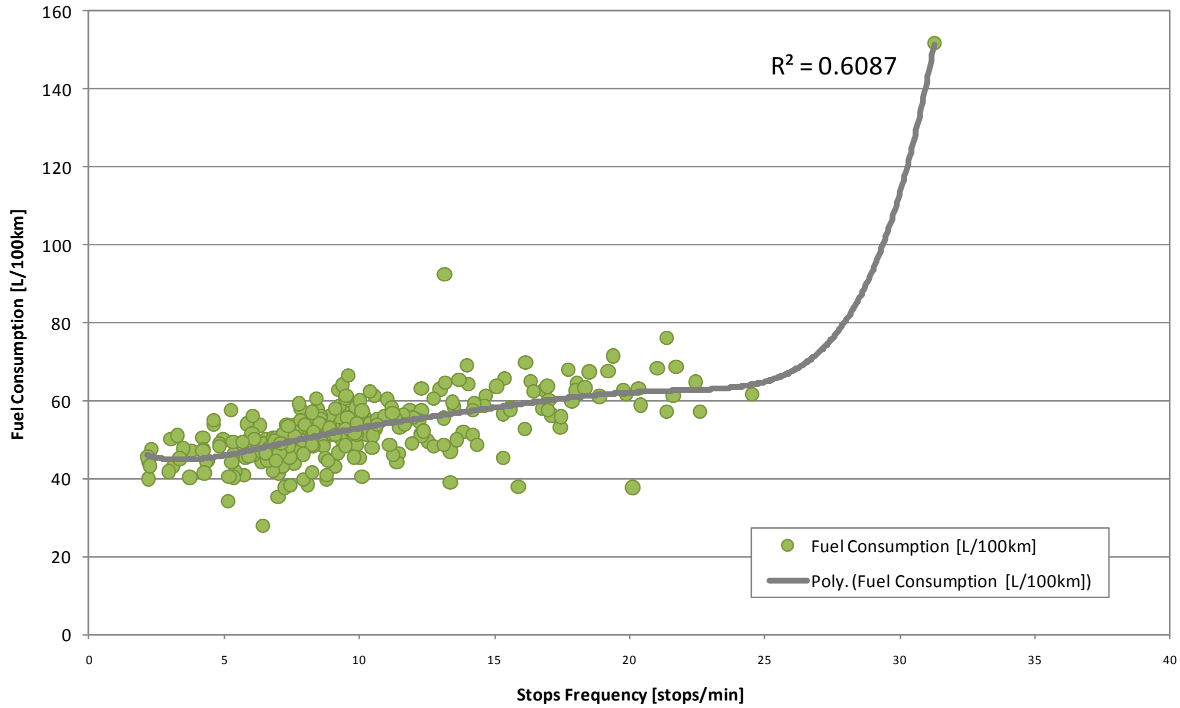


Figure 5-3: Fuel Consumption Correlation to Stop Frequency Per Minute for 257 Route Segments

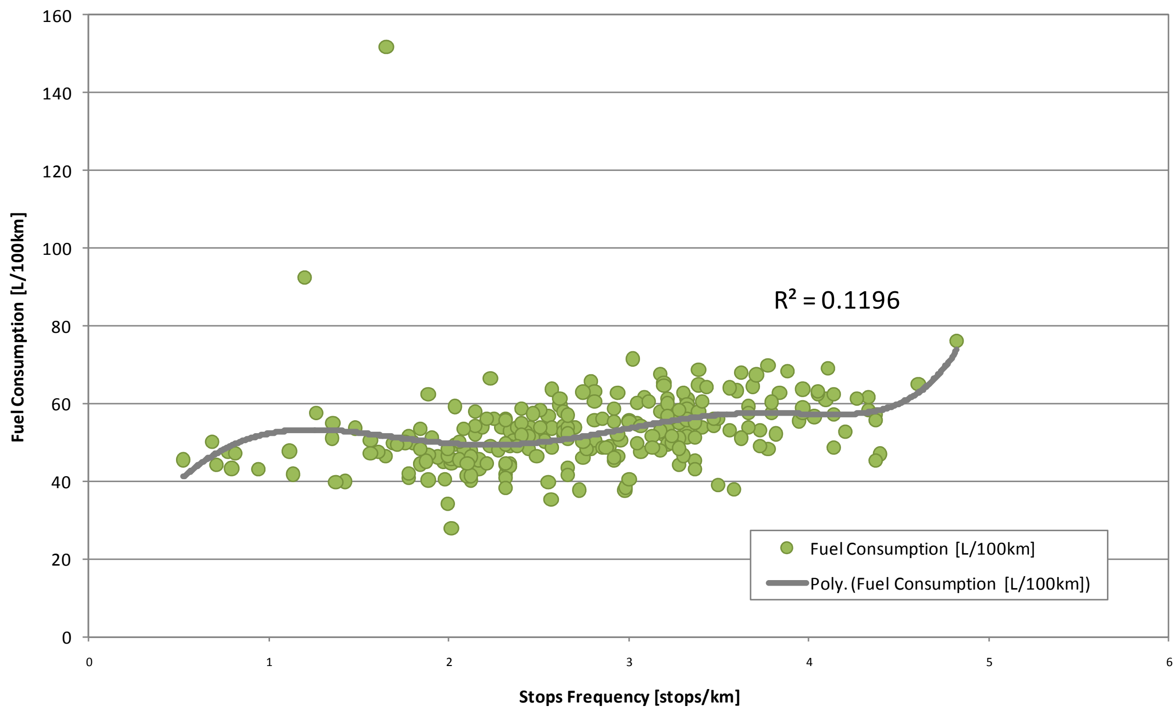


Figure 5-4: Fuel Consumption Correlation to Stop Frequency Per km for 257 Route Segments

The results clearly demonstrate that there is a correlation between average route speed and fuel consumption. Additionally, there appears to be a correlation between fuel consumption and stop frequency, particularly for stop frequency per minute of operation. All results, however, exhibit a large amount of deviation from the trend lines, underscoring that the single-factor correlations are insufficient in fully accounting for the variations in fuel consumption.

Based upon the scatter plots, the average speed and time-based stop frequency were identified as key route metrics that are correlated to fuel consumption. An analytical model correlating fuel consumption to average speed and stop frequency was developed and is provided as Figure 5-5.

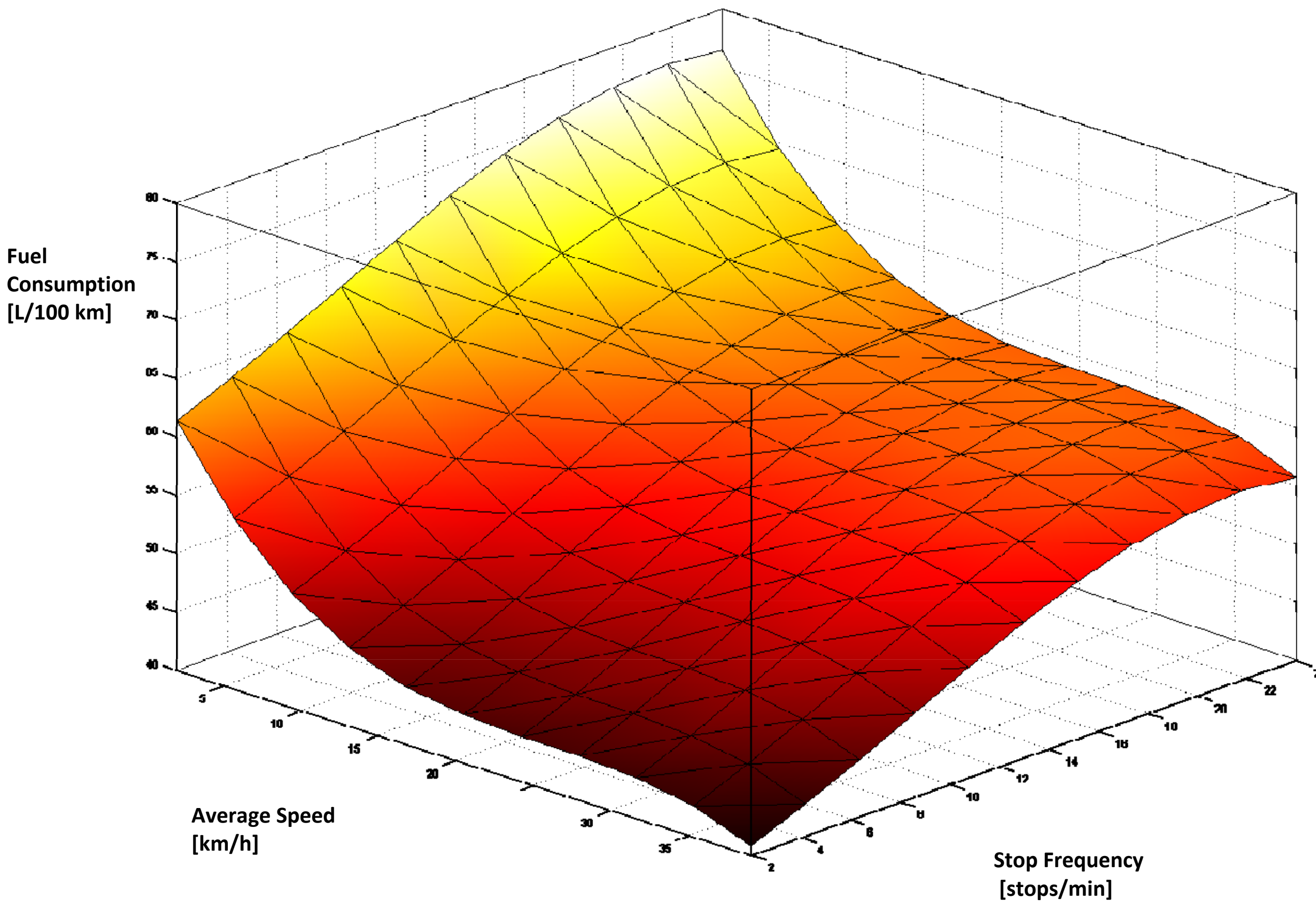


Figure 5-5: Fuel Consumption Model as a Function of Stop Frequency Per km and Average Speed

The numerical form of the model is a simple cubic polynomial of the form:

$$FuelConsumption\left[\frac{L}{100km}\right] = \alpha + \beta_{1,1}v_{ave} + \beta_{2,1}\omega_{stop} + \beta_{1,2}v_{ave}^{2} + \beta_{2,2}\omega_{stop}^{2} + \beta_{1,3}v_{ave}^{3} + \beta_{2,3}\omega_{stop}^{3}$$

Where v_{ave} and ω_{stop} represent the average speed and stop frequency respectively in coded format with minimum value of 2 for both and maximum values of 32 and 39, respectively. The values for the alpha and beta parameters are provided in the table below.

Table 5-1: Parameters for Analytic Fuel Consumption Model

Parameter	Value
α	58.06
$\beta_{1,1}$	-2.361
$\beta_{1,2}$	8.998
$\beta_{2,1}$	6.967
$\beta_{2,2}$	-11.543
$\beta_{3,1}$	-7.998
$\beta_{3,2}$	-6.577

Using the fuel consumption model to predict the hybrid vehicle fuel consumption as a function of the average speed and stop frequency of the route, fuel consumption values were predicted for the 257 route segments. The predicted values were compared to the actual values and are provided below. A perfect model would result in all points being on the X-Y axis, corresponding to predicted values directly matching actual values. The figure shows that for the 257 parsed route segments the model maintains a uniform accuracy across the range of fuel consumption values achieved (i.e. the errors do not increase or decrease across the observed fuel consumption ranges); however, the prediction error averages approximately 4 L/100 km with errors as high as 14 L/100 km observed.

Since the route segments are shorter than those that would be of interest to the fleet dispatcher or fleet manager, the predicted and actual routes are plotted for an entire day of operation. That result is provided as Figure 5-7, which shows improved prediction accuracy when longer drive cycles are considered. Prediction errors as high as 12 L/100 km are still observed.

The results suggest that an analytic model provides general trend information but is not able to adequately integrate the complexities of the hybrid powertrain and bus operation (including varying vehicle mass). A simulation-based approach is evaluated next as an alternative method for predicting fuel consumption.

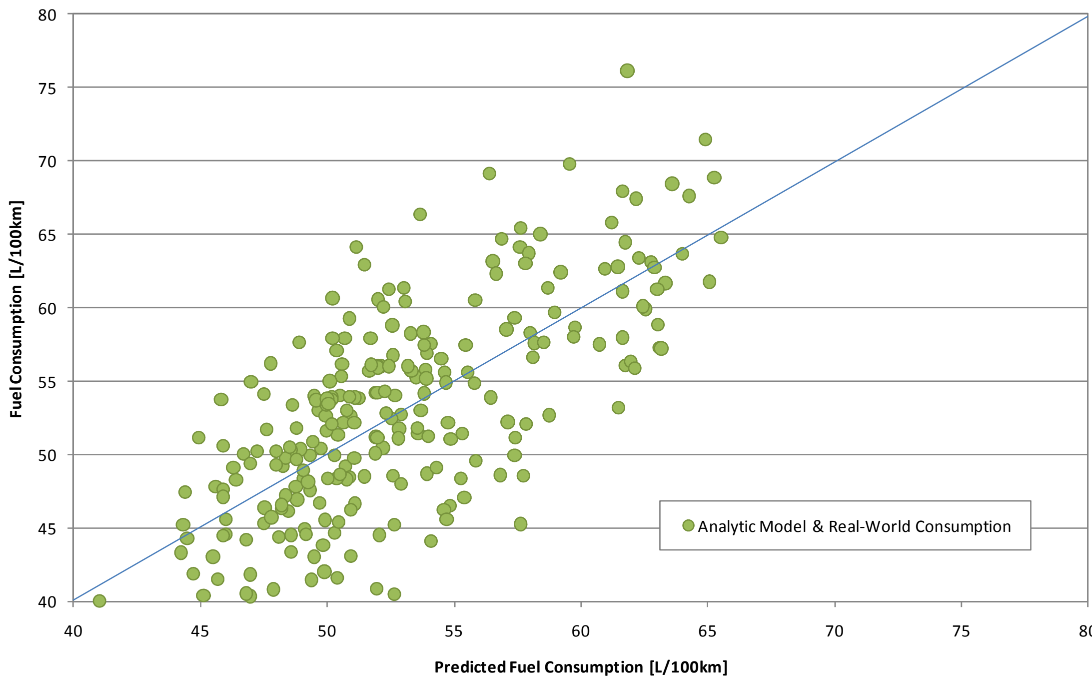


Figure 5-6: Comparison of Predicted and Actual Fuel Consumption Using the Analytic Model for the 257 Route Segments

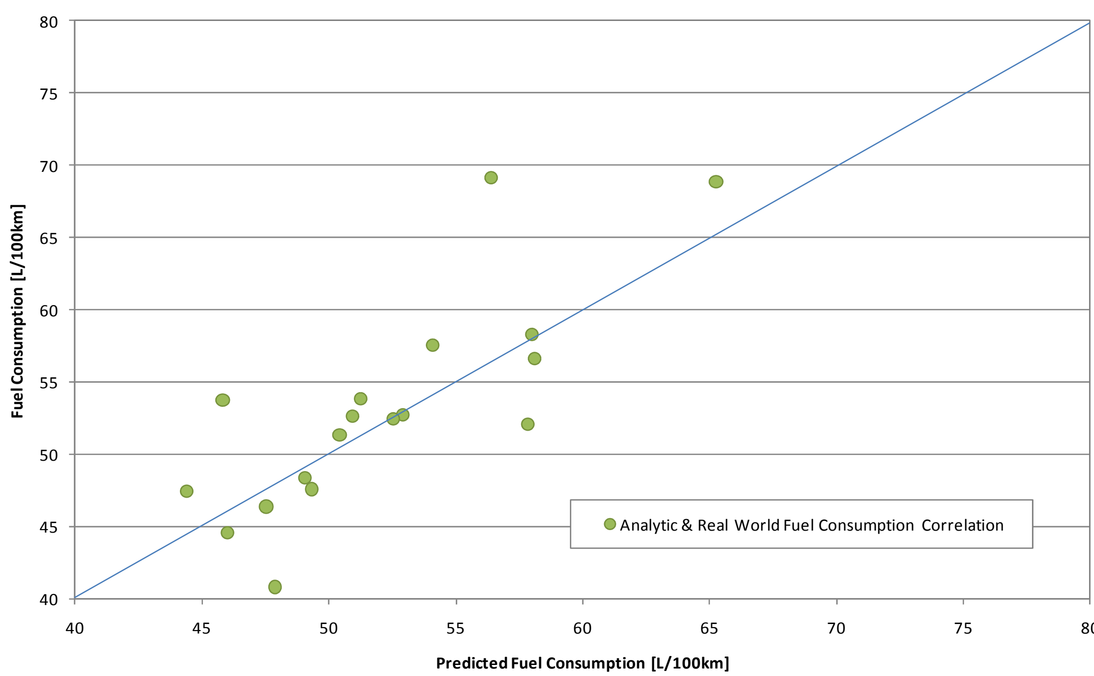


Figure 5-7: Comparison of Predicted and Actual Fuel Consumption Using the Analytic Model for the 19 Key Routes

5.2.2 Simulation-Based Decision-Making Tool

Phase 2b will include extensive use of vehicle energy simulations for the purposes of comparing energy storage technologies using a model-based design approach; however, the simulation-based approach will be introduced here as a method for providing fuel consumption estimates for the current Orion VII hybrid and conventional vehicles.

Using the operational data obtained in Phase 1 and described in Section 4.7, Orion VII models were developed for both the hybrid and conventional topologies. In addition to the operation data captured during data-logging, CrossChasm has component data developed for the Orion V bus and available in the Powertrain System Analysis Toolkit (PSAT) & Autonomie component libraries. PSAT & Autonomie are software packages developed by Argonne National Laboratory used to build virtual vehicle models based upon Matlab and Simulink. The primary purpose of PSAT is to evaluate the vehicle design and control decisions during the vehicle development process. For this project, high-fidelity bus models were built based upon operational and component-library data.

The conventional and hybrid vehicles were simulated over the drive cycles captured and compared to actual values. The resulting correlation between predicated and actual fuel consumption values is provided as Figure 5-8 below. The result clearly demonstrates a high level of prediction accuracy.

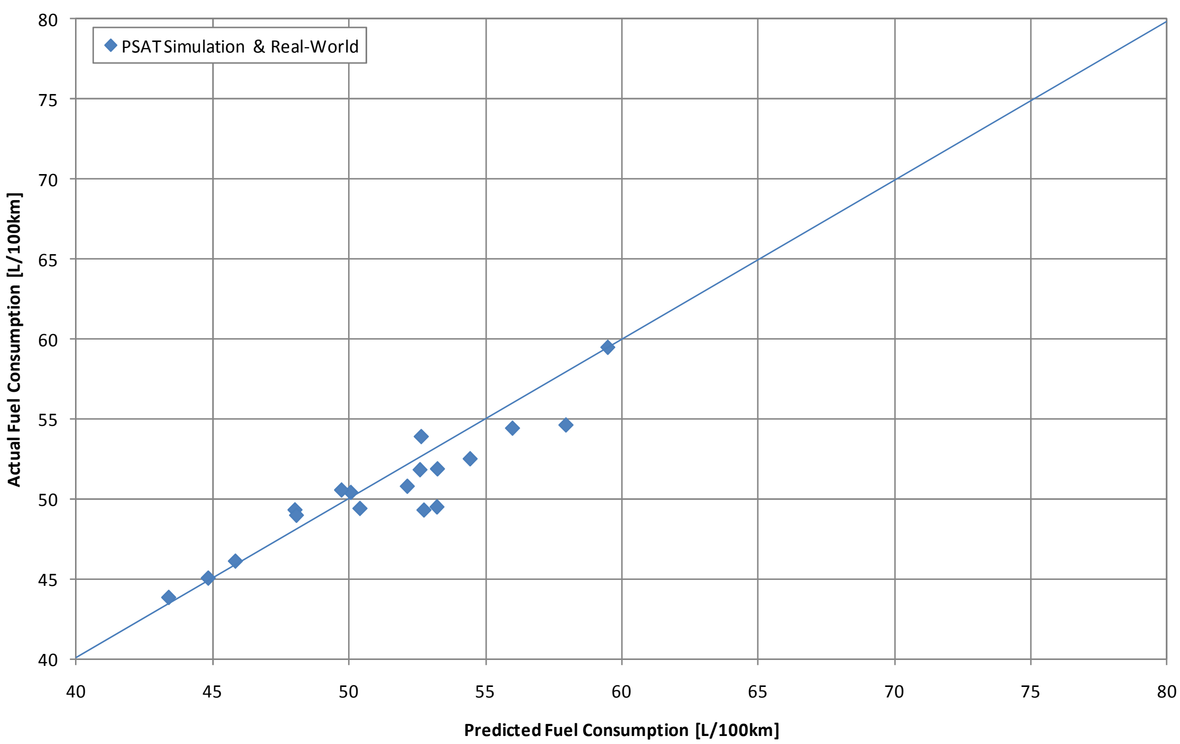


Figure 5-8: Comparison of Predicted and Actual Fuel Consumption Using the PSAT Simulations

5.2.3 Comparison of the Analytic & Simulation-Based Decision-Making Tools

The previous two sub-sections describe the development of analytic and simulation-based prediction tools. The results are presented for the individual drive cycles below. The figure clearly demonstrates that the simulation-based (PSAT) predictions provide a high level of prediction accuracy. In most cases the analytic models provide reasonable fuel consumption predictions; however, there are clear examples (such as TTC_2010_02_13_cycle and TTC_Route29) where the analytic model prediction differs drastically from the actual fuel consumption values. Upon analysis of the drive cycle characteristics there was no immediately discernable factor that would cause the significant prediction error in these cases.

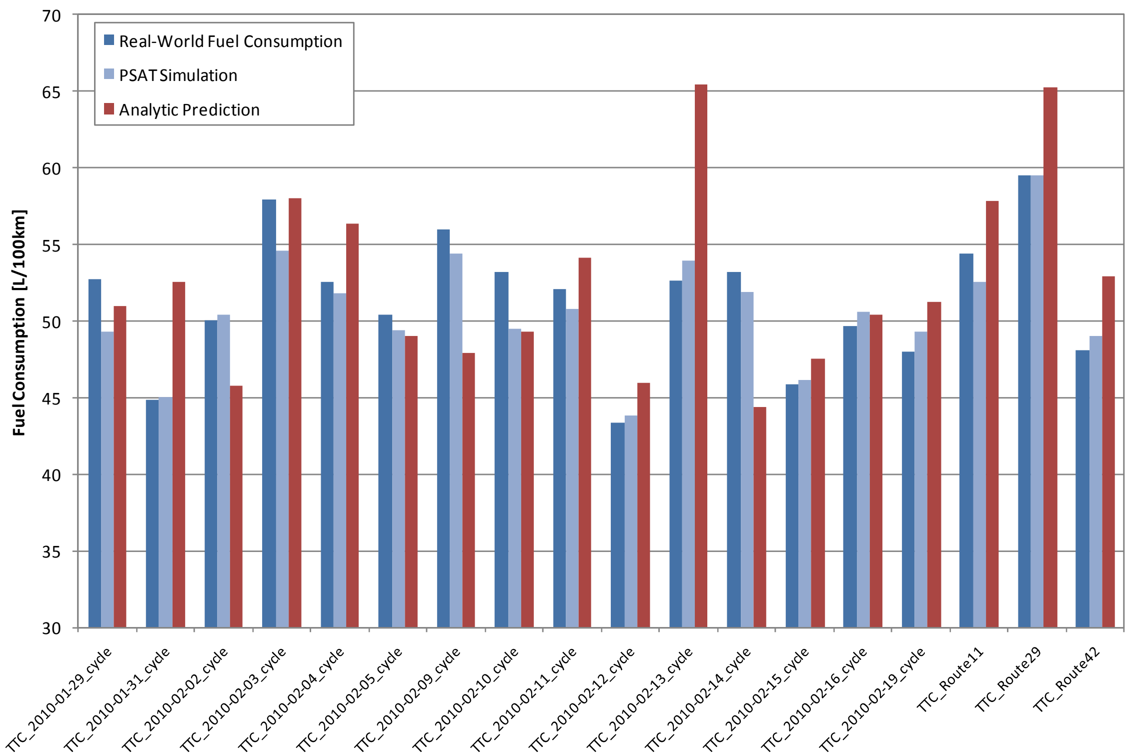


Figure 5-9: Comparison of Actual, Analytic Prediction, and Simulation-Based Fuel Consumptions

5.3 Current Hybrid and Conventional Powertrain Comparison

As shown in the previous section, the simulation-based (PSAT) fuel consumption predictions generate highly accurate predictions of fuel consumption in the hybrid vehicle. Additionally, the operational data captured in Phase 1 and PSAT/Autonomie Orion component libraries enabled the development of a conventional Orion VII bus model. Given that the hybrid topology demonstrated strong correlation to real-world results and that conventional vehicles are simpler and therefore easier to model, it is assumed that the conventional Orion VII model would provide fuel consumption predictions within a reasonably small amount of error. Consequently, simulations were run for both the hybrid and conventional Orion VII models for the TTC drive cycles and additional drive cycles introduced in Section 4.8. The resulting fuel consumption results are provided below.

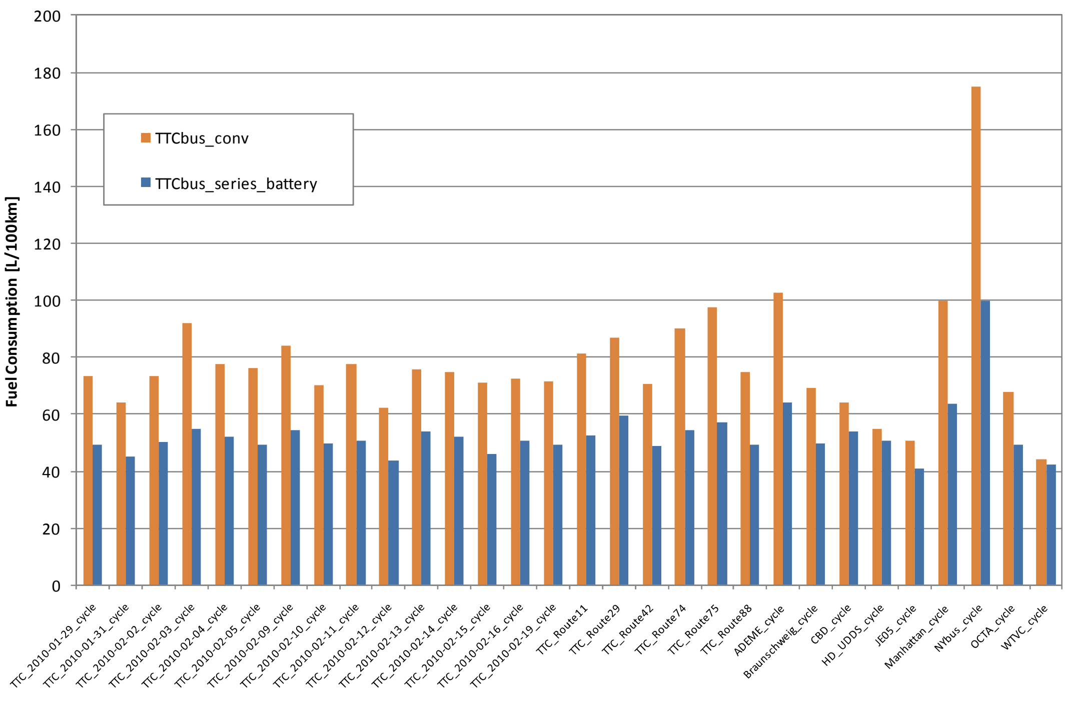


Figure 5-10: Comparison of Fuel Consumption for Convention and Hybrid Orion VII PSAT Models

The fuel consumption results clearly underscore the substantial impact of drive cycle characteristics on fuel consumption. It is also important to note that the impact of drive cycle on conventional and hybrid powertrains is not equivalent. Two main implications of this result are:

1) Results cannot be assumed to be transferable between different transit operators. Specifically, the hybrid gains that would be experienced by the transit authority in New York would be substantially different than those experienced by the TTC.

2) The differential fuel consumption between the hybrid and conventional variants is heavily dependent on drive cycle characteristics. This is further illustrated by plotting the differential fuel consumption, provided below.

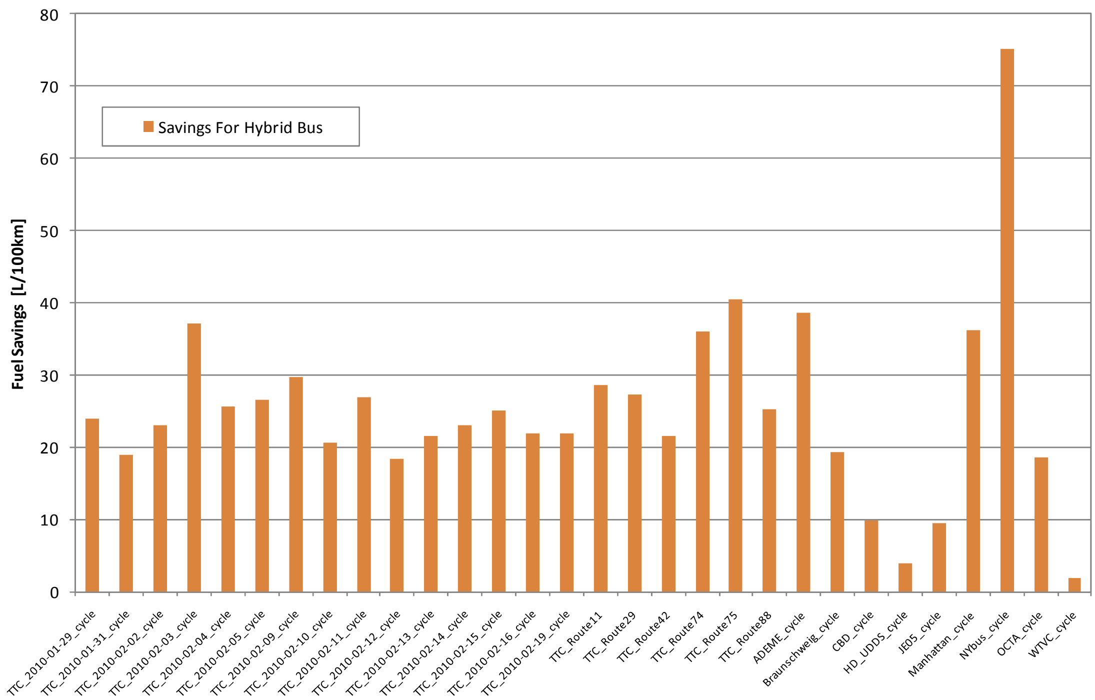


Figure 5-11: Fuel Savings Between Convention and Hybrid Orion VII PSAT Models (the difference between the bars in Figure 5-10)

The results demonstrate that the fuel savings that a fleet operator could expect to see as a result of purchasing a hybrid Orion VII bus ranges from less than 3 L/100 km to more than 75 L/100 km. This result further underscores that pragmatic hybrid bus procurement requires an identification of a transit operators specific drive cycles and the resulting business case for purchasing the hybrid variant.

5.4 Phase 2a Summary Results

The following primary results were obtained from the Phase 2a work:

1. Real-world fuel consumption of Hybrid Orion VII bus varied between 43 and 65 L/100 km for the range of TTC routes captured,
2. Correlations between fuel consumption and route metrics were obtained using scatter plots,
3. An analytic fuel consumption prediction model was developed and evaluated. The model successfully captured fuel consumption trends; however, there remained drive cycles with substantial fuel consumption prediction error,
4. A simulation-based (PSAT) model of the Hybrid Orion VII bus was developed. Predicted fuel consumption values were shown to correlate very closely to actual fuel consumption values,

5. A simulation-based (PSAT) model of the Conventional Orion VII bus was also developed, and
6. Comparison between the hybrid and conventional variants across a number of drive cycles demonstrated a substantial sensitivity to drive cycle. Meaning that a proper assessment of drive cycles is critical to pragmatic procurement of hybrid buses.

6. Phase 2b – Model-Based Design and Comparison of Various Energy Storage Technologies

Phases 1 and 2a focused on the performance, assessment, and prediction of the performance of existing buses. Those results, and decision tools, have been targeted towards assisting the transit operator. This section shifts the focus towards the design and development of the next-generation of hybrid bus, seeking to utilize the Phase 1 data and model-based design techniques to evaluate the performance of various energy storage technologies. The objective is to identify which energy storage technology would perform best in the next generation of hybrid buses.

This section will describe the model development and key parameters used in the creation of the high-fidelity PSAT hybrid bus models.

6.1 Model Development

The Orion VII hybrid topology is a series topology, allowing for high engine operating efficiencies. The downside of the series topology is that all energy from the engine must be converted to electricity and then to back to mechanical to drive the wheels. The conversion efficiency losses are further amplified if the system charges the battery before using the power. A PSAT architecture configuration for the Series topology is provided below. The main components are summarized in Table 6-1

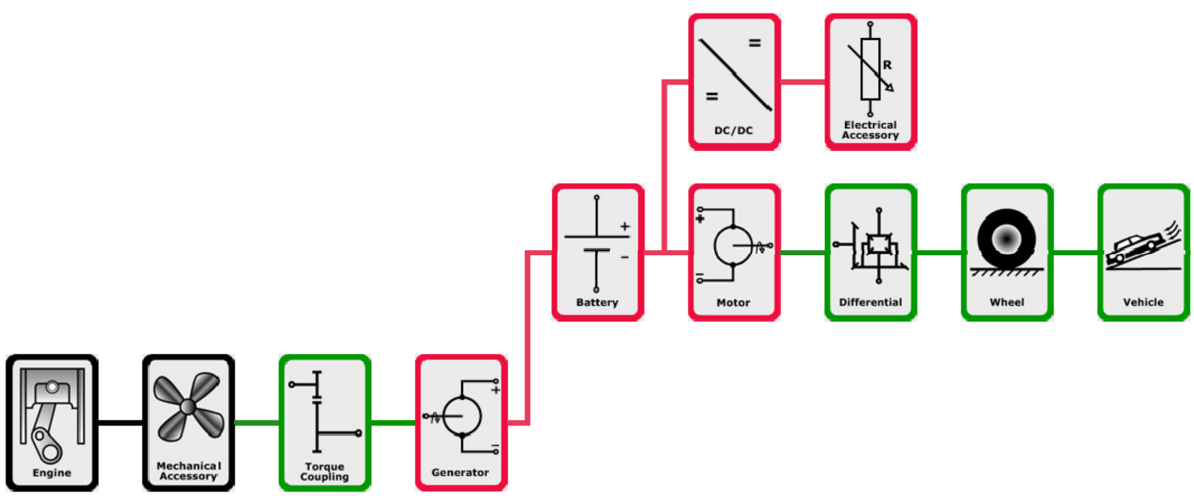


Figure 6-1: Orion VII Series Hybrid Topology

Table 6-1: Current Orion VII Hybrid Component Inventory

Component	Description
Driver	Standard PSAT Bus Driver Model
Engine	Custom Cummins ISB 280 Model
Mechanical Accessory	~5kW Accessory Load
Generator	Custom Genset Model Based Upon Operational Data
Energy Storage	A123 BAE Hybrid Bus Pack Model (based on M1 cells)
Motor	Custom BAE Induction Motor Model
Final Drive	Custom Model
Electrical Auxiliaries	Baseline 3.3-6.0kW load
Chassis	Standard Orion VII "Next-Gen" chassis model

For the future bus model, a split hybrid architecture was selected and is schematically shown below using the PSAT layout. The split architecture is more complicated than the series topology as it is a combination of both series and parallel hybrid systems. In the split architecture the engine can both power the wheels directly (similar to a parallel hybrid topology) through a planetary gearset and can drive a generator to produce electricity (similar to a series topology). It should be noted that the PSAT layout suggests a slightly different physical connection pattern. In reality, and how PSAT actually models the system, the traction motor sits between the planetary gear set and the differential. The result is that there are only three shafts connected to the planetary gear set, unlike the four that are shown in the default PSAT schematic.

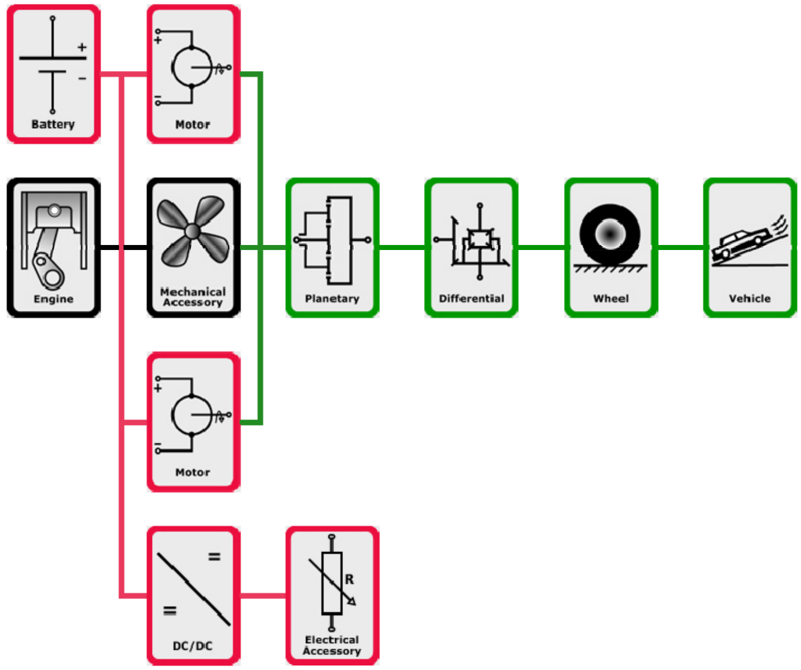


Figure 6-2: Split Hybrid Bus Topology

This split architecture is very similar in topology to the architecture used in the Nova-Allison hybrid transit bus. There are three main reasons the split architecture was selected as the modeling platform:

1. The split architecture provides the majority of the operating modes of both the series and the parallel topologies, thereby enabling the highest achievable system efficiencies.
2. Since an objective of the project was to provide a head-to-head comparison of various energy storage technologies (battery, battery-ultracap, ultracap, and flywheel) it was preferred to have a common architecture for all technologies. Since the parallel and series architectures naturally lend themselves to either high-energy or high-power energy storage technologies, a selection of either the series or the parallel topology would unfairly favour certain technologies. The split topology provided the most unbiased platform for comparison.
3. A challenge for the split architecture in the light-duty automotive space, although it is the Prius architecture, is the size, cost, and complexity of the split architecture. The size and economics involved in the transit but industry minimize the significance of these challenges.

A substantial amount of work was performed in optimizing the hybrid control logic for each topology under consideration. The control logic was tuned for each technology to balance engine operating efficiency with total energy pathway efficiency and minimize the overall fuel consumption. The result is near-optimal hybrid control logic for all energy storage technologies under consideration.

6.2 Simulation Results

All the energy storage technologies were simulated for both the TTC drive cycles and the additional drive cycles provided by Environment Canada. The resulting fuel consumption values are provided in Figure 6-3. The results demonstrate that all four split bus models have lower fuel consumption than both the current conventional vehicle and the current hybrid vehicle. Since both the current and the future battery-hybrid models are based upon the A123 M1 cells, the bulk of the energy savings are related to split topology and refined control logic.

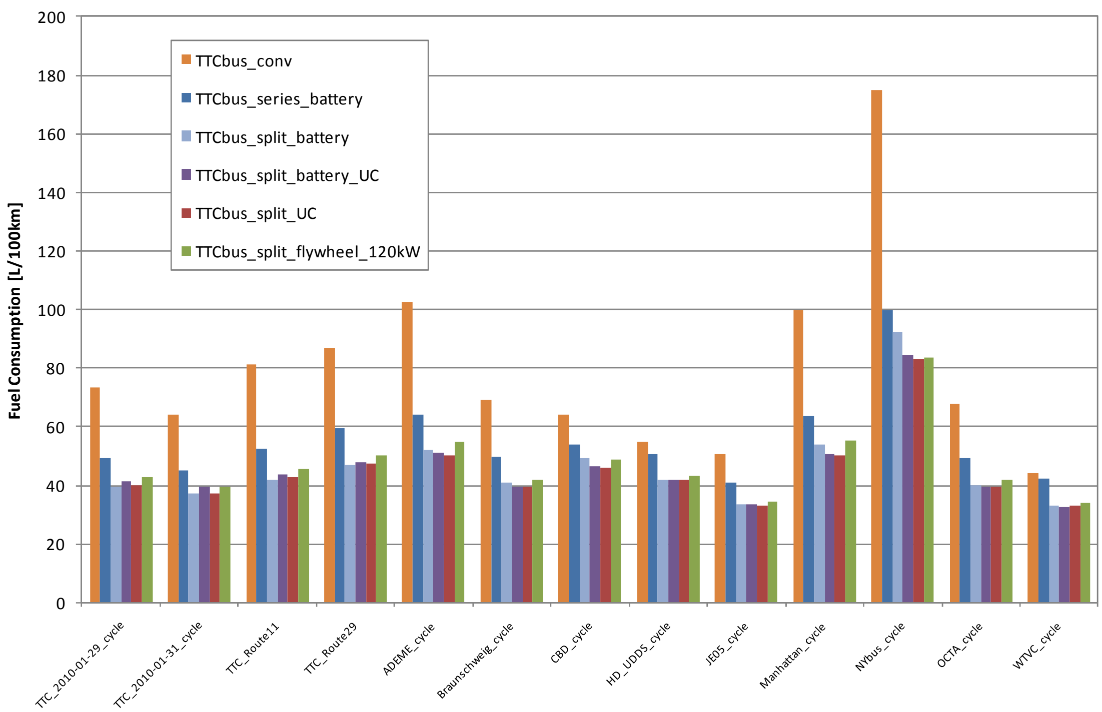


Figure 6-3: Comparison of Current and Future Simulated Buses

To improve the ability to compare between the four energy storage combinations, the results of the future bus models are repeated in Figure 6-4, but with fewer drive cycles and without the currently available buses. The results demonstrate that the battery-hybrid provides the lowest energy consumption on a few routes, while the ultracap-hybrid has the lowest fuel consumption on the remainder of the routes. In general, the battery-hybrid was the optimal option for less aggressive drive cycles while the ultracap-hybrid was the preferred option for more aggressive routes. All vehicles under consideration were capable of maintaining the desired drive schedule speeds. The battery-ultracap hybrid did have the lowest energy consumption for energy routes, due to the additional losses related to the need to have a dc/dc converter on either the battery system or the ultracapacitor pack. The flywheel had similar performance to the ultracap-hybrid; however, the flywheel system exhibited higher overall fuel consumptions due to higher losses related to the power conversion losses between the electrical and mechanical states.

It is **important to note** however, that these results demonstrate 'beginning-of-life' performance. Given that battery degradation is a known issue for transit bus batteries and that the ultracap-hybrid and flywheel-hybrid systems have reasonably similar fuel consumption values but are expected to have significantly longer lifetimes, the results suggest that either an ultracap-hybrid or a flywheel-hybrid may provide the lowest total cost of bus ownership/operation under most drive cycle conditions.

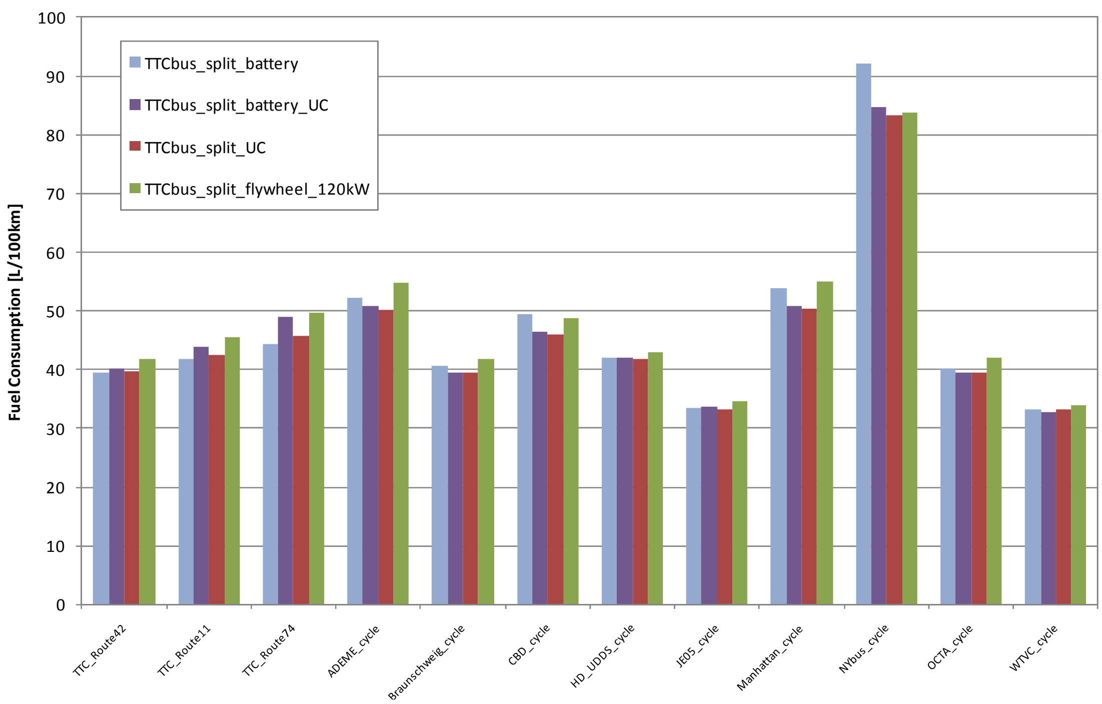


Figure 6-4: Comparison of Only Future Simulated Buses

6.3 Potential Flywheel Improvements

As the project team included a firm developing flywheel technology, quantifications of the achievable efficiency gains were sought. These consisted of system efficiency projections after refinement of the I^2R and switching losses, elimination of filter inductors, decrease of the flywheel speed, and decrease of the support equipment loads. The result of these improvements is projected to be an increase in one-way conversion efficiency from 94% to 97.5% and a reduction in parasitic (stand-by) losses of 42%. Re-running the PSAT models with the improved flywheel system generated fuel savings of approximately 0.9 to 1.3L/100 km as compared to the existing flywheel system results. Should those improvements to the flywheel system be achieved, similar fuel consumption values for the ultracap-hybrid and flywheel-hybrid powertrains are expected, with the ultracap-hybrid having a very modest advantage.

6.4 Phase 2b Summary Results

The following primary results were obtained from the Phase 2b work:

1. Split architecture is capable of significant fuel consumption reductions over current Series configuration,
2. The optimal energy storage choice is subject to route metrics (the more aggressive/'urban' cycles require an ultracap-hybrid while less aggressive/less 'urban' cycles demonstrate lowest fuel consumption numbers with a battery-hybrid,
3. With the exception of battery-ultracap hybrid topology, all Energy Storage System (ESS) alternatives are reasonably competitive **based upon beginning of life values**.
4. Although not analyzed within this study, it is possible that the ultracap or flywheel options would be preferred when considering lifetime performance and costs (due to battery degradation and resulting fuel consumption increases and replacement costs).

7. Phase 3 – Best-Practices

In addition to this report outlining the technical results, part of the project included the aggregation of hybrid transit bus experience from an existing transit operator. Based upon TTC's experience and the results observed herein, the following four recommendations are provided as 'best-practices' for consideration during hybrid bus procurement.

7.1 Generate Your Procurement Decisions Based Upon Your Own Fleet Metrics

There are a few key transit operators that are often the early-adopters, and/or beta customers, for new bus technology; once such example is New York City Transit (MTA). For hybrid buses, the TTC waited for New York City's initial experiences with hybrid buses to be generated.

The initial results were very positive, with substantial fuel savings and limited reliability issues. As a result, TTC made substantial purchases of hybrid buses. As found in operation, and further supported by the results in this study, the drive cycles of New York City buses differ substantially from TTC routes. There were two negative consequences that resulted.

The first was that the TTC did not have fuel savings nearly as large as the New York City buses. The second was that since TTC has substantially higher average speeds that over the course of a couple years the TTC had caught up to, and surpassed, the mileage on the New York buses. As a consequence, the TTC unintentionally became the beta tester of the systems and was the first to identify the battery degradation issue that will be discussed below.

The best-practice derived from this experience is the need to base procurement decisions upon the drive cycles specific to each fleet. Given the cycle sensitivity of these technologies, it is critical to ensure that the decisions are based upon the specific case under consideration.

7.2 Consider Service and Facility Requirements during Procurement

Hybrid buses do have unique facility and personnel training requirements. Specifically, this includes an overhead working bay from which the battery compartment can be accessed. As experienced in this study, facilities that were equipped for natural gas buses will already have this infrastructure as it would have been built to access the tanks.

Given the nature of the technology, additional training of the service personnel is required. In the case of large transit operators with multiple facilities this can be problematic as the personnel with the required training/capabilities may be located at a garage that services routes that aren't ideally suited for hybrid vehicles. In the case of the TTC this was one of the original complications.

7.3 Battery Degradation is an Issue and an On-going Concern

The observed battery lifetime for the initial lead-acid battery packs was substantially less than originally quoted by the manufacturer. Consequently substantial additional costs were born when the batteries began to fail well before their anticipated end-of-life. The 'best practice' related to this experience is to avoid the lead-acid based hybrids since the current generation of lead-acid battery technology has not been delivering reliable results. The second 'best practice' is to ensure the procurement contract has specific allocations for battery warranty, and most importantly a clear definition of the lead time on replacement packs.

7.4 Fuel Monitoring is Highly Beneficial for Hybrid Vehicles

Most of the current fleets are equipped with GPS tracking; however, fuel consumption remains mainly untracked. The result is that there is no feedback to the dispatcher to enable efficient route assignments for the specific technology, thereby foregoing substantial potential savings in fuel costs. Additionally, increases in fuel consumption can be an early indicator of component failure in these hybrid systems. In the case of TTC this occurred when a number of units began to have failing transaxles due to oil leaks. This was ultimately discovered when the failing hybrid vehicles were unable to reach highway speeds. Retroactively monitoring the fuel consumption data uncovered that fuel consumption rates had risen drastically prior to the substantial component failures. As a result, it was identified that fuel monitoring is a good mechanism to detect upcoming component failure in advance.

8. Recommendations

To summarize the recommendations inherent in the best-practices section above, the following three main recommendations are made for **fleets**:

1. **Base your procurement decisions upon your specific route profiles.** The results generated by another transit authority can, and will likely be, substantially different from the results you would obtain unless your drive cycles are very similar. The analytic tool developed and reviewed herein can provide initial estimates for this, and in cases were additional accuracy would be beneficial; the simulation-based approach can be reliably and cost-effectively integrated into the process.

2. **Base your purchase decisions factoring in total cost considerations.** This is related to the first point, but highlights the need to consider all related costs (in addition to the fuel costs). This includes maintenance, component replacement, and additional training costs. It is important to note that additional operations costs may be incurred if a decision is made to isolate routes to maximize the benefits of hybrids buses; therefore, these additional costs must be weighed with the associated benefits.

3. **Track your vehicles' fuel consumption**. For both preventative maintenance purposes and for route dispatching optimization, track your vehicles' fuel consumption. This is a highly effective way to reduce overall operating costs and improve your fleet's operational efficiency.

The following two main recommendations are made for **manufacturers and component suppliers**:

1. **Consider developing ultracap and/or flywheel hybrids.** The results herein demonstrate that these technologies are competitive, if not better, at the beginning-of-life of the system when compared to the battery hybrids. Given that these technologies are anticipated to have better lifetime performance, these energy storage technologies appear to be a natural fit for this application. As mentioned in the introduction, early releases of buses with these technologies are being released. The results observed herein suggest that substantial additional benefit may be achieved by further development and deployment of powertrains with these technologies incorporated.

2. **Continue to electrify the auxiliary loads.** In reviewing the current hybrids, the loads associated with HVAC and system cooling remain, in many cases, driven off the engine. The result is that a substantial amount of the potential efficiency gains due to hybridization can't be achieved since the engine must remain on. There are already a number of examples of electrifying the auxiliary loads and there remains substantial additional opportunity for improvement.

The following general recommendations are provided:

1. **Build an ultracap and/or flywheel hybrid.** This would enable the validation of the results and benefits estimated herein. The simulation results estimate that substantial benefit can be achieved by integrating these technologies as the energy storage medium. The physical build of the powertrain will enable the validation of these results and assessment of the technologies in the context of real-world operation, commercial viability, and benefit.

2. **Build the next-generation hybrids on a modular testbed to reduce the time and cost required**. As shown through this project, the optimal energy storage medium depends on a number of factors. Given that developing and building hybrid powertrains is a costly endeavor it is recommended that a modular testbed be used for the development and build of these powertrains. This will result in a highly re-useable testbed that can be used to develop and evaluate difference energy storage technologies and control strategies in an expedited and lower cost manner.

3. **Use the testbed to evaluate the various hybrid technologies over a wide range of drive cycles and auxiliary load profiles**. The results of this study clearly identify the sensitivity of performance to drive cycle. Correspondingly, it is recommended that physical builds of hybrid powertrains be evaluated over a wide range of drive cycles representing the breadth of drive cycles observed in real-world operation. The result will enable the selection of the energy storage technology that will provide the best real-world performance for a given fleet/city based upon their usage patterns.

4. **Use the testbed data to refine and improve the component and system models**. Given the immense value of model-based design and the ability to generate performance estimates in a simulation environment, it is strongly suggested that any data generated through the real-world build and evaluation of these components and powertrains be used to improve and refine the associated models for future use.

Appendix A

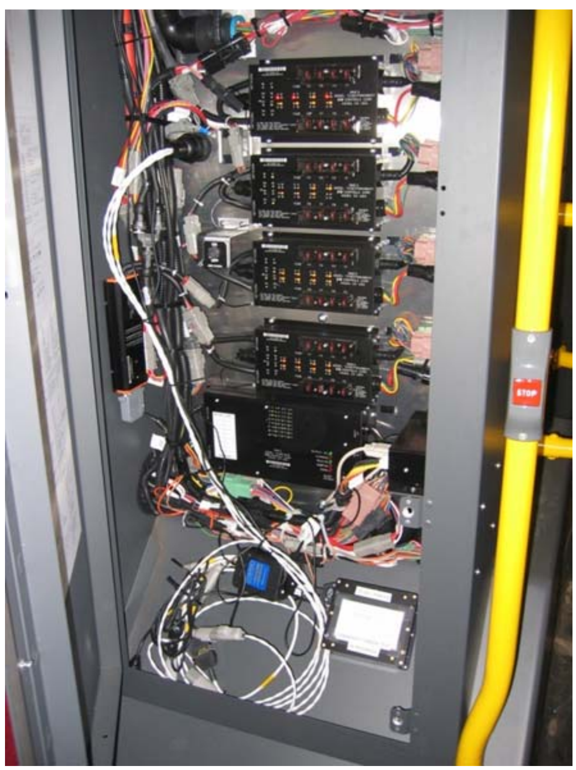
Summary of TTC Duty Cycle Survey

Appendix A: Summary of TTC Duty Cycle Survey

Inertia Engineering + Design installed ISAAC data acquisition system to Bus #1825 on January 15 2010 (see Picture 1 and 2). Duty cycle data has been logged from January 19 2010 to March 05 2010. A summary of 20 days' duty cycle data was presented here.

Definition of summary:

Parameter	Definition
Date	Logged date
TTC Route Travelled	Route number travelled on above day
Time of Record(hour)	Time period from when the bus leaves the TTC garage to bus returns back to the garage
Distance Travelled(km)	Total distance travelled on above time period
Total Number of Stop	Stop means bus speed equals zero km/h – this could be a passenger pick-up / drop-off stop, a signaled traffic stop or the vehicle is stopped in traffic
Total Travel Time (hour)	Driving time, when bus speed is greater than zero
Total Stop Time(hour)	Stop time, when bus is not moving speed is zero
Average Speed (kph)	Distance travelled/time of record
Average Number of Stop (/km)	Total number of stop/distance travelled



A data acquisition system was installed in the bus and connected to the SAE J-1939 CAN bus port to log the following channels:

- Transmission Output Shaft Speed
- Drivers Demand Engine Percent Torque
- Actual Engine Percent Torque
- Engine Speed
- Wheel Based Vehicle Speed
- Brake Switch
- Engine Fuel Rate
- Engine Average Fuel Economy
- Engine Coolant Temperature

A GPS antenna was also installed to track the vehicle's geographic location in order to determine on which route is was driving. The following channels were logged from the GPS signal:

- GPS Time
- GPS Latitude
- GPS Longitude

Date	2010-01-29
TTC Route Travelled	106 York University
Time of Record(hour)	16.5
Distance Travelled(km)	317.8
Total Number of Stop	2478.0
Total Travel Time (hour)	11.4
Total Stop Time(hour)	5.0
Average Speed (kph)	19.3
Average Number of Stop (/km)	7.8

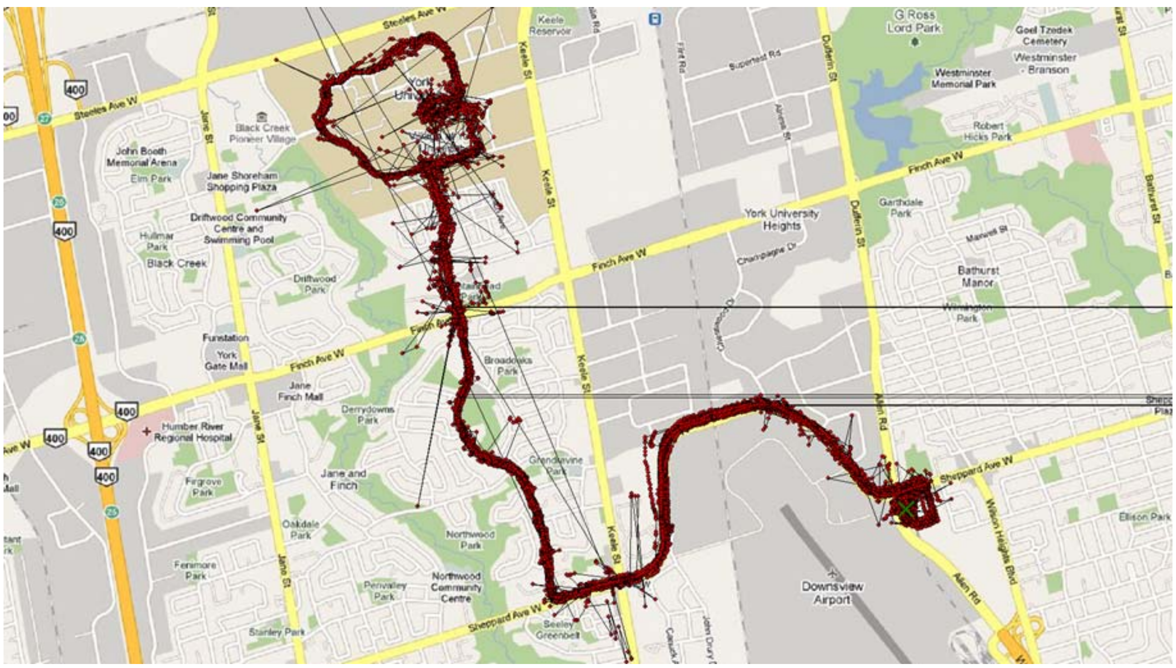


Table A-1 Summary of 2010-01-29

Date	2010-01-31
TTC Route Travelled	97 Yonge
Time of Record(hour)	13.0
Distance Travelled(km)	223.7
Total Number of Stop	1913.0
Total Travel Time (hour)	8.3
Total Stop Time(hour)	4.7
Average Speed (kph)	17.2
Average Number of Stop (/km)	8.6

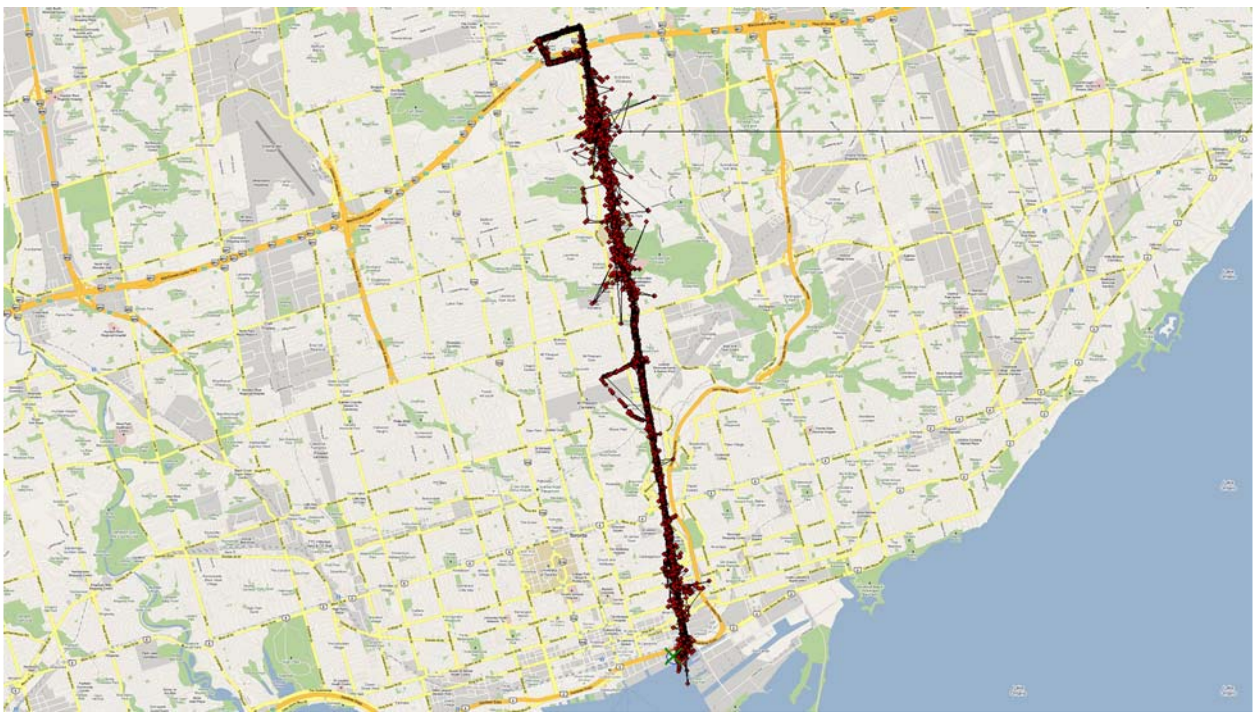


Table A-2 Summary of 2010-01-31

Date	2010-02-02
TTC Route Travelled	106 York University
Time of Record(hour)	12.5
Distance Travelled(km)	241.9
Total Number of Stop	1748.0
Total Travel Time (hour)	8.6
Total Stop Time(hour)	4.0
Average Speed (kph)	19.3
Average Number of Stop (/km)	7.2

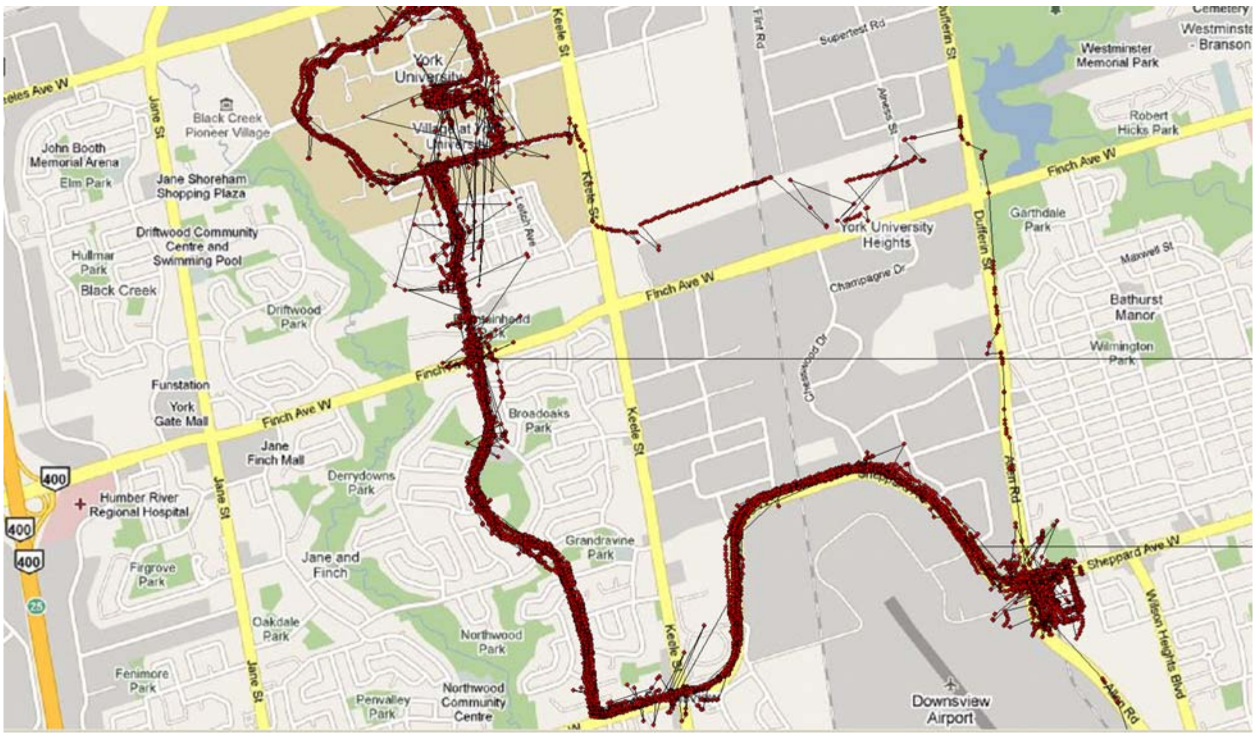


Table A-3 Summary of 2010-02-02

Date	2010-02-03
TTC Route Travelled	75 Sherbourne
Time of Record(hour)	18.4
Distance Travelled(km)	233.7
Total Number of Stop	3518.0
Total Travel Time (hour)	10.9
Total Stop Time(hour)	7.5
Average Speed (kph)	12.7
Average Number of Stop (/km)	15.1

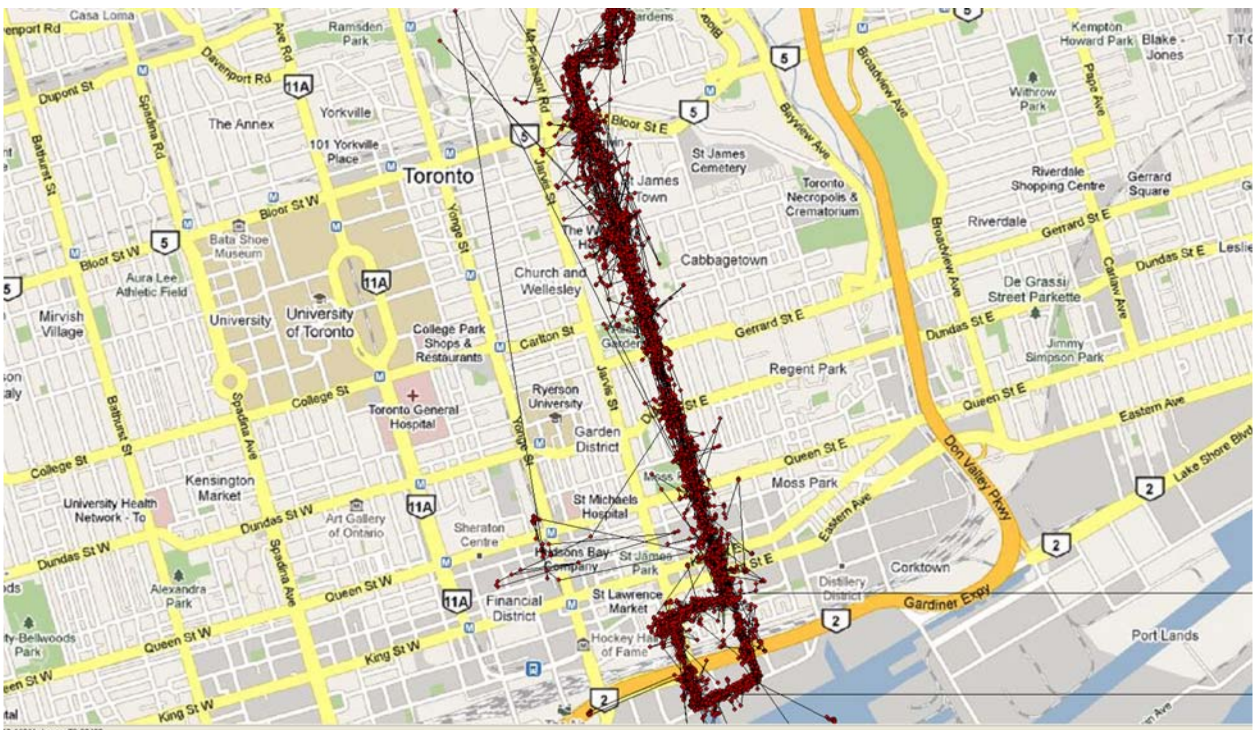


Table A-4 Summary of 2010-02-03

Date	2010-02-04
TTC Route Travelled	125 Drewry
Time of Record(hr)	14.0
Distance Travelled(km)	240.8
Total Number of Stop	2370.0
Total Travel Time (hour)	9.1
Total Stop Time(hour)	5.0
Average Speed (kph)	17.1
Average Number of Stop (/km)	9.8

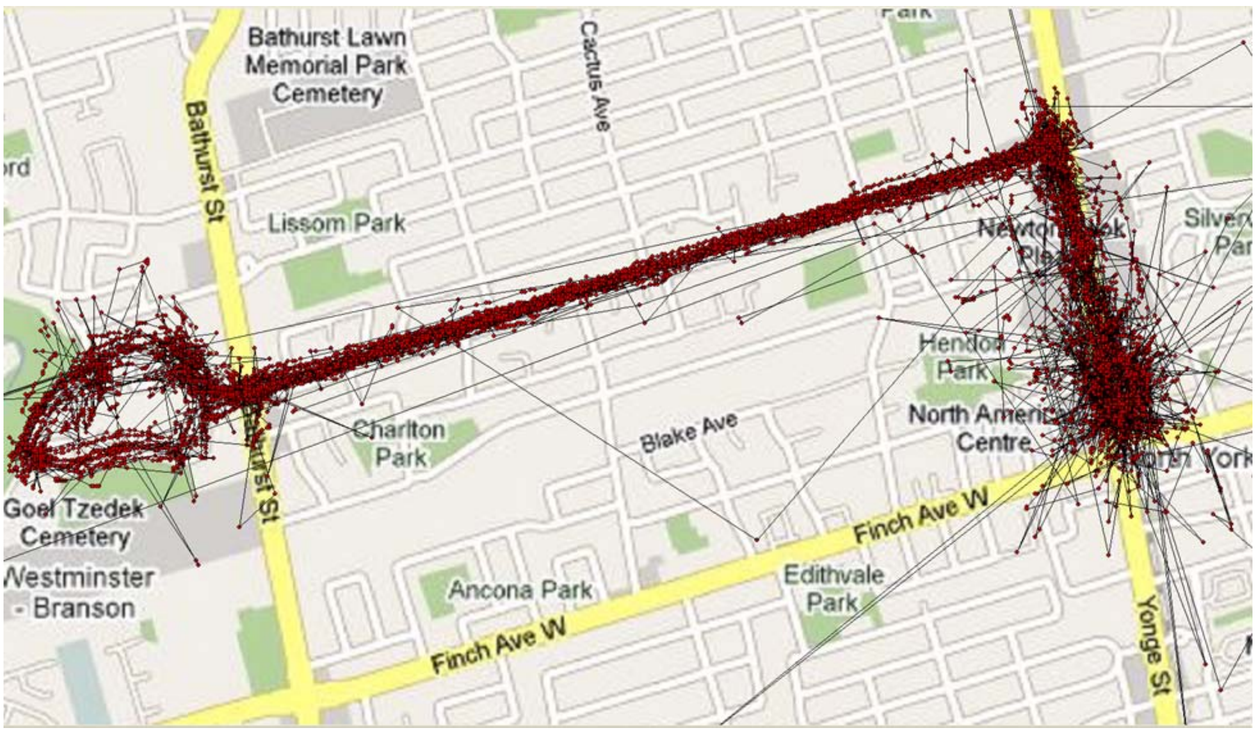


Table A-5 Summary of 2010-02-04

Date	2010-02-05
TTC Route Travelled	106 York University
Time of Record(hr)	12.4
Distance Travelle(km)	206.3
Total Number of Stop	2476.0
Total Travel Time (hour)	8.3
Total Stop Time(hour)	4.1
Average Speed (kph)	16.6
Average Number of Stop (/km)	12.0

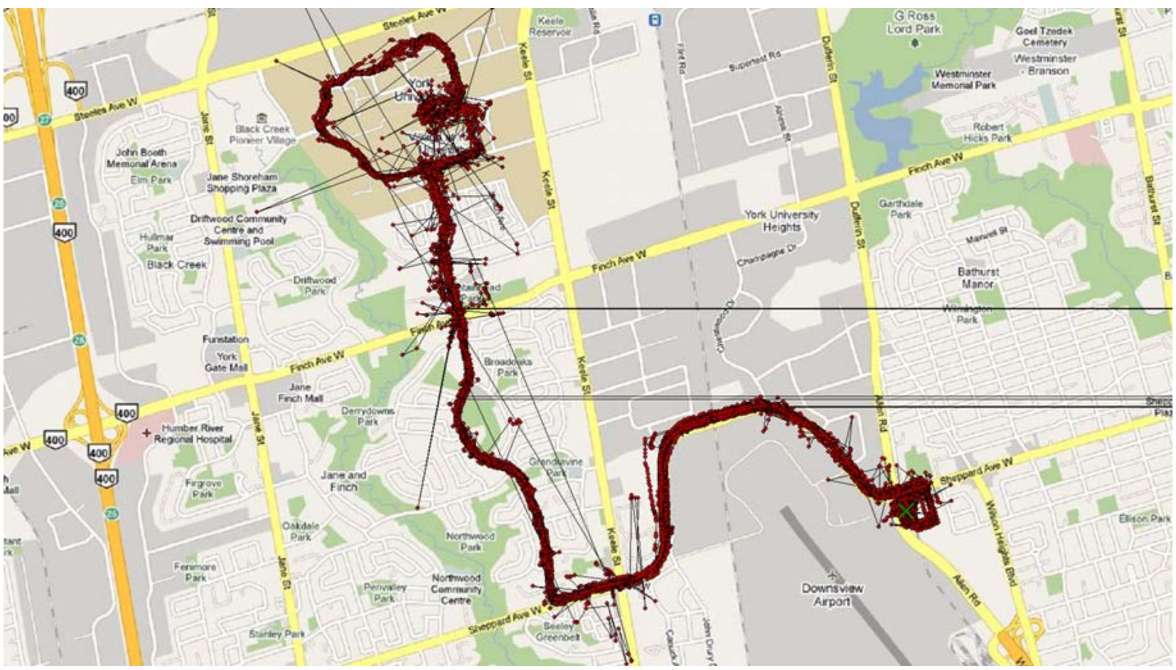


Table A-6 Summary of 2010-02-05

Date	2010-02-06
TTC Route Travelled	162 Lawrence-Donway
Time of Record(hr)	16.0
Distance Travelled(km)	330.8
Total Number of Stop	1503.0
Total Travel Time (hour)	11.0
Total Stop Time(hour)	4.9
Average Speed (kph)	20.7
Average Number of Stop (/km)	4.5

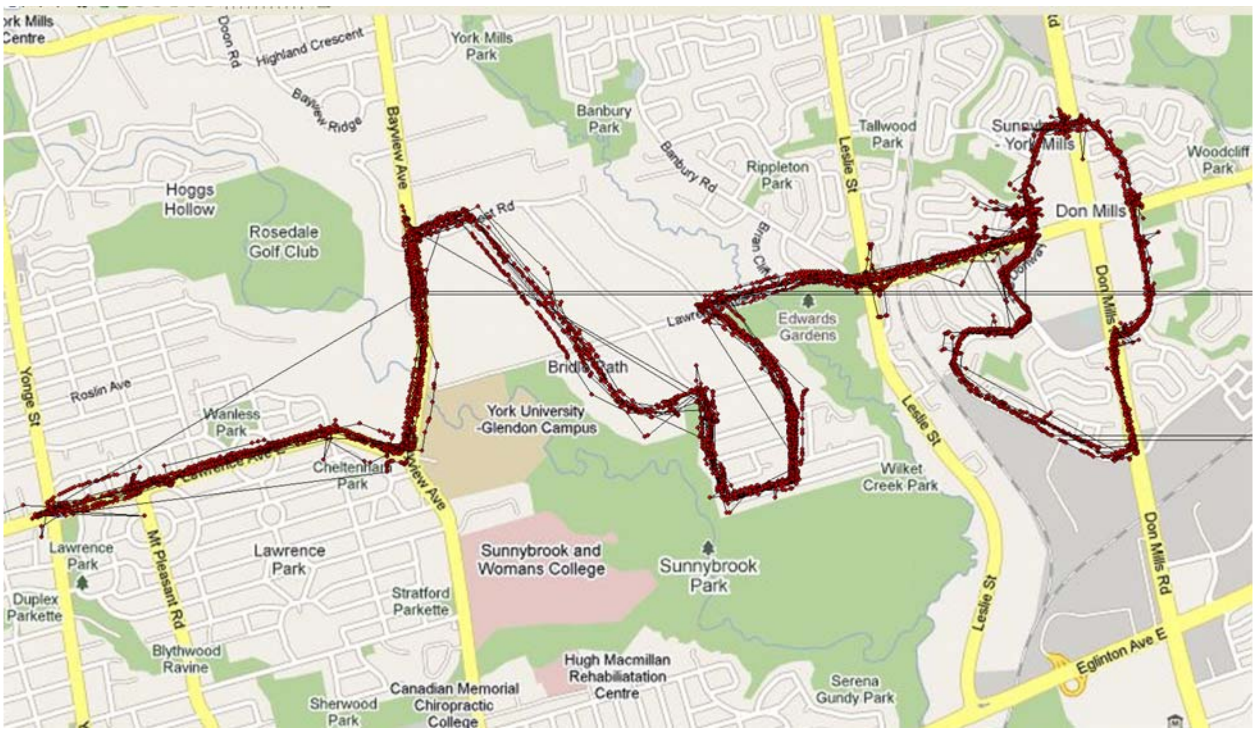


Table A-7 Summary of 2010-02-06

Date	2010-02-09
TTC Route Travelled	97 Yonge
Time of Record(hr)	15.8
Distance Travelled(km)	230.8
Total Number of Stop	2403.0
Total Travel Time (hour)	9.2
Total Stop Time(hour)	6.6
Average Speed (kph)	14.6
Average Number of Stop (/km)	10.4

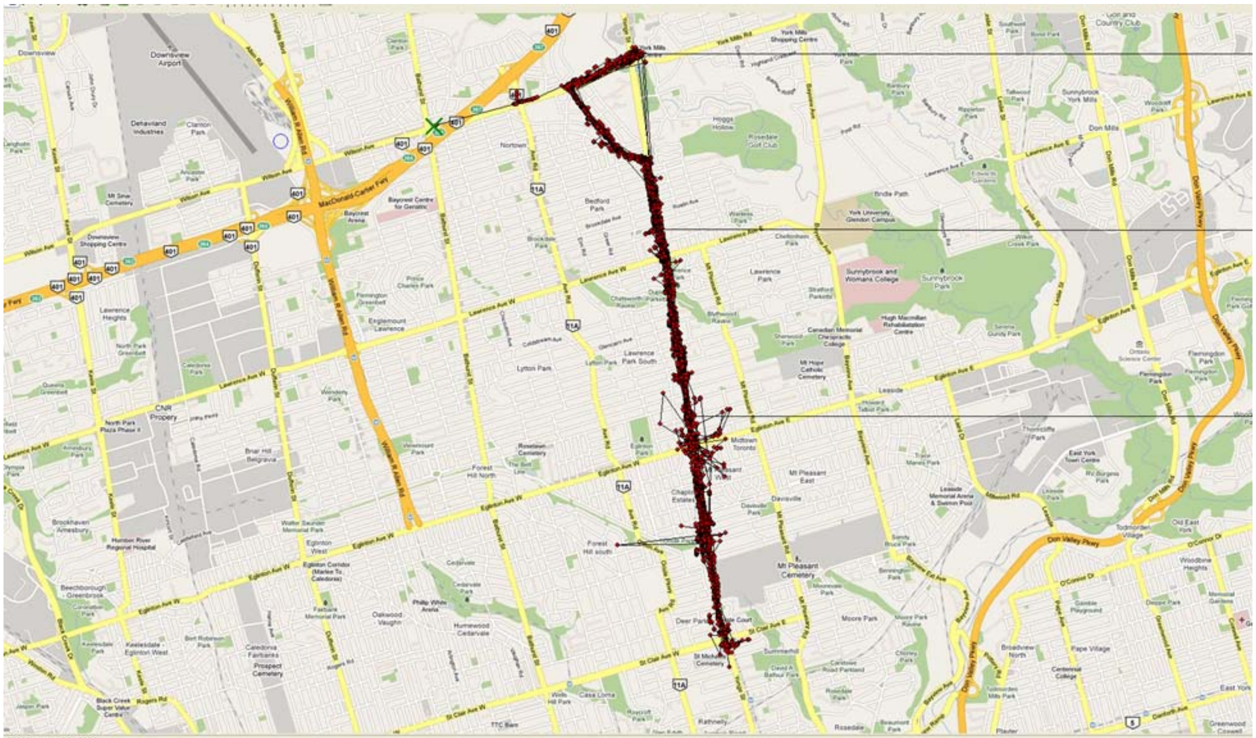


Table A-8 Summary of 2010-02-09

Date	2010-02-10
TTC Route Travelled	122 Graydon Hall
Time of Record(hr)	14.0
Distance Travelled(km)	286.2
Total Number of Stop	1914.0
Total Travel Time (hour)	9.7
Total Stop Time(hour)	4.3
Average Speed (kph)	20.4
Average Number of Stop (/km)	6.7

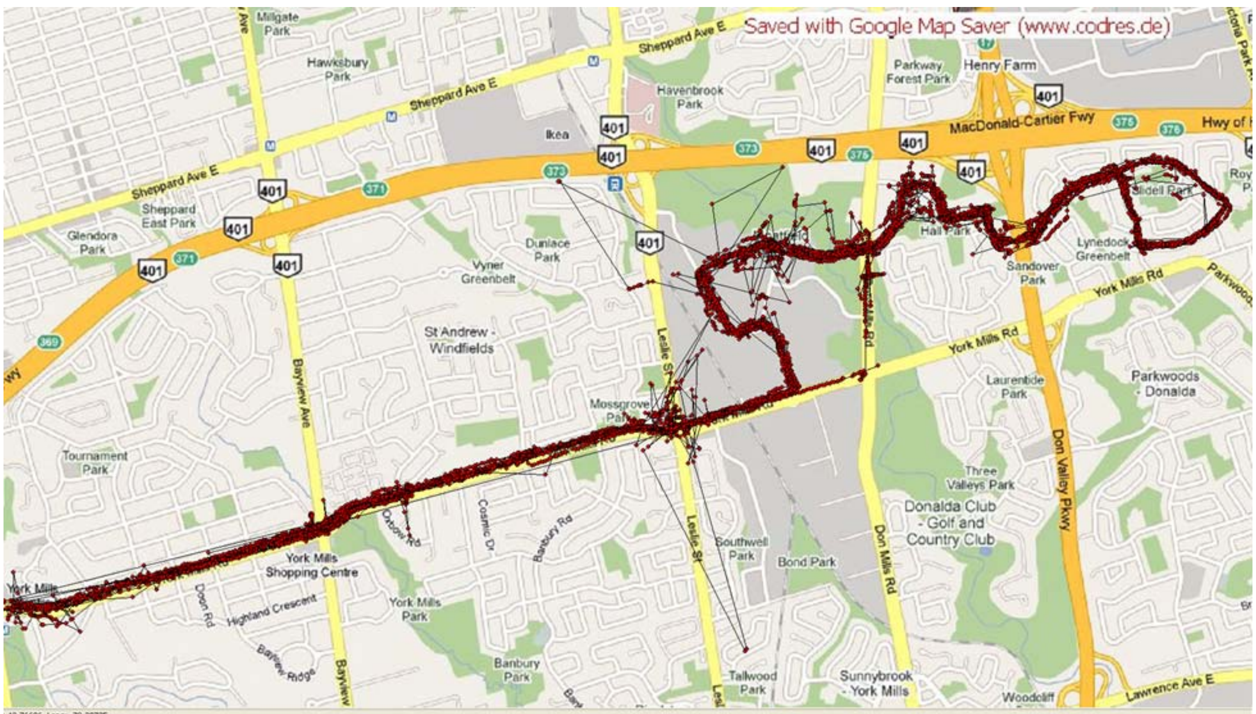


Table A-9 Summary of 2010-02-10

Date	2010-02-11
TTC Route Travelled	75 Sherbourne
Time of Record(hr)	13.6
Distance Travelled(km)	195.5
Total Number of Stop	1591.0
Total Travel Time (hour)	7.6
Total Stop Time(hour)	5.9
Average Speed (kph)	14.4
Average Number of Stop (/km)	8.1

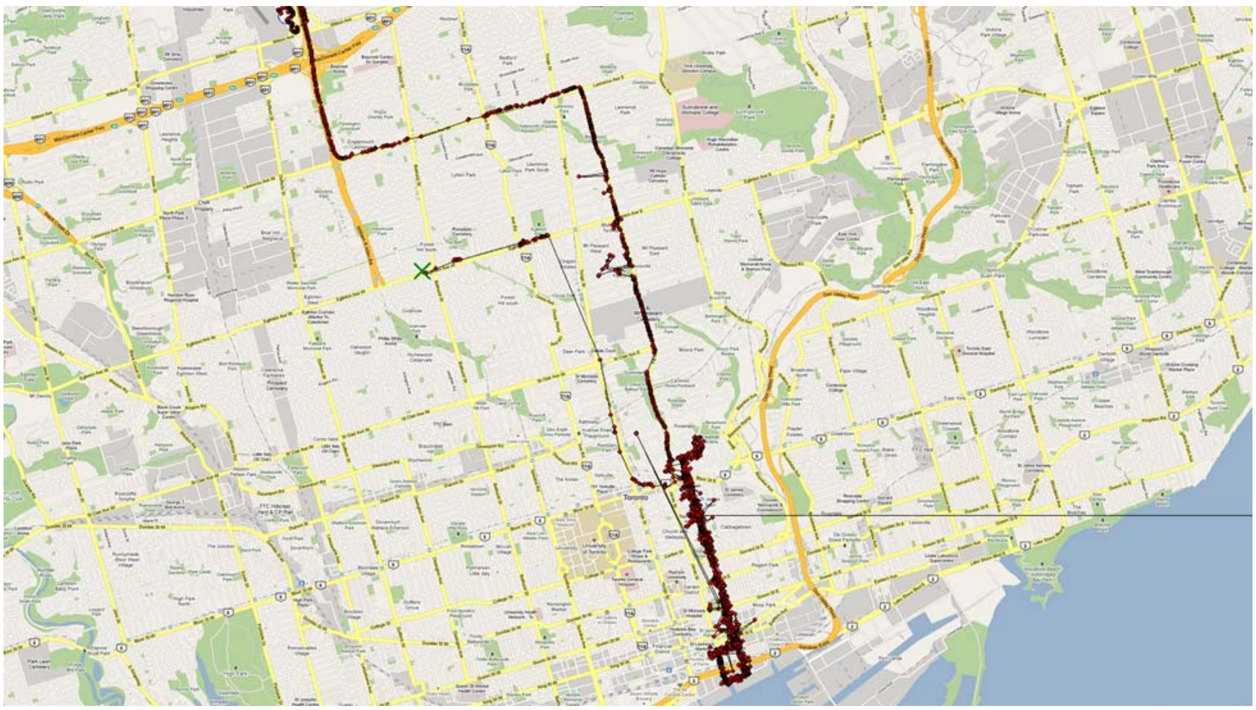


Table A-10 Summary of 2010-02-11

Date	2010-02-12
TTC Route Travelled	107 Keele North
Time of Record(hr)	16.1
Distance Travelled(km)	350.6
Total Number of Stop	1934.0
Total Travel Time (hour)	11.1
Total Stop Time(hour)	5.0
Average Speed (kph)	21.8
Average Number of Stop (/km)	5.5

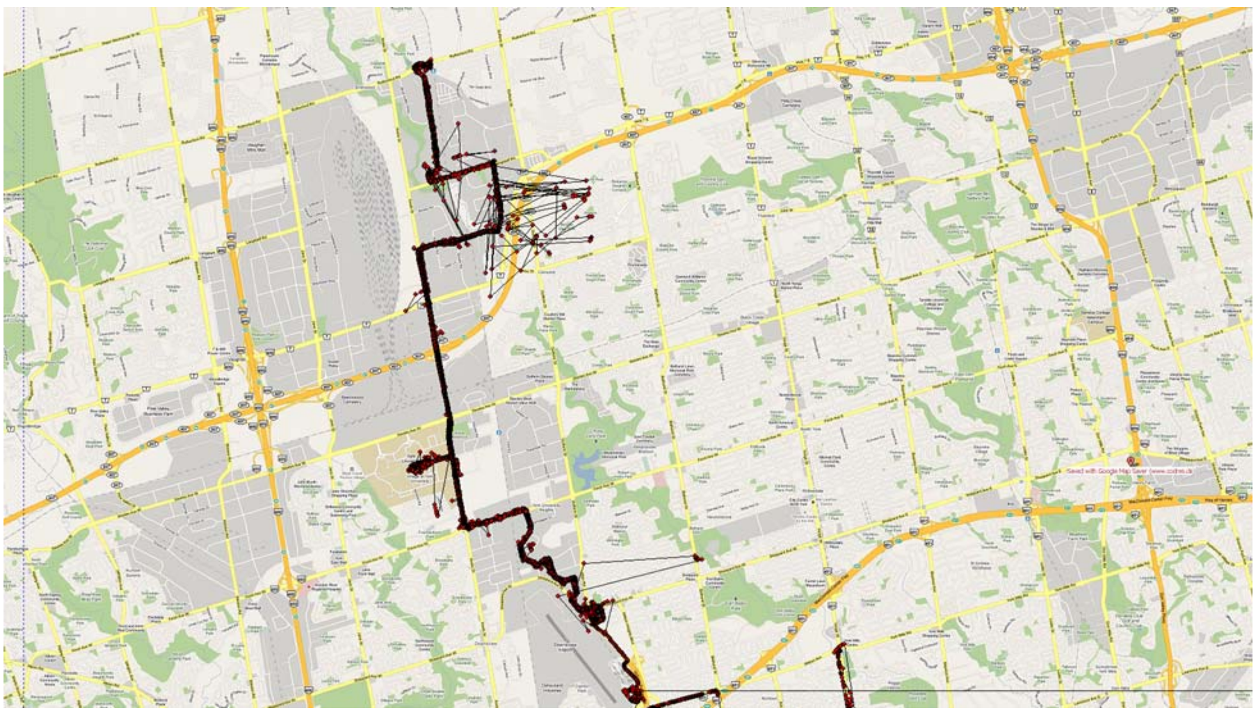


Table A-11 Summary of 2010-02-12

Date	2010-02-13
TTC Route Travelled	97 Yonge
Time of Record(hr)	17.0
Distance Travelled(km)	325.7
Total Number of Stop	3277.0
Total Travel Time (hour)	11.8
Total Stop Time(hour)	5.2
Average Speed (kph)	19.1
Average Number of Stop (/km)	10.1

Table A-12 Summary of 2010-02-13

Date	2010-02-14
TTC Route Travelled	97 Yonge/7 Bathurst
Time of Record(hr)	11.4
Distance Travelled(km)	206.7
Total Number of Stop	2120.0
Total Travel Time (hour)	7.5
Total Stop Time(hour)	3.9
Average Speed (kph)	18.1
Average Number of Stop (/km)	10.3

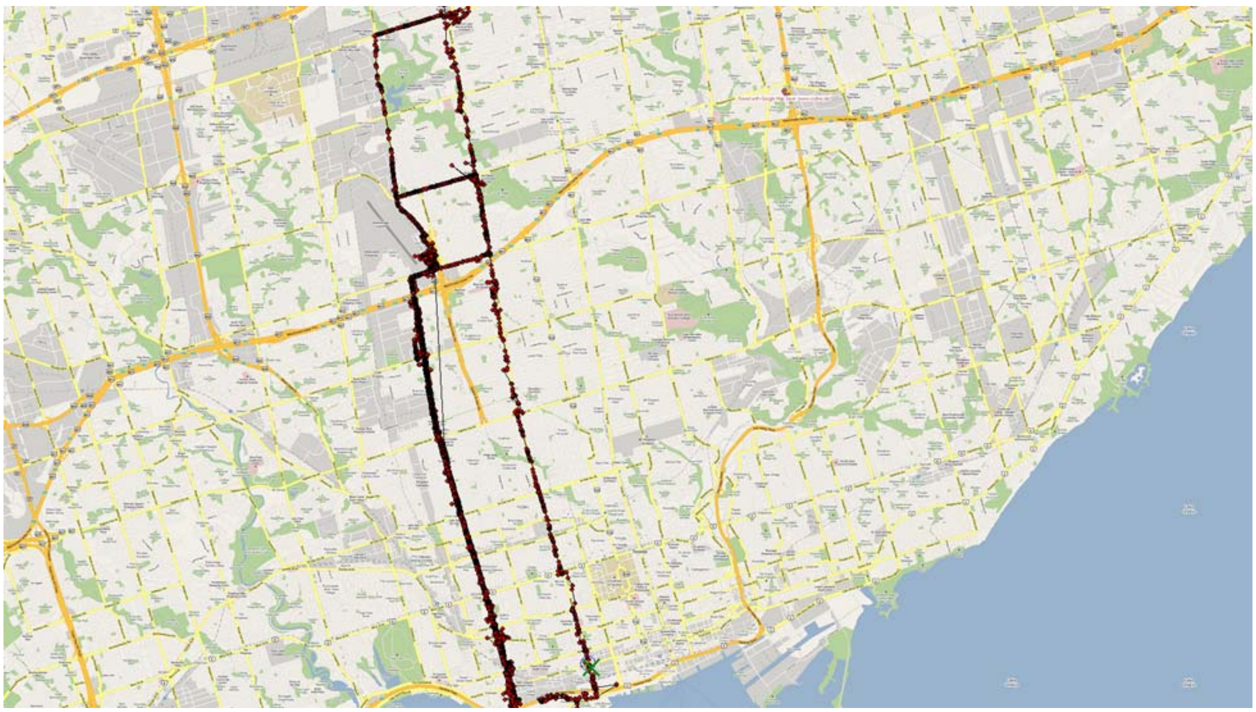


Table A-13 Summary of 2010-02-14

Date	2010-02-15
TTC Route Travelled	109 Ranee
Time of Record(hr)	7.5
Distance Travelled(km)	126.5
Total Number of Stop	1057.0
Total Travel Time (hour)	5.0
Total Stop Time(hour)	2.5
Average Speed (kph)	16.9
Average Number of Stop (/km)	8.4

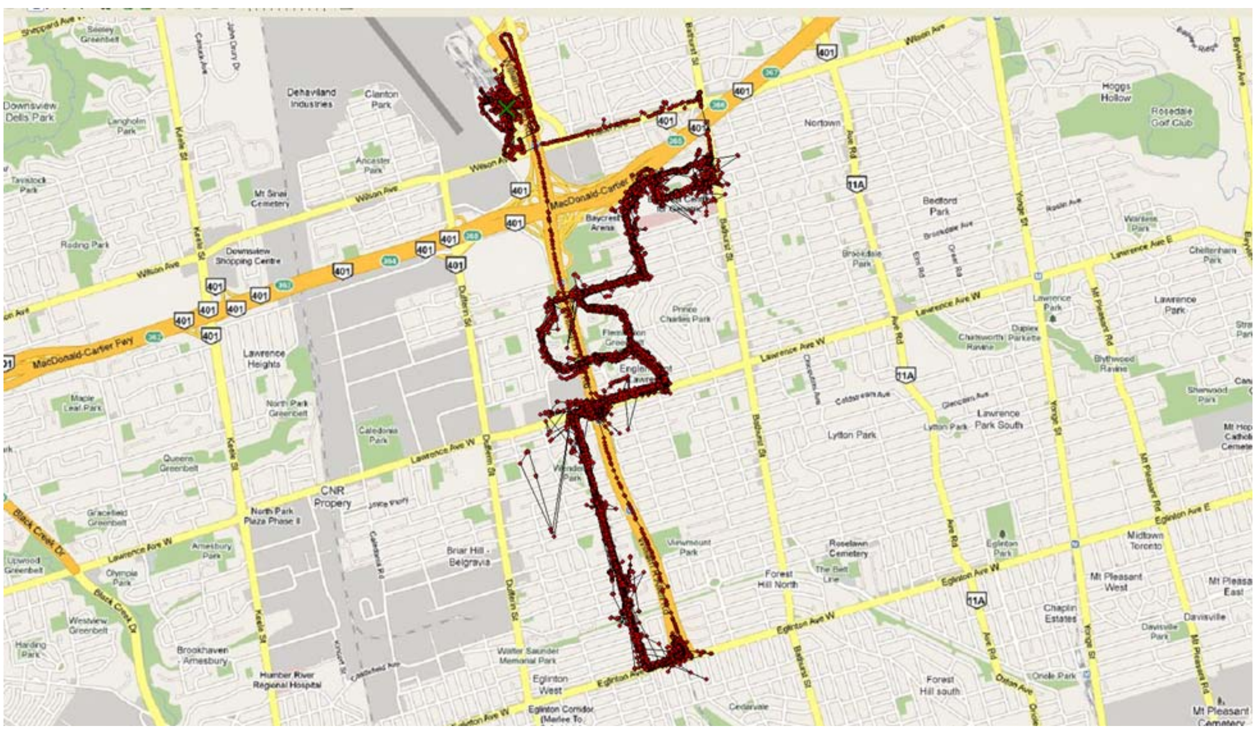


Table A-14 Summary of 2010-02-15

Date	2010-02-16
TTC Route Travelled	106 York University
Time of Record(hr)	14.5
Distance Travelled(km)	279.0
Total Number of Stop	2263.0
Total Travel Time (hour)	10.1
Total Stop Time(hour)	4.4
Average Speed (kph)	19.2
Average Number of Stop (/km)	8.1

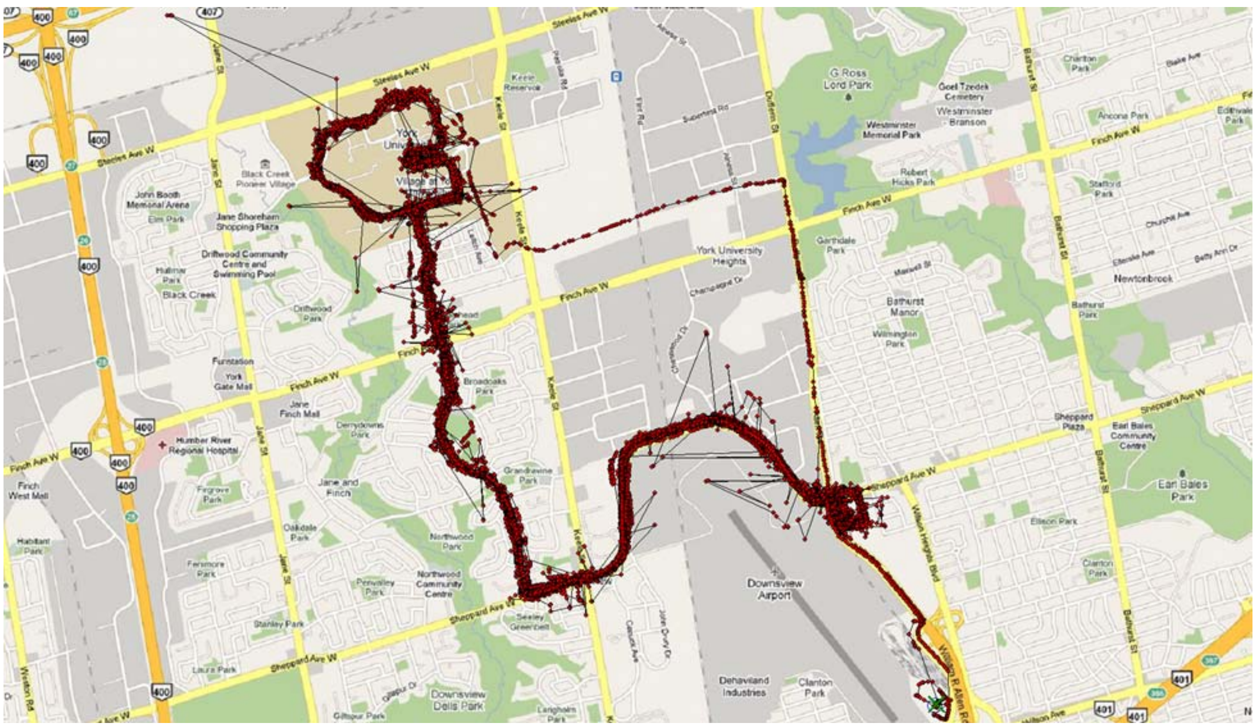


Table A-15 Summary of 2010-02-16

Date	2010-02-18
TTC Route Travelled	11 Bayview
Time of Record(hr)	7.9
Distance Travelled(km)	133.1
Total Number of Stop	1191.0
Total Travel Time (hour)	5.0
Total Stop Time(hour)	2.9
Average Speed (kph)	16.8
Average Number of Stop (/km)	8.9

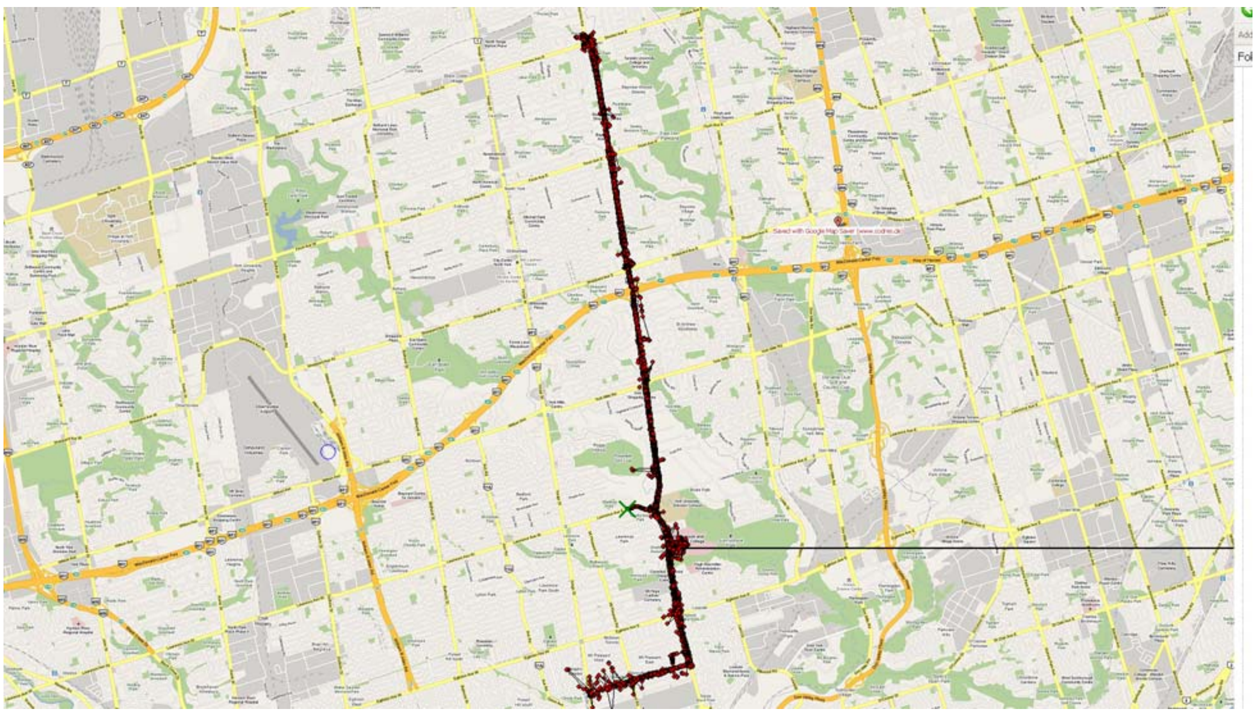


Table A-16 Summary of 2010-02-18

Date	2010-02-19
TTC Route Travelled	105 Dufferin North/97 Yonge
Time of Record(hr)	14.9
Distance Travelled(km)	268.9
Total Number of Stop	2120.0
Total Travel Time (hour)	9.5
Total Stop Time(hour)	5.4
Average Speed (kph)	18.0
Average Number of Stop (/km)	7.9

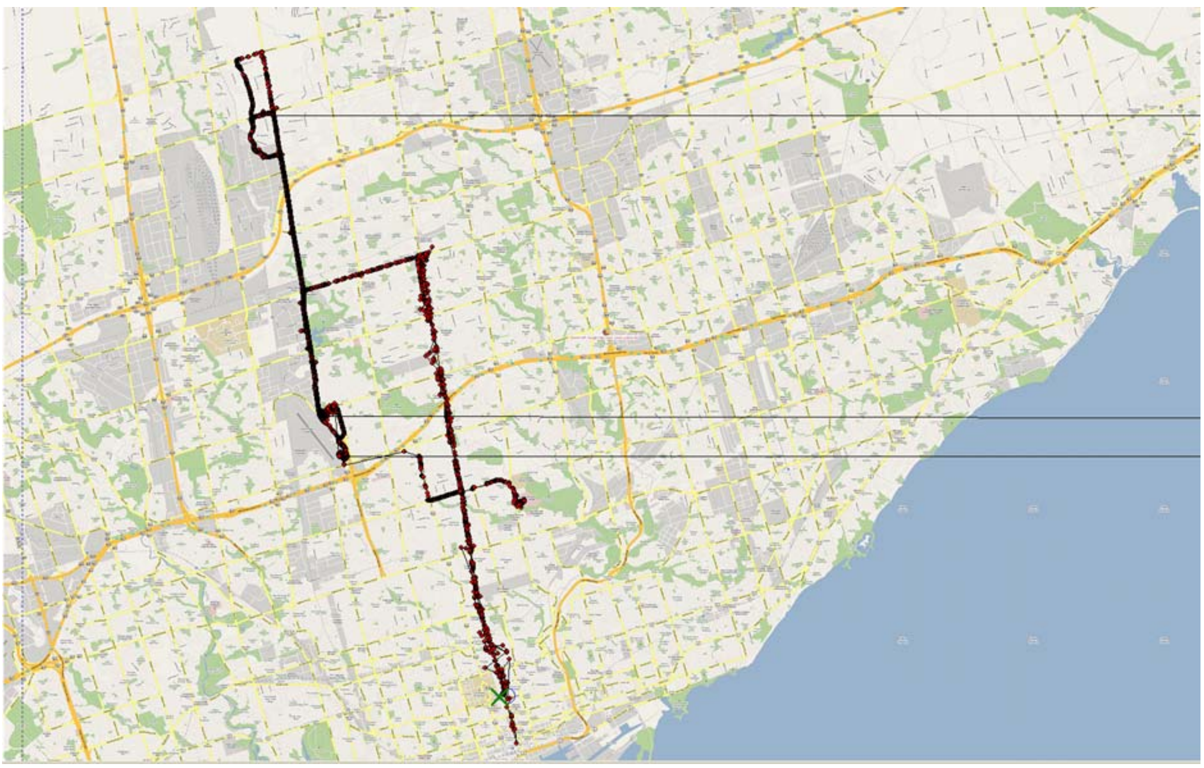


Table A-17 Summary of 2010-02-19

Date	2010-02-20
TTC Route Travelled	97 Yonge
Time of Record(hr)	4.9
Distance Travelled(km)	115.2
Total Number of Stop	599.0
Total Travel Time (hour)	3.3
Total Stop Time(hour)	1.6
Average Speed (kph)	23.3
Average Number of Stop (/km)	5.2

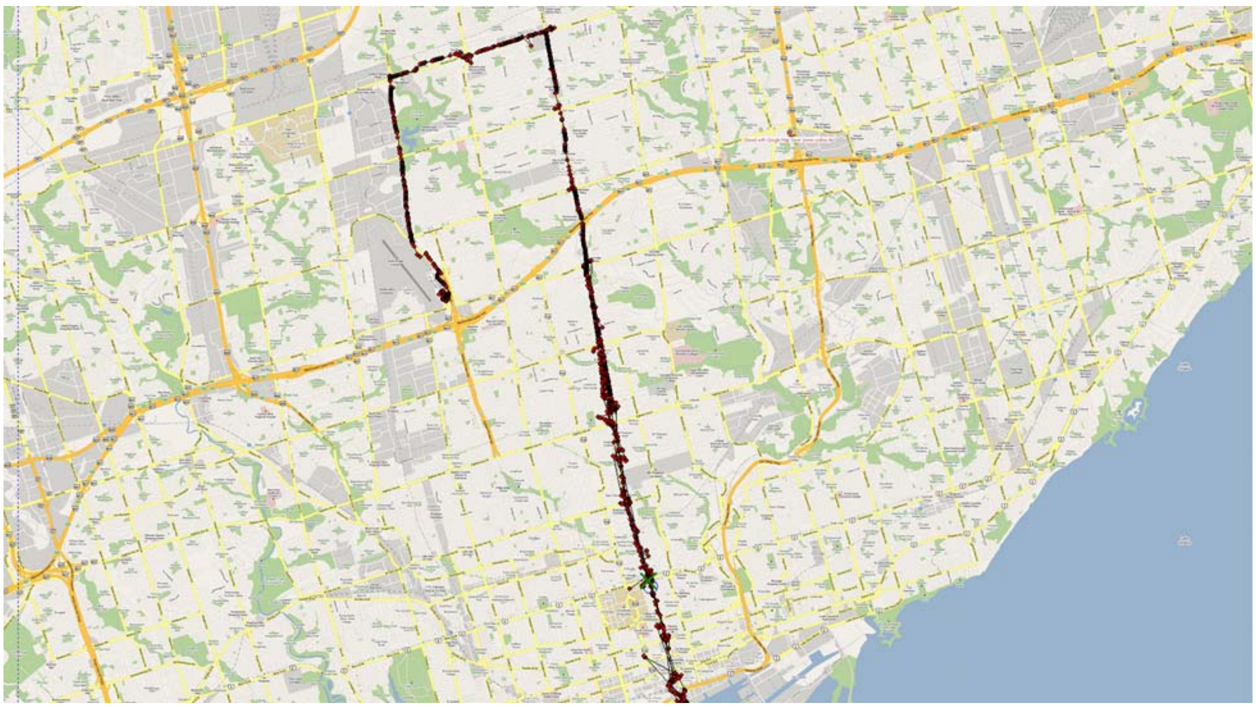


Table A-18 Summary of 2010-02-20

Date	2010-02-21
TTC Route Travelled	98 Willowdale-Senlac/97 Yonge
Time of Record(hr)	12.1
Distance Travelled(km)	274.5
Total Number of Stop	1636.0
Total Travel Time (hour)	8.6
Total Stop Time(hour)	3.5
Average Speed (kph)	22.6
Average Number of Stop (/km)	6.0

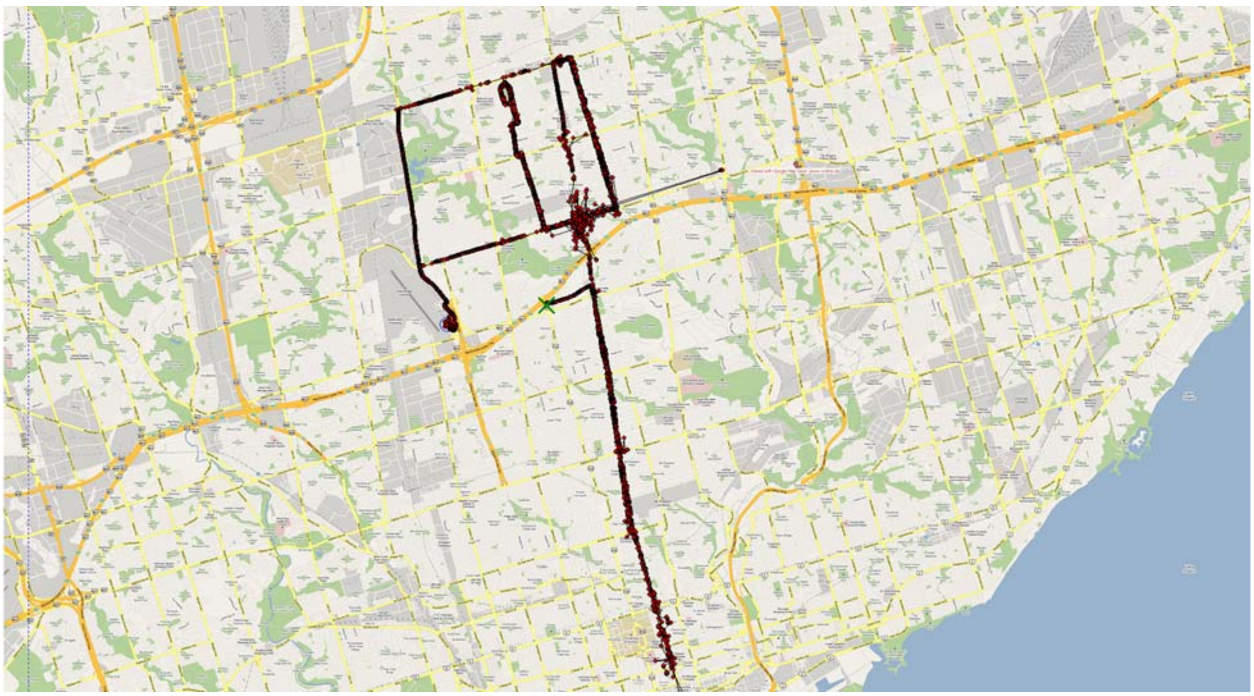


Table A-19 Summary of 2010-02-21

Date	2010-02-22
TTC Route Travelled	105 Dufferin North/122 Graydon
Time of Record(hr)	9.1
Distance Travelled(km)	178.1
Total Number of Stop	1000.0
Total Travel Time (hour)	6.2
Total Stop Time(hour)	3.0
Average Speed (kph)	19.5
Average Number of Stop (/km)	5.6

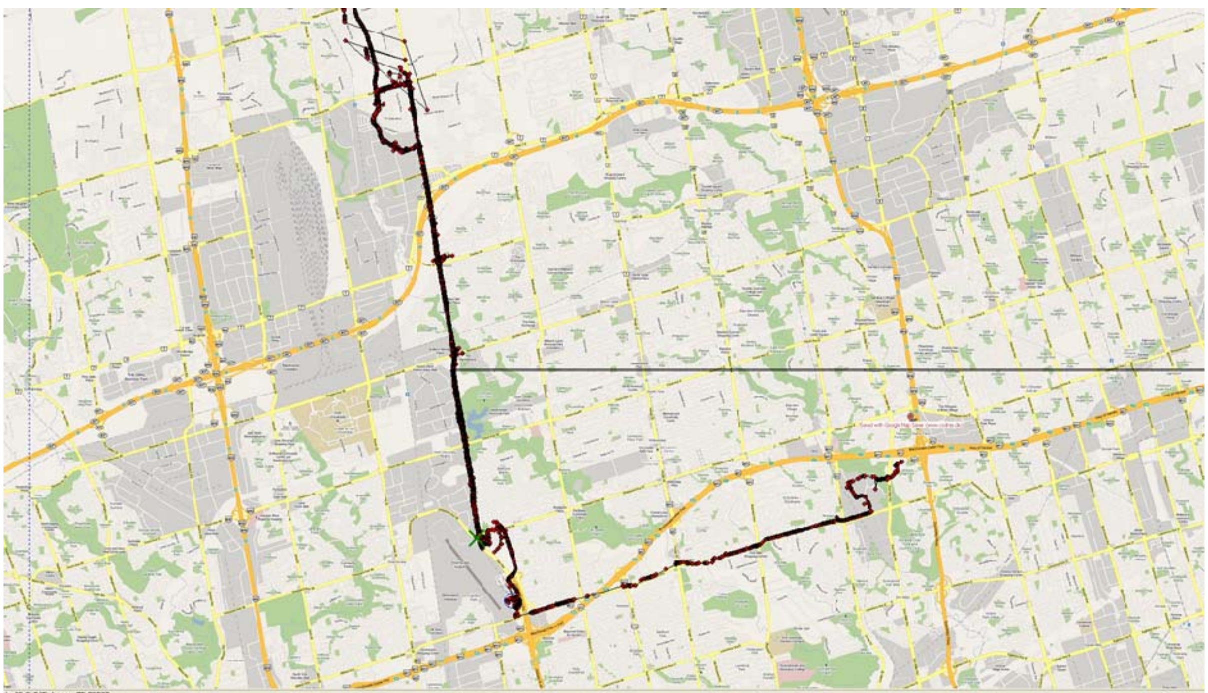
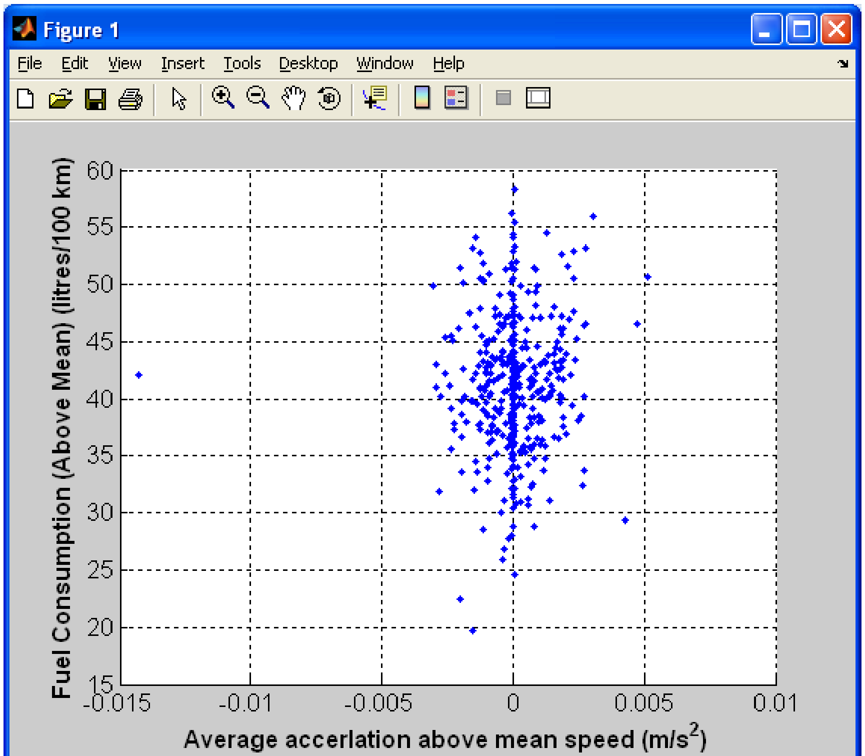


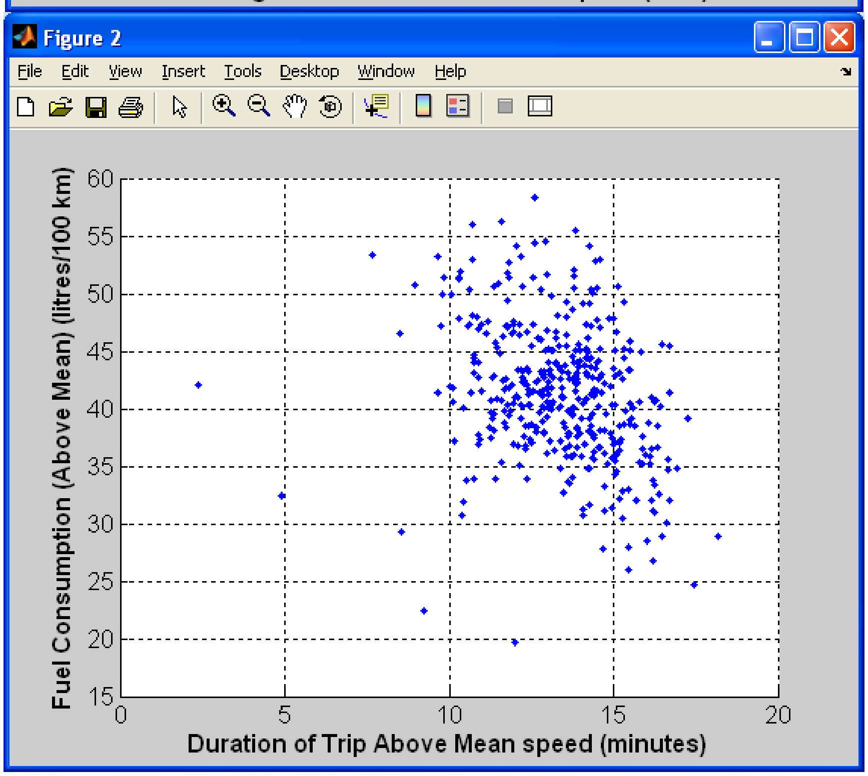
Table A-20 Summary of 2010-02-22

Appendix B

Single-Factor Correlations Between Fuel Consumption & Route Metrics

Appendix B: Single-Factor Correlations Between Fuel Consumption & Route Metrics





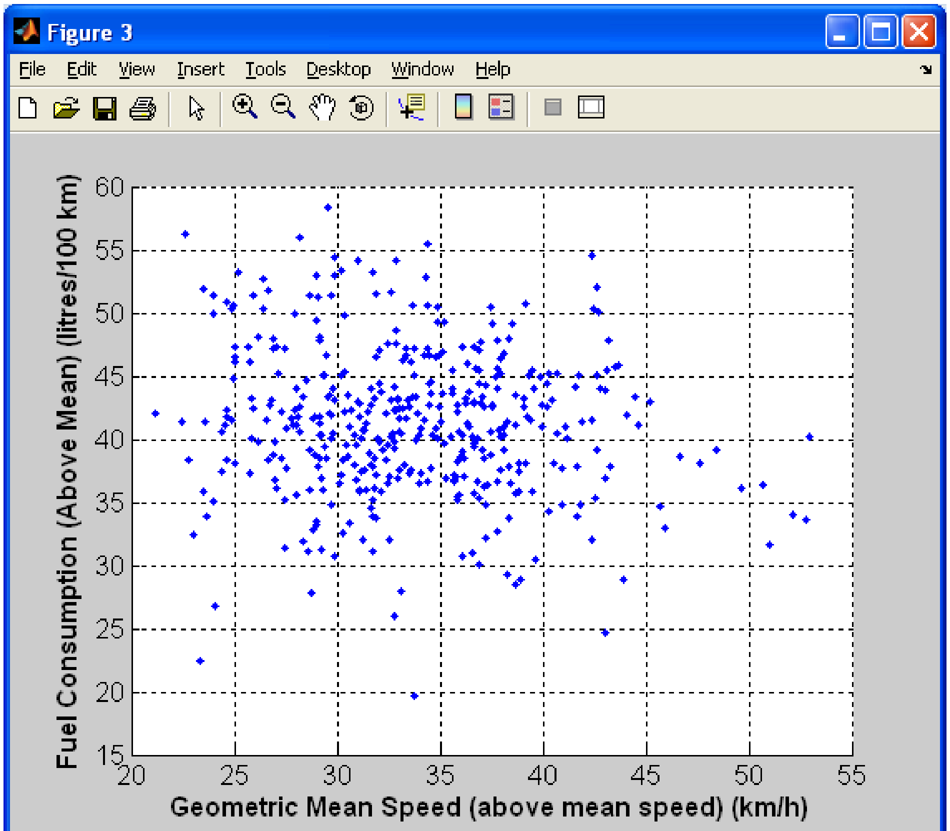


Figure 3
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (Above Mean) (litres/100 km)
Geometric Mean Speed (above mean speed) (km/h)
15 20 25 30 35 40 45 50 55 60
20 25 30 35 40 45 50 55

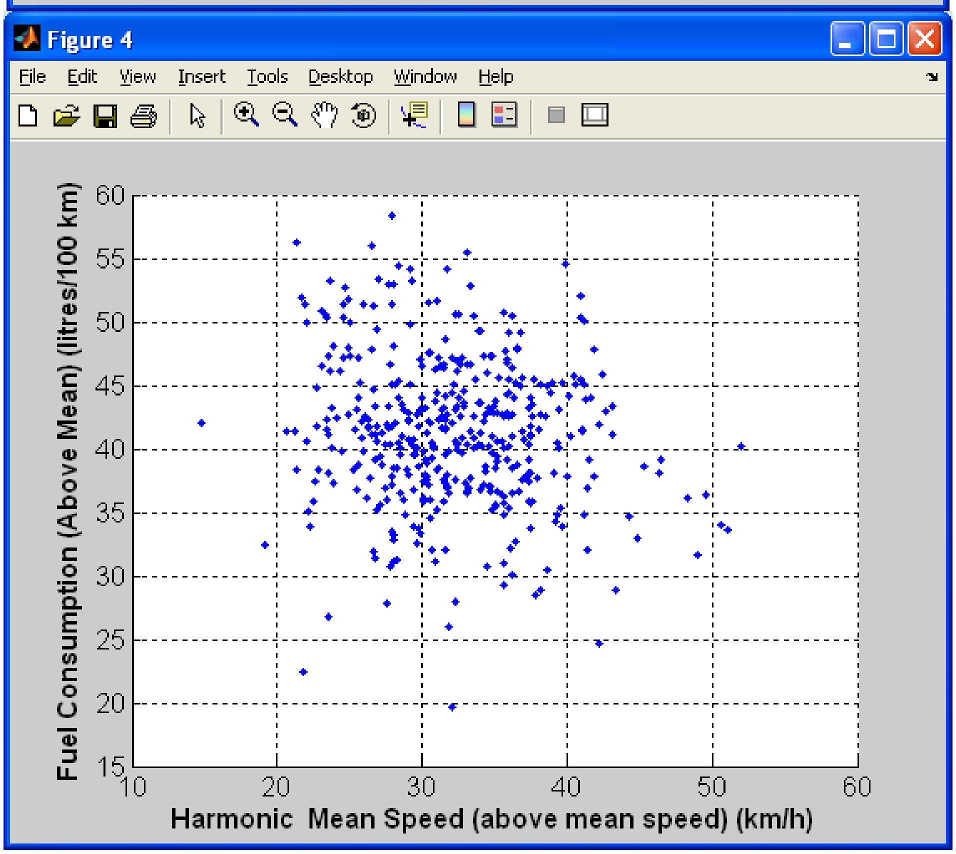


Figure 4
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (Above Mean) (litres/100 km)
Harmonic Mean Speed (above mean speed) (km/h)
15 20 25 30 35 40 45 50 55 60
10 20 30 40 50 60

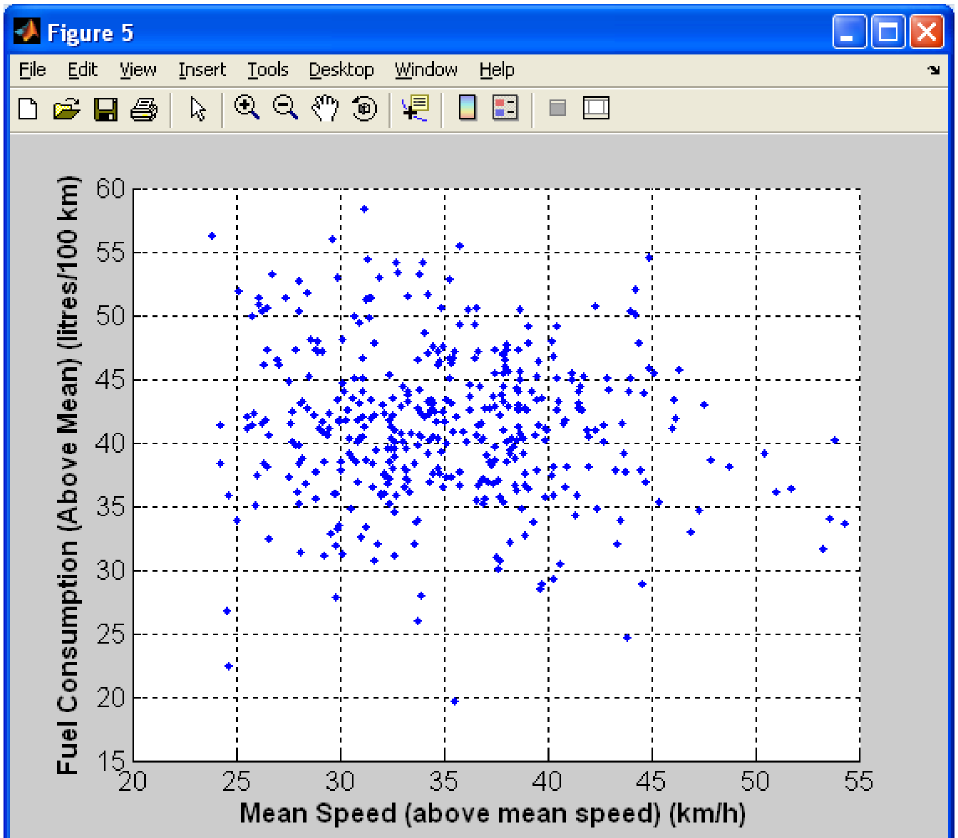


Figure 5
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (Above Mean) (litres/100 km)
60
55
50
45
40
35
30
25
20
15
20
25
30
35
40
45
50
55
Mean Speed (above mean speed) (km/h)

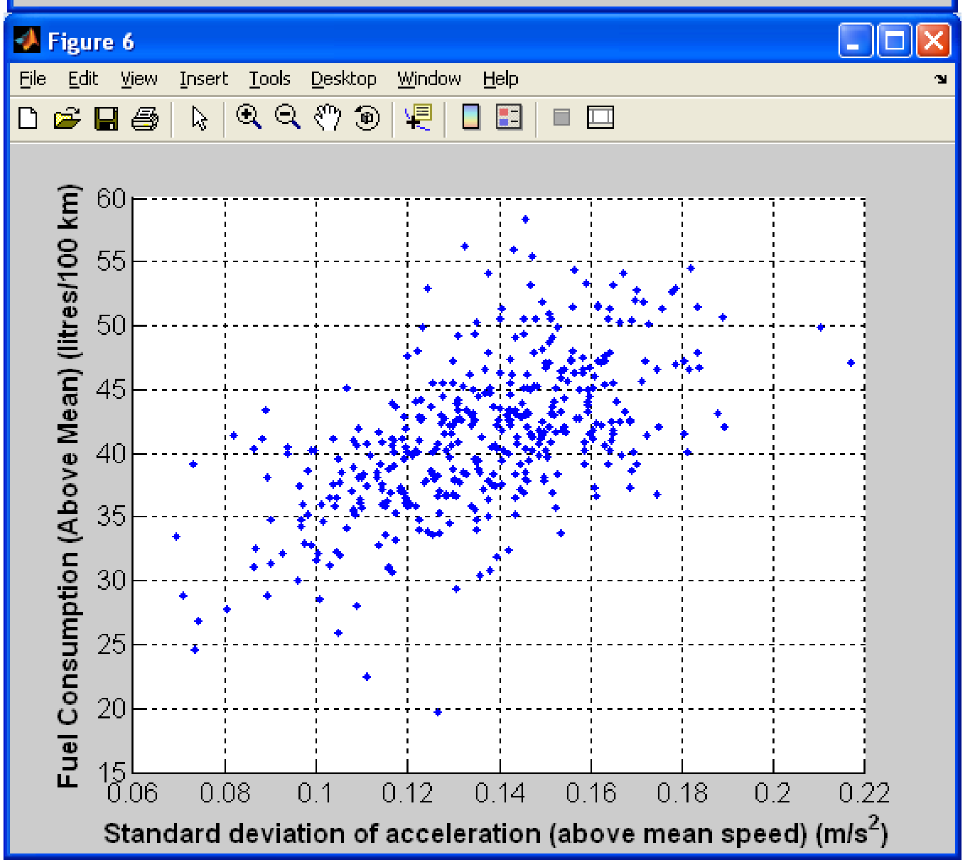


Figure 6
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (Above Mean) (litres/100 km)
60
55
50
45
40
35
30
25
20
15
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
Standard deviation of acceleration (above mean speed) (m/s2)

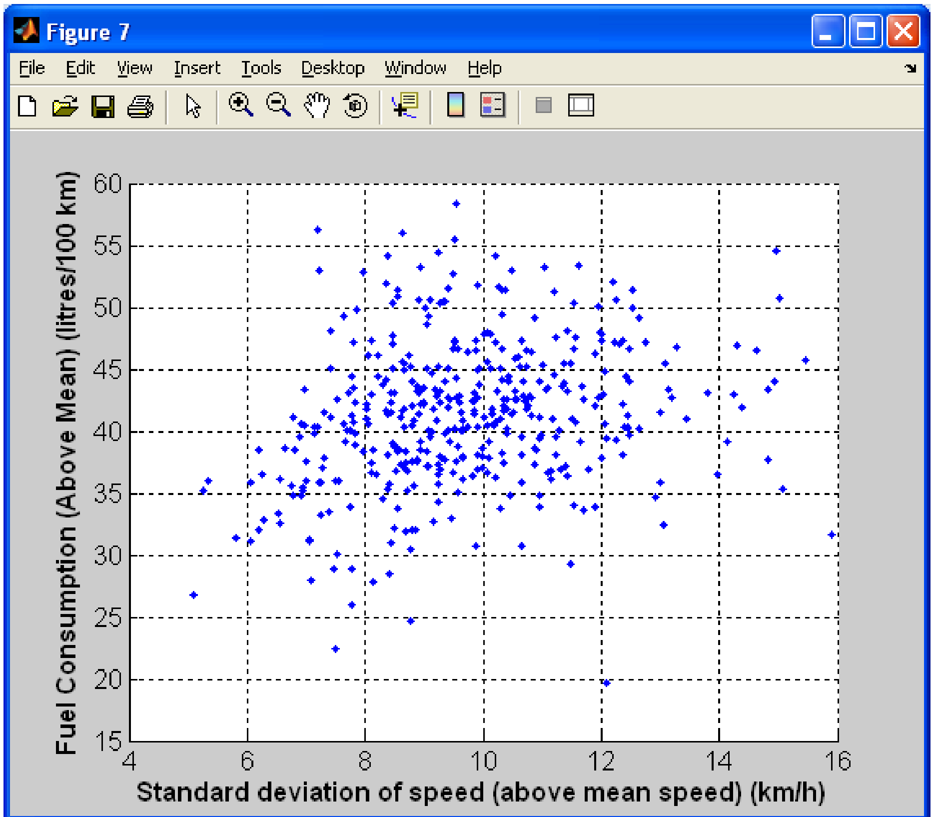


Figure 7
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (Above Mean) (litres/100 km)
60
55
50
45
40
35
30
25
20
15
4
6
8
10
12
14
16
Standard deviation of speed (above mean speed) (km/h)

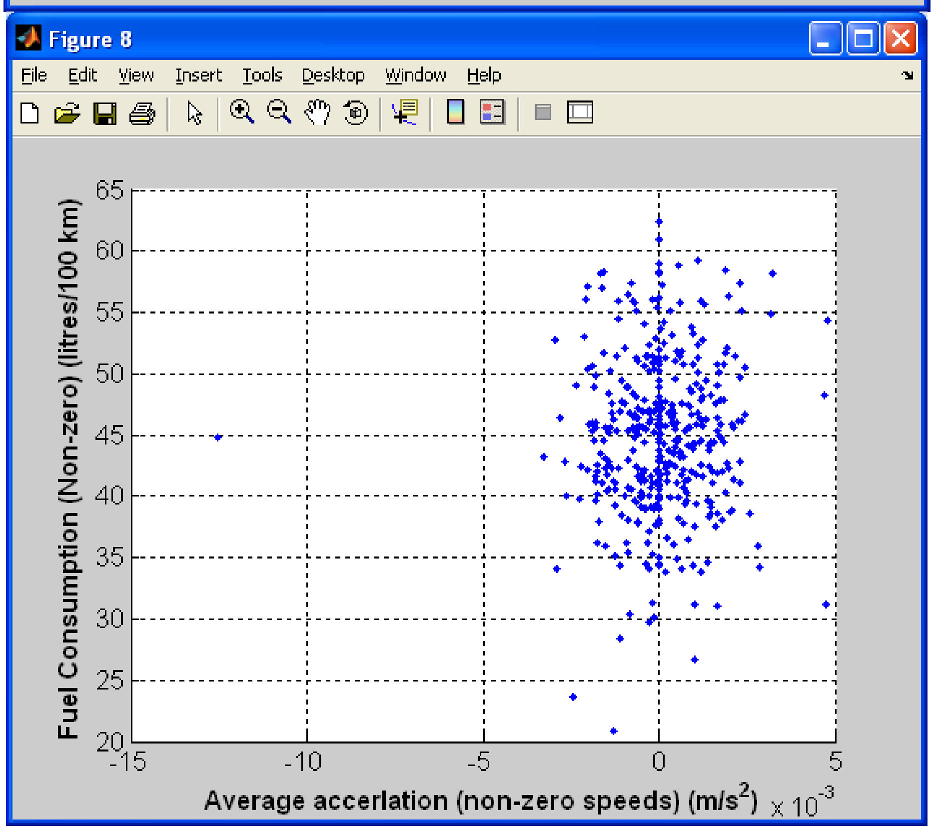


Figure 8
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (Non-zero) (litres/100 km)
65
60
55
50
45
40
35
30
25
20
-15
-10
-5
0
5
Average accerlation (non-zero speeds) (m/s2) x 10-3

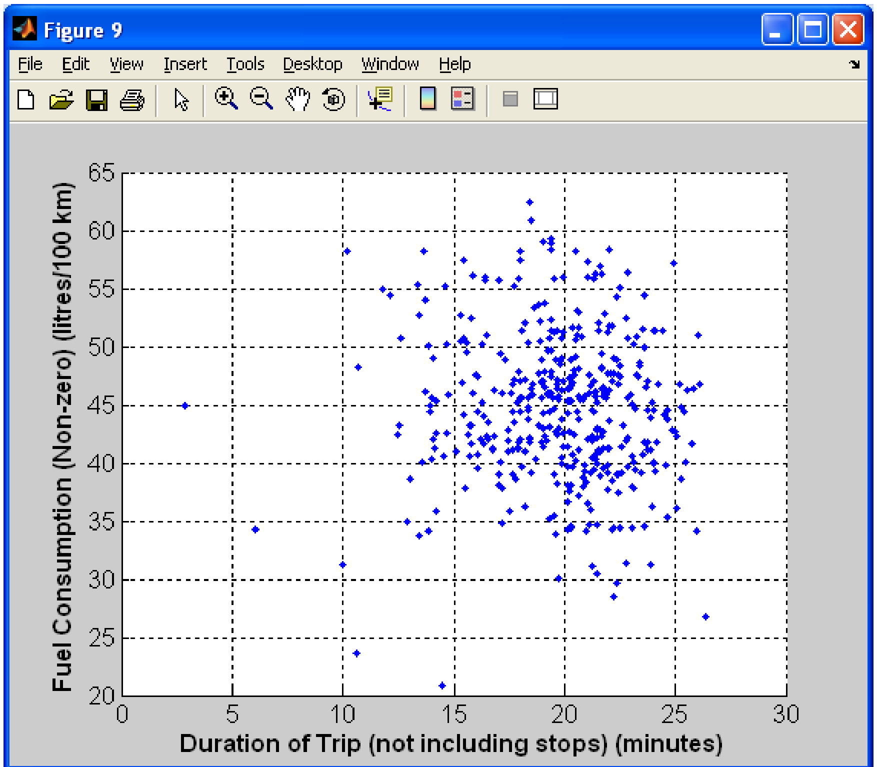


Figure 9
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (Non-zero) (litres/100 km)
65
60
55
50
45
40
35
30
25
20
0
5
10
15
20
25
30
Duration of Trip (not including stops) (minutes)

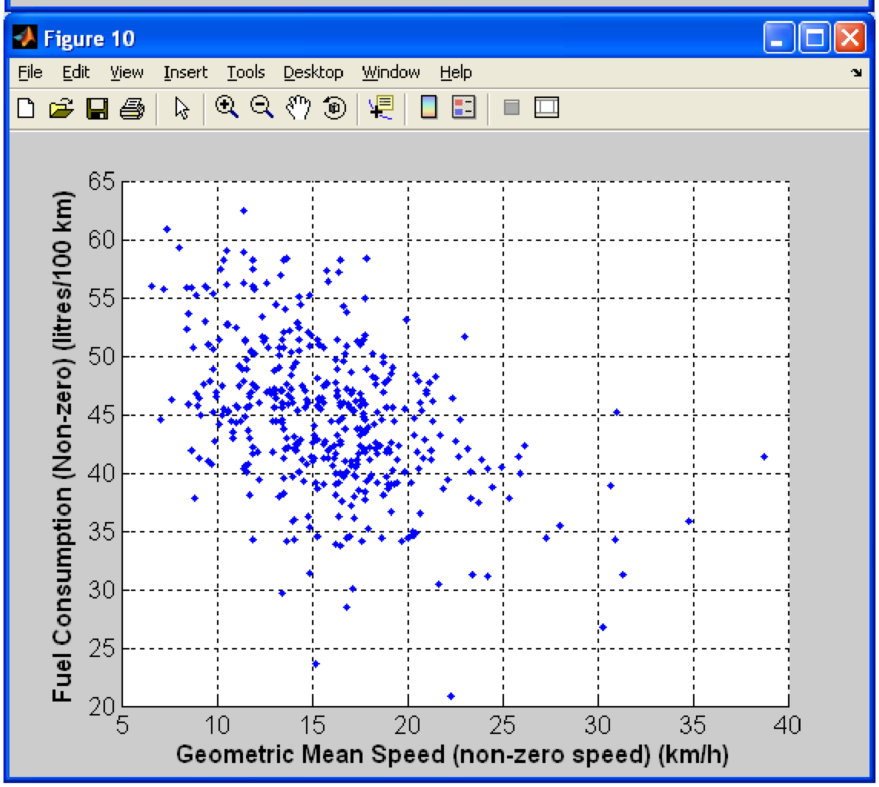


Figure 10
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (Non-zero) (litres/100 km)
65
60
55
50
45
40
35
30
25
20
5
10
15
20
25
30
35
40
Geometric Mean Speed (non-zero speed) (km/h)

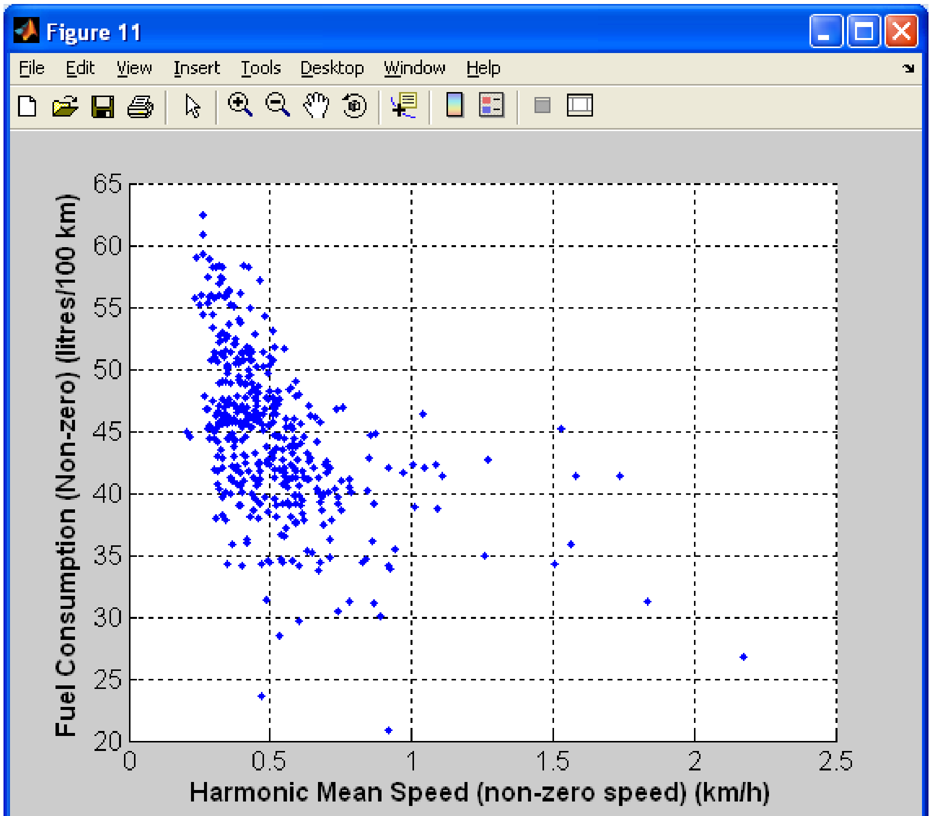


Figure 11
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (Non-zero) (litres/100 km)
Harmonic Mean Speed (non-zero speed) (km/h)
65
60
55
50
45
40
35
30
25
20
0
0.5
1
1.5
2
2.5

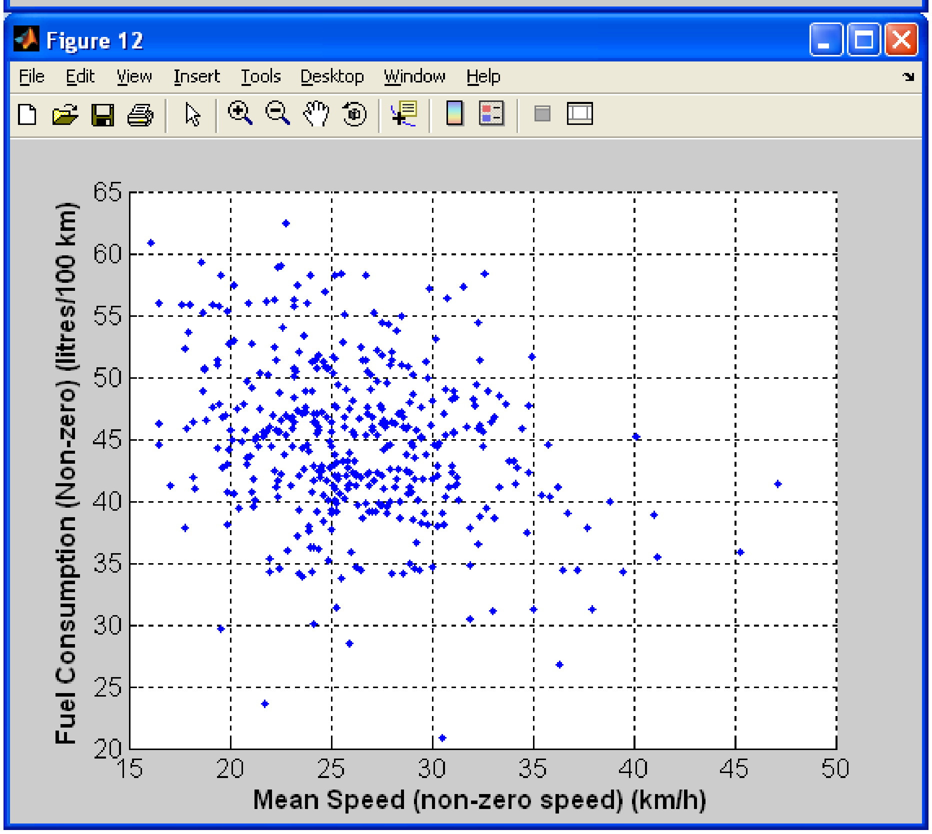


Figure 12
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (Non-zero) (litres/100 km)
Mean Speed (non-zero speed) (km/h)
65
60
55
50
45
40
35
30
25
20
15
20
25
30
35
40
45
50

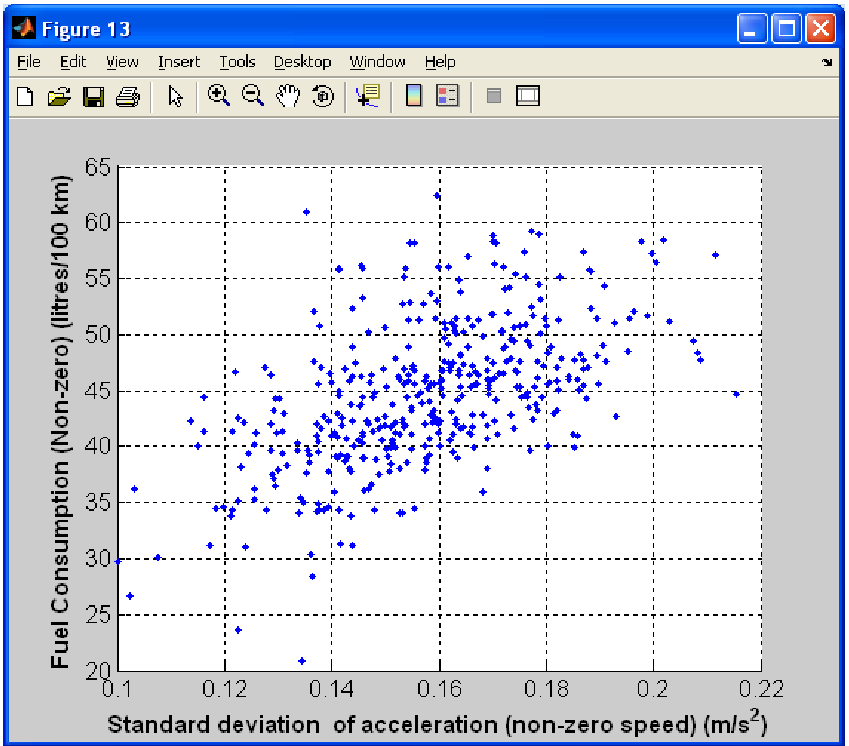


Figure 13
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (Non-zero) (litres/100 km)
65
60
55
50
45
40
35
30
25
20
0.1
0.12
0.14
0.16
0.18
0.2
0.22
Standard deviation of acceleration (non-zero speed) (m/s2)

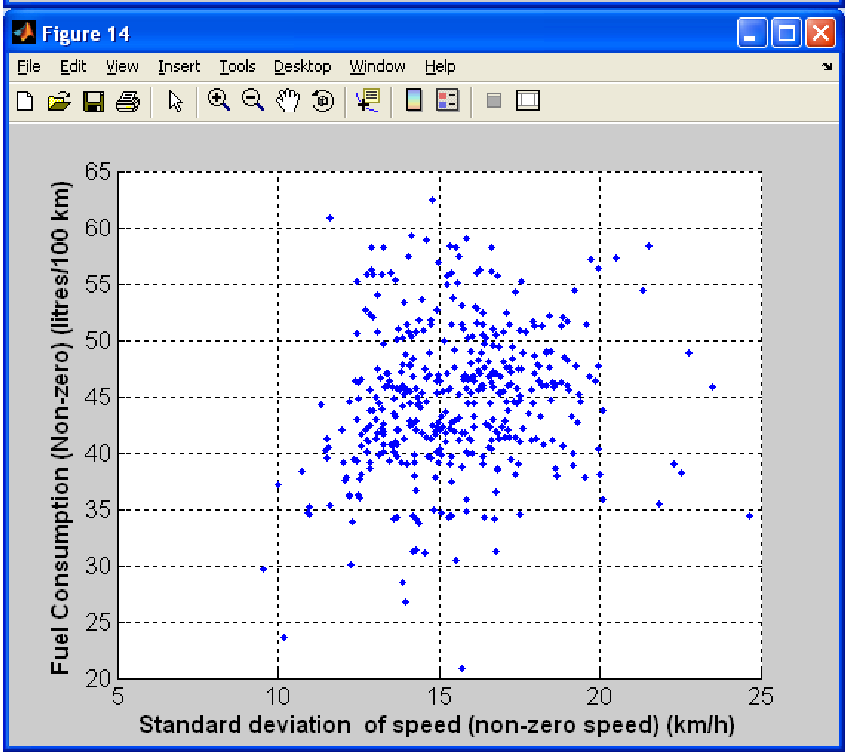


Figure 14
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (Non-zero) (litres/100 km)
65
60
55
50
45
40
35
30
25
20
5
10
15
20
25
Standard deviation of speed (non-zero speed) (km/h)

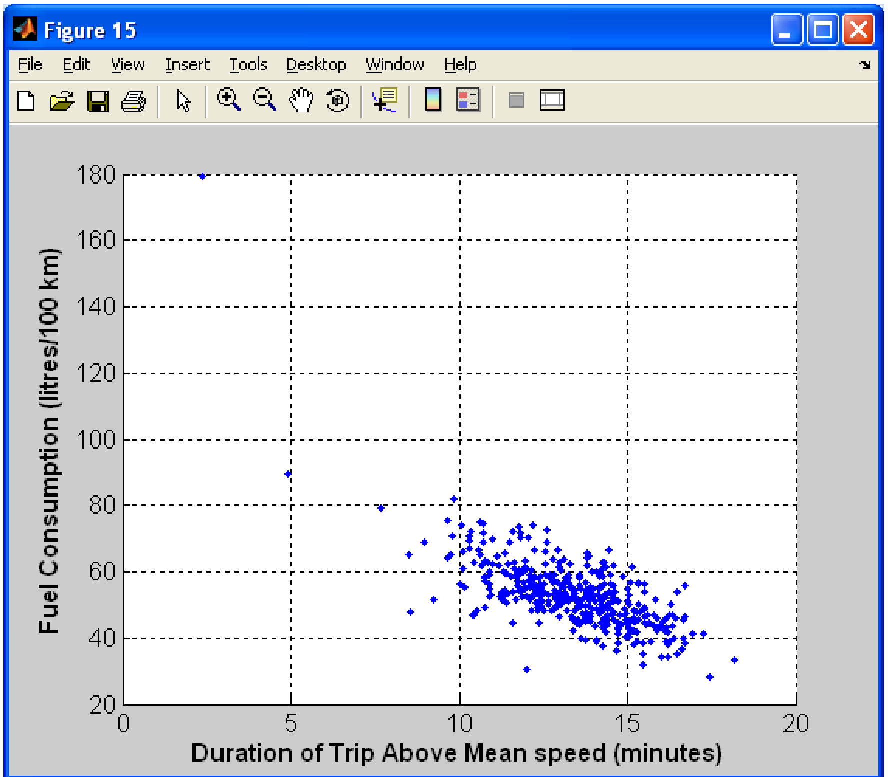


Figure 15
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (litres/100 km)
180
160
140
120
100
80
60
40
20
0
5
10
15
20
Duration of Trip Above Mean speed (minutes)

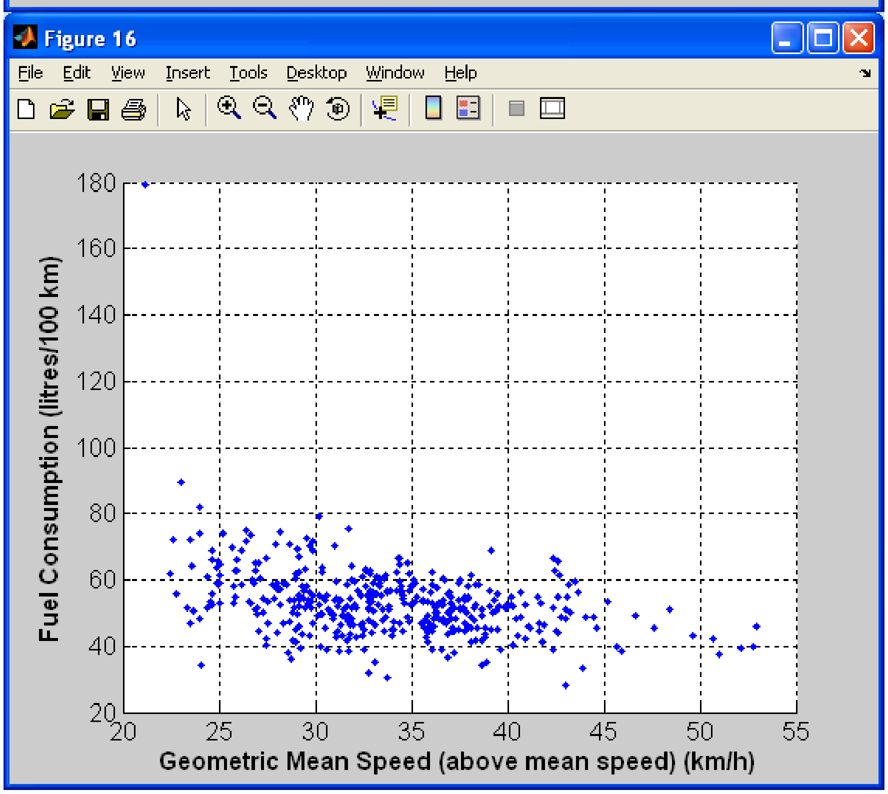


Figure 16
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (litres/100 km)
180
160
140
120
100
80
60
40
20
25
30
35
40
45
50
55
Geometric Mean Speed (above mean speed) (km/h)

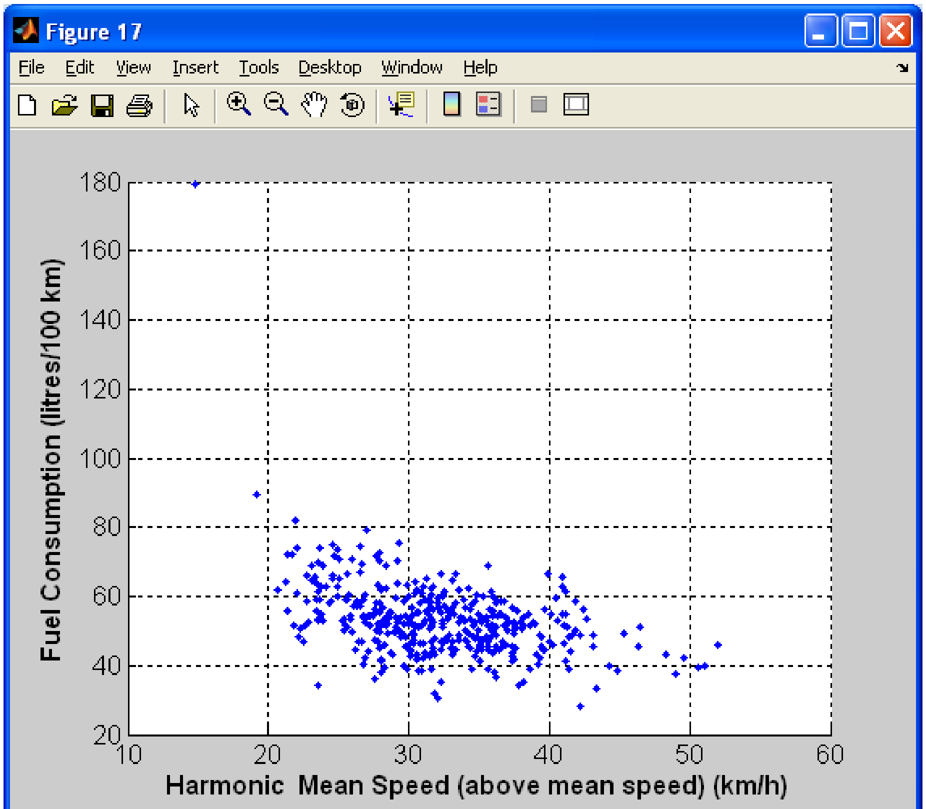


Figure 17
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (litres/100 km)
180
160
140
120
100
80
60
40
20
10
20
30
40
50
60
Harmonic Mean Speed (above mean speed) (km/h)

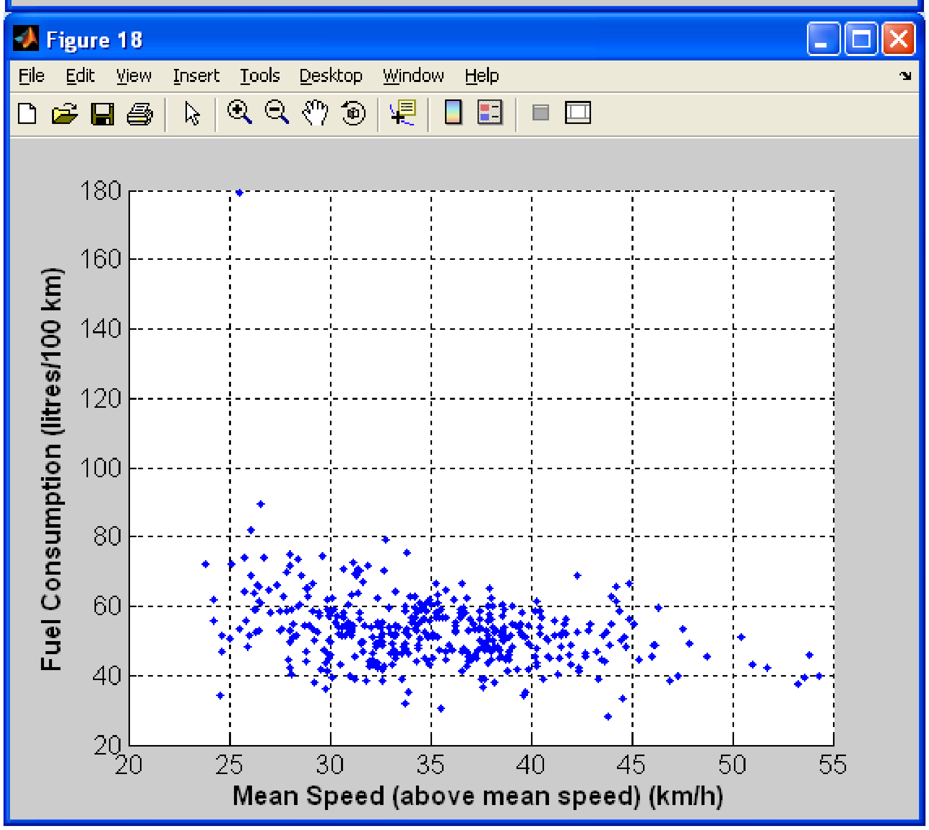


Figure 18
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (litres/100 km)
180
160
140
120
100
80
60
40
20
20
25
30
35
40
45
50
55
Mean Speed (above mean speed) (km/h)

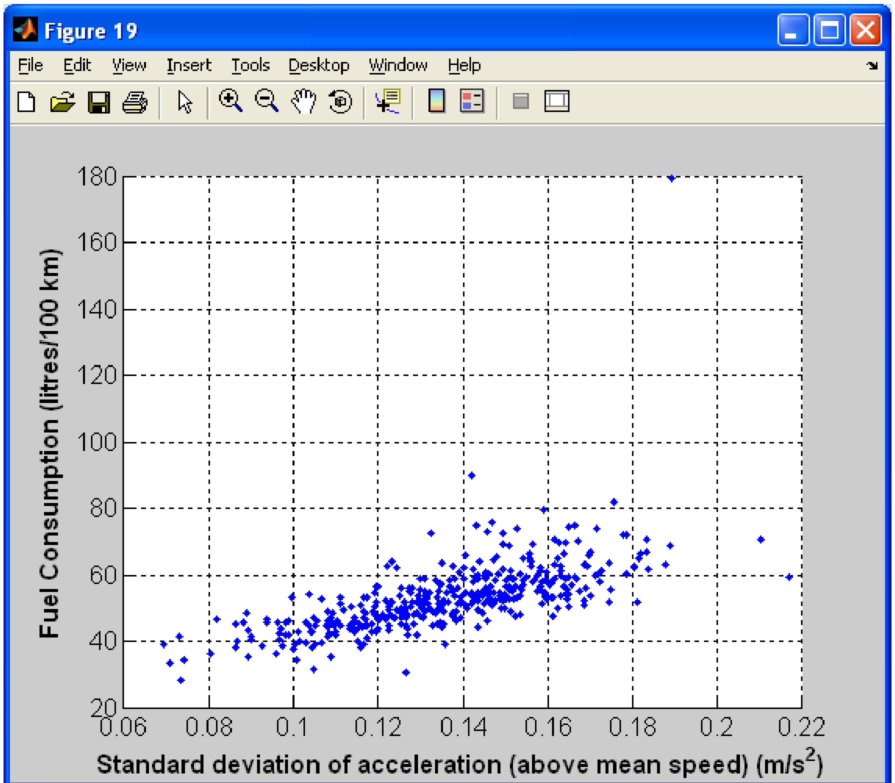


Figure 19
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (litres/100 km)
180
160
140
120
100
80
60
40
20
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
Standard deviation of acceleration (above mean speed) (m/s2)

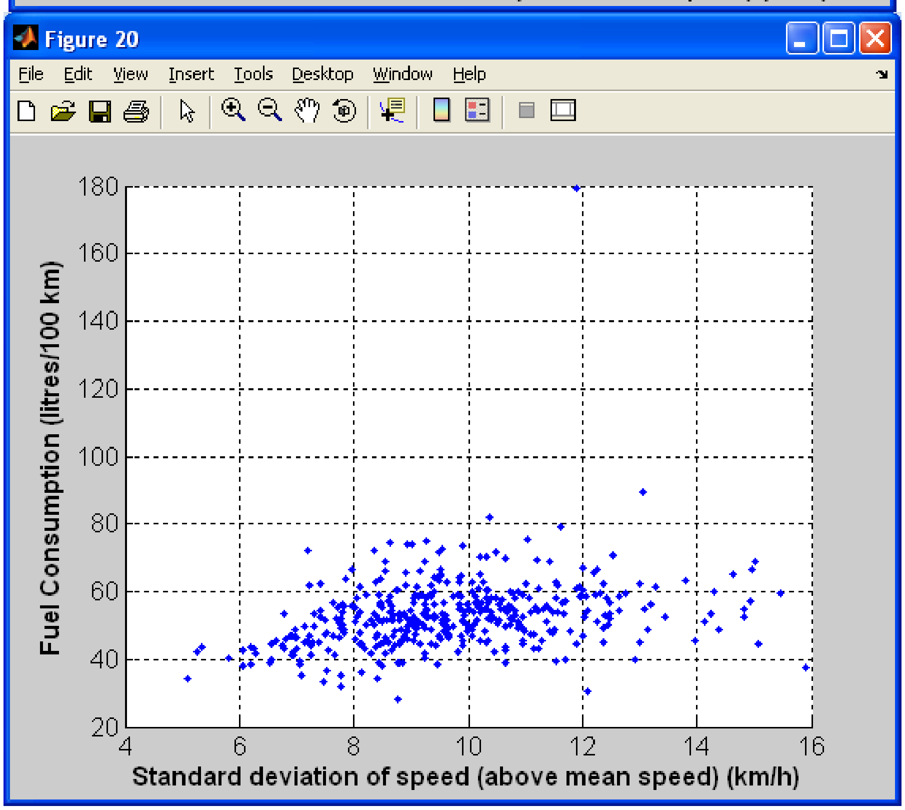


Figure 20
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (litres/100 km)
180
160
140
120
100
80
60
40
20
4
6
8
10
12
14
16
Standard deviation of speed (above mean speed) (km/h)

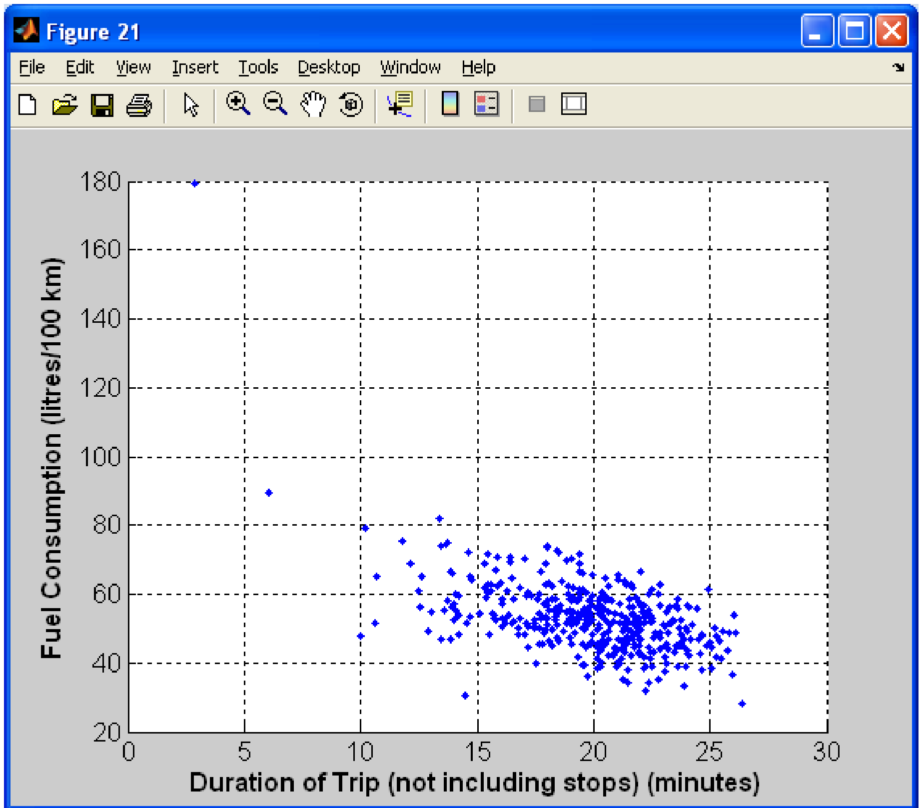


Figure 21
File Edit View Insert Tools Desktop Window Help
180
160
140
120
100
80
60
40
20
0
5
10
15
20
25
30
Fuel Consumption (litres/100 km)
Duration of Trip (not including stops) (minutes)

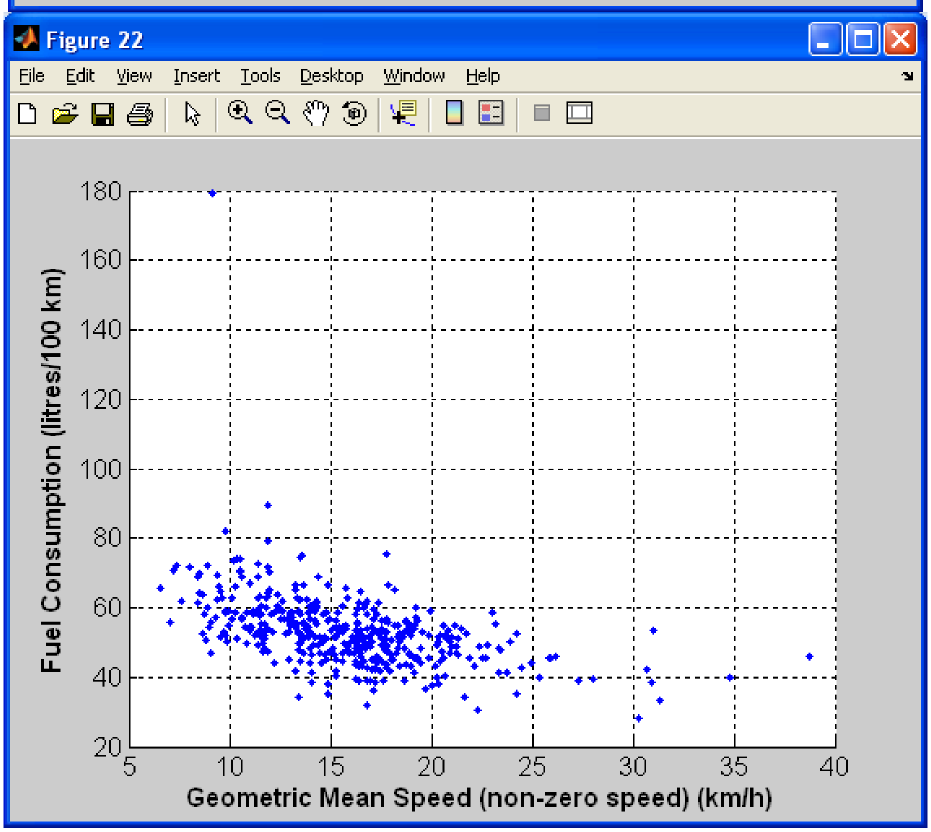


Figure 22
File Edit View Insert Tools Desktop Window Help
180
160
140
120
100
80
60
40
20
5
10
15
20
25
30
35
40
Fuel Consumption (litres/100 km)
Geometric Mean Speed (non-zero speed) (km/h)

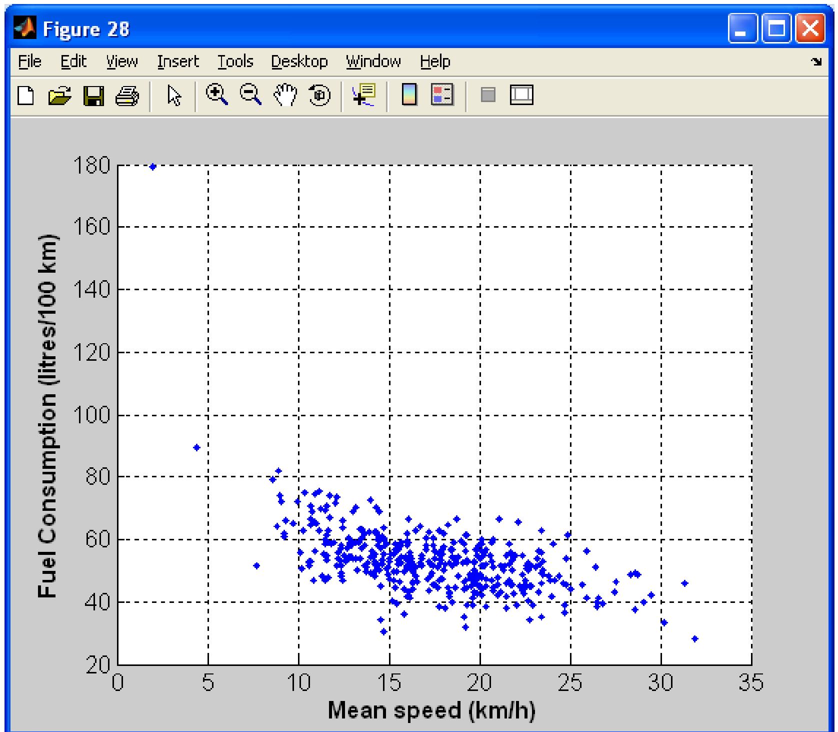


Figure 28
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (litres/100 km)
180
160
140
120
100
80
60
40
20
0
5
10
15
20
25
30
35
Mean speed (km/h)

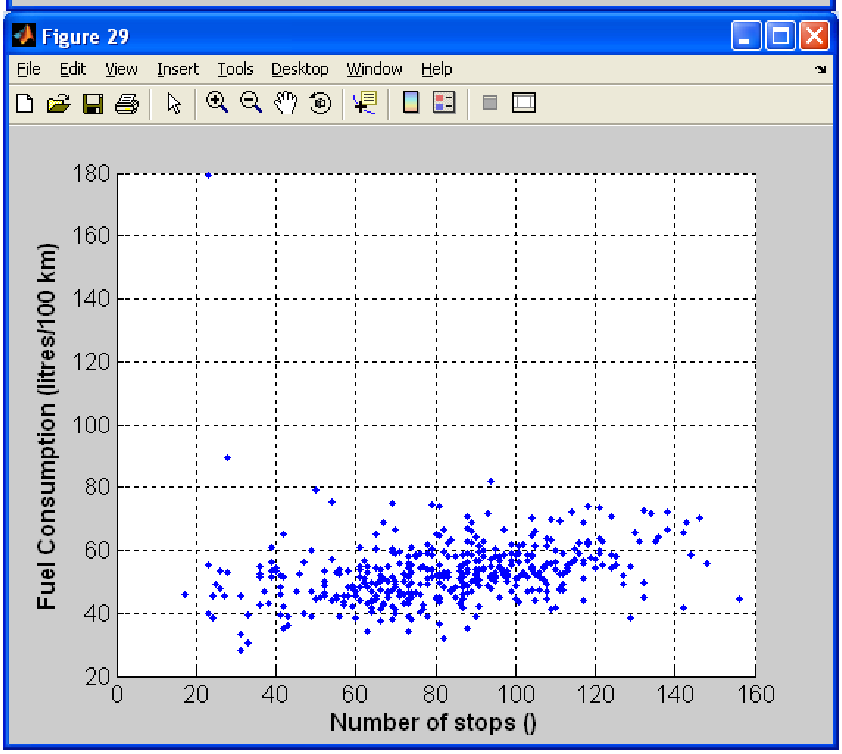


Figure 29
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (litres/100 km)
180
160
140
120
100
80
60
40
20
0
20
40
60
80
100
120
140
160
Number of stops ()

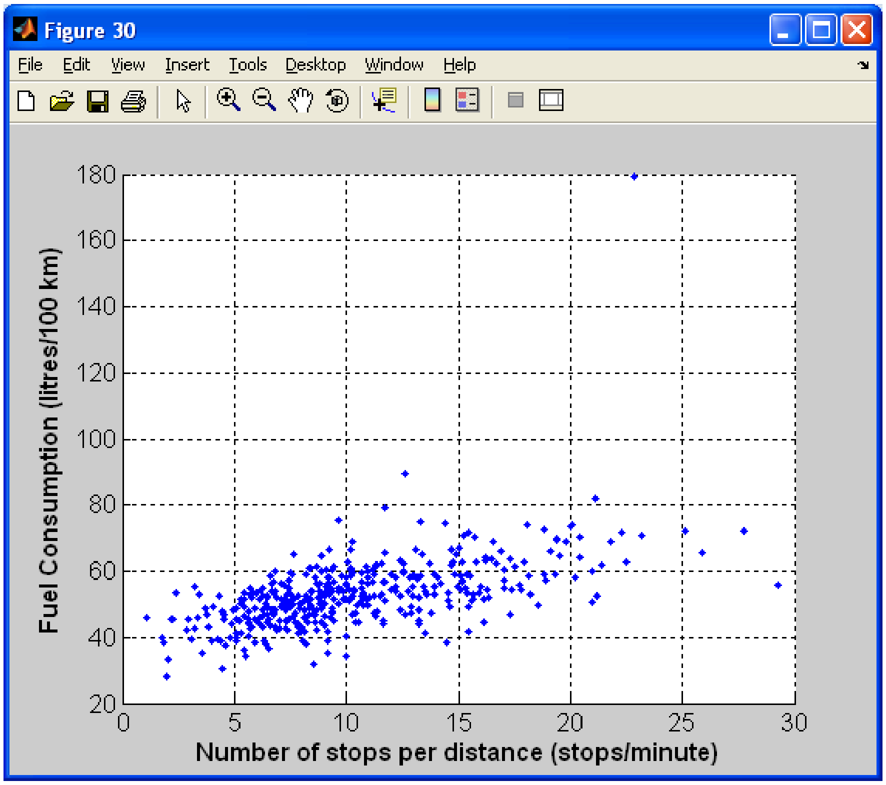


Figure 30
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (litres/100 km)
180
160
140
120
100
80
60
40
20
0
5
10
15
20
25
30
Number of stops per distance (stops/minute)

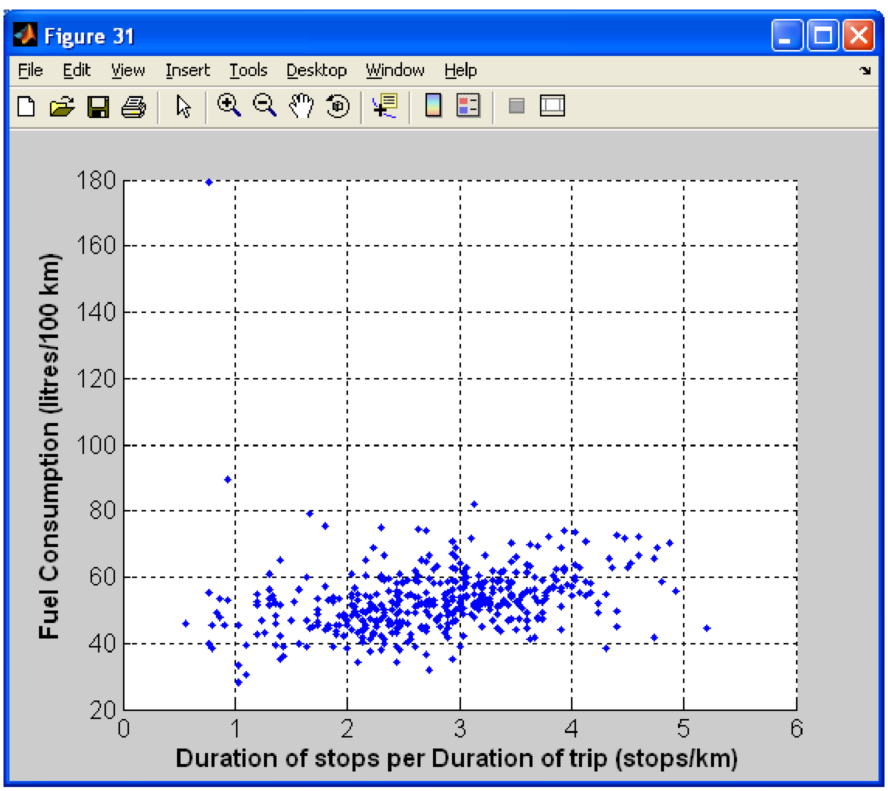


Figure 31
File Edit View Insert Tools Desktop Window Help
Fuel Consumption (litres/100 km)
180
160
140
120
100
80
60
40
20
0
1
2
3
4
5
6
Duration of stops per Duration of trip (stops/km)