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Coordinated Ramp Metering Control with Variable Speed Limits for Swiss Freeways

Gestion coordonnée des accès aux bretelles avec limitations de vitesse variables pour les autoroutes suisses

Koordinierte Zuflussregelung mit variierenden Geschwindigkeitsbegrenzungen für Schweizer Nationalstrassen

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Laboratory of Urban Transport Systems (LUTS)
Prof. Nikolas Geroliminis
Mohsen Ramezani
Mehmet Yildirimoglu
Paul Anderson

Projet de recherche VSS 2011/914 sur demande de l'association suisse des professionnels de la route et des transports (VSS)

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Impressum

Service de recherche et équipe de projet

Direction du projet
Prof. Nikolas Geroliminis

Membres
Paul Anderson
Mohsen Ramezani
Mehmet Yildirimoglu

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Auteur de la demande

Association suisse des professionnels de la route et des transports (VSS)

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Table of Content

Résumé

Ce projet est la suite naturelle d'une série de projets déjà réalisés et visant à développer des politiques de gestion du trafic efficaces sur les autoroutes suisses. À partir des recommandations de l'OFROU, nous explorons plusieurs alternatives pour développer les futures stratégies de régulation des accès à l'autoroute (ramp metering) afin de dépasser les limitations de ce qui est actuellement en place et améliorer les performances du système autoroutier. Par le biais d'une nouvelle approche, nous développons une stratégie de contrôle coordonné des débits d'accès aux bretelles avec limitations de vitesse variables en nous appuyant sur les données de densité et flux obtenus par des détecteurs de boucle.

Même si la régulation des accès est une solution connue pour diminuer la congestion, des inégalités peuvent apparaître dans le cas où la demande est forte : les usagers sur les bretelles subissent un retard bien plus important que ceux déjà sur l'autoroute. Par ailleurs, lorsque les bretelles sont petites, les queues créées par la stratégie de metering peuvent se propager dans le réseau secondaire et y engendrer des retards importants. On trouve en de nombreux endroits sur le réseau autoroutier suisse ces deux problèmes, ce qui fait que l'implémentation de stratégies de metering localisées est peu efficace dans la plupart des cas. Étant donnés les standards suisses élevés pour le temps de trajet et l'efficacité du réseau, il est nécessaire de développer de nouvelles stratégies de gestion du trafic qui permettront d'assurer des flux de déplacements élevés tout en conservant un faible risque d'engorgement. Ce projet de recherche vise à développer des stratégies de contrôle du trafic innovantes combinant le ramp metering coordonné et les limitations de vitesses variables.

Lors de la première phase du projet, l'autoroute A1 entre Lausanne et Genève a été choisie pour y réaliser la collecte de données. Comme la quantité de données issues des détecteurs de boucle était limitée, deux autres sources de données ont été utilisées : des comptages manuels sur les routes à proximité des bretelles de Nyon et Coppet ont été réalisés par 10 étudiants en Master à l'EPFL et des données ont été collectées par deux caméras haute résolution installées dans les zones des bretelles d'entrée de Coppet et Nyon. Les données disponibles sont donc issues de cinq sources différentes : détecteurs sur l'autoroute (un seul détecteur entre les deux sorties), comptages manuels aux sorties/entrées de Nyon et Coppet, détecteurs sur les rampes d'entrée et de sortie à Gland, Nyon et Coppet, détecteurs du système de limitations de vitesse variables, détecteurs sur les bretelles et les caméras situées à Coppet et Nyon couvrant la direction de Genève. Du fait de la variété des supports et des formats existants, les jeux de données ont d'abord été nettoyés, harmonisés et triés. Ils ont ensuite été combinés afin de sélectionner un jour représentatif de la situation de congestion et ainsi créer un profil de demande.

Dans la seconde partie du projet fut développé un algorithme de ramp metering coordonné s'appuyant sur un zonage dynamique et dans lequel sont considérées des limitations de vitesse variables afin de traiter de manière équitable les usagers présent sur l'autoroute, ceux qui désirent y entrer et ceux qui sont en dehors. Le système autoroutier est découpé en zones dont la longueur peut varier dynamiquement et ces longueurs sont estimées en temps réel. Dans chaque zone, les taux de metering sont choisis indépendamment des conditions dans les autres zones. L'objectif de l'algorithme est de conserver des niveaux de densité sur toutes les rampes en dessous des seuils de congestion et de ne pas autoriser l'apparition de basses vitesses sur l'autoroute en appliquant des contraintes temporelles sur les retards au niveau des rampes. Les taux de metering diminuent lorsque la densité sur l'autoroute approche du seuil de congestion et augmentent lorsque le temps d'attente sur les rampes approche du seuil maximal acceptable. Lorsqu'il n'est pas possible de conserver les rampes et l'autoroute sous le seuil de congestion et de retard du fait du niveau de demande, l'algorithme cherche à retarder autant que possible le dépassement de ces seuils en utilisant la capacité de stockage encore disponible sur les rampes d'accès à proximité du point d'engorgement.

L'efficacité des nouvelles stratégies de contrôle a été prouvée en comparant la situation

avec le cas où aucune stratégie de contrôle n'est appliquée et les cas où d'autres algorithmes répandus sont utilisés. Cette comparaison s'est faite en utilisant un modèle de microsimulation pour le site étudié de l'autoroute A1. Pour ce faire, on a utilisé le module AIMSUN API. Plusieurs indicateurs d'efficacité ont été estimés et analysés. L'algorithme proposé s'appuie sur la coordination des débits de contrôle et les limitations de vitesse variables. Il réussit à ralentir la survenue des engorgements, à accélérer le retour à la normale du système suite à des épisodes de congestion et à améliorer les performances globales sur l'autoroute et les rampes d'accès/sortie (grâce notamment à une augmentation des vitesses et des flux ainsi qu'une réduction des retards et des arrêts). Avec la nouvelle stratégie de contrôle, le retard total sur l'autoroute diminue d'environ 30% ; sur l'ensemble du système, les retards sont diminués de 12% environ. Les effets du ramp metering sur les usagers n'empruntant pas l'autoroute sont faibles. Cela suggère que cette nouvelle stratégie est très efficace dans la mesure où elle ne réduit pas seulement les retards sur les bretelles mais aussi sur l'ensemble du système sans pénaliser ceux qui n'utilisent pas l'autoroute. Les résultats indiquent aussi que cette stratégie est extrêmement efficace pour conserver une longueur de queue acceptable (i.e. sous le maximum autorisé) et réduire les retards sur les rampes d'accès et de sortie. Une autre observation intéressante que l'on peut faire en analysant les résultats de la simulation est que la nouvelle stratégie menée de manière globale et coordonnée réduit davantage les queues sur les rampes que des stratégies de ramp metering isolées et localisées

Zusammenfassung

Die Einfahrtsbewirtschaftung als Massnahme des Verkehrsmanagements stellt eine weit akzeptierte Strategie zur Verstetigung des Verkehrsflusses auf der Stammstrecke von Autobahnen im Bereich hochbelasteter Einfahrten dar. Die dabei eingesetzte Vereinzelung der Fahrzeuge zielt auf eine verträgliche Bewirtschaftung der Verkehrsströme ab. Im Rahmen des Einsatzes isolierter Einfahrtsbewirtschaftungen ergeben sich jedoch im netzweiten Kontext verschiedene Ungleichgewichte. Hochbelastete Einfahrten stellen oft verkehrliche Engstellen dar, bei denen es zu Störungen im Verkehrsablauf kommt. Die verschiedenen Verkehrsströme erfahren in diesem Zusammenhang unterschiedlich lange Reisezeiten.

Bei kurzen Einfahrtsrampen, die an Autobahnen in der Schweiz häufig anzutreffen sind, besteht zudem ein limitierter Stauraum. Ein Überstauen der Einfahrtsrampen ist dabei zu vermeiden und entsprechend sind Massnahmen bei der Steuerungsstrategie von Einfahrtsbewirtschaftungen vorzusehen.

Unter den zuvor beschriebenen Rahmenbedingungen können isolierte Einfahrtsbewirtschaftungen nicht die volle Effizienz erbringen. Das vorliegende Forschungsprojekt möchte durch innovative Kombination von einzelnen Verkehrsmanagementmassnahmen einen Zusammenbruch des Verkehrsflusses länger hinauszögern. Eine koordinierte Bewirtschaftung mehrerer Einfahrten sowie die Koppelung der Einfahrtsbewirtschaftungen mit den dynamischen Verkehrsleitsystemen auf der Autobahn soll das Risiko des Systemzusammenbruchs bei hohem Verkehrsfluss reduzieren und eine verlässliche Reisezeit ermöglichen. Die Koordination der einzelnen Massnahmen erfolgt dabei über einen Steuerungsalgorithmus.

Im ersten Teil des Projektes wurde eine Modellsituation erstellt. Das Teilstück der A1 von Lausanne bis Genf erwies sich als geeigneter Forschungsperimeter. Das zu betrachtende Strassennetz wurde für die Mikrosimulation modelliert. Damit genügend Daten für die Verkehrsmatrizen (Nachfrage) und zur Kalibrierung der Mikrosimulation zur Verfügung standen, wurden Daten aus verschiedenen Quellen herangezogen (Verkehrszählstellen Autobahn, Hauptstrassen, Rampen und Detektoren des bestehenden Verkehrsleitsystems) sowie manuelle Erfassungen (Knotenströme) durchgeführt. Die Daten der verschiedenen Quellen wurden homogenisiert und für eine weitere Verarbeitung aufbereitet.

Das Verhalten der Verkehrsteilnehmer beim Fahrstreifenwechsel vom Beschleunigungsstreifen auf den Normalstreifen stellt innerhalb dieser Forschung einen wichtigen Aspekt dar und wurde mittels Videoaufnahmen an den Anschlüssen Nyon und Coppet in Fahrtrichtung Genf analysiert. Die Parameter der Mikrosimulation wurden entsprechend gesetzt.

Im zweiten Teil wurde ein dynamischer, zonenbasierter Steuerungsalgorithmus für die koordinierte Bewirtschaftung der Einfahrtsrampen definiert, der die variable Geschwindigkeitsharmonisierung auf der Autobahn berücksichtigt. Der Streckenabschnitt der Autobahn wurde in Zonen aufgeteilt, wobei die Länge der einzelnen Zonen dynamisch ist und in Echtzeit geschätzt wird. Innerhalb von jeder Zone werden die Zuflussraten unabhängig von den Bedingungen in den anderen Zonen gewählt. Das Ziel des Algorithmus ist es, auf allen Einfahrtsrampen das Niveau der Verkehrsdichte unter einem spezifizierten Staulimit zu halten und eine Überstauung der Einfahrtsrampe zu verhindern. Der Zeitverlust auf den Einfahrtsrampen wird dabei beschränkt.

Die Zuflussraten werden reduziert, wenn die Verkehrsdichte auf der Autobahn steigt und sich einem Schwellwert für den Verkehrszustand „Stau“ nähert. Dem entgegen werden die Zuflussraten erhöht, wenn sich die Wartezeiten auf den Einfahrtsrampen dem Schwellwert für die akzeptierte Wartezeit nähert. Bei hohem Verkehrsfluss auf der Stammachse der Autobahn sowie den Einfahrtsrampen versucht der Algorithmus

möglichst lange ein Systemoptimum aufrecht zu erhalten und eine Überschreitung der Schwellwerte zu vermeiden. Dabei bezieht er auch den Stauraum an den Einfahrtsrampen stromaufwärts gelegener Anschlüsse mit ein. Abhängig von den vorliegenden Verkehrsbelastungen kann sich somit die Steuerungsstrategie über mehrere Anschlüsse erstrecken. Für die Mikrosimulation wurde die Steuerungsstrategie als Erweiterungsmodul per Anwendungsprogramm-Schnittstelle (API) eingebunden.

Auf Basis der mikroskopischen Simulationen wurde für den beschriebenen Forschungsperimeter die Effizienz der neuen Steuerungsstrategie ermittelt. Dabei wurden Vergleiche mit dem unkontrollierten Fall sowie mit Anwendungsszenarien unterschiedlicher Verkehrsmanagementmassnahmen sowie Algorithmen durchgeführt. Aufbauend auf verschiedenen Indikatoren wurden die Resultate der Szenarien miteinander verglichen.

Der dynamische, zonenbasierte Steuerungsalgorithmus für die koordinierte Bewirtschaftung der Einfahrtsrampen mit einhergehender dynamischer Geschwindigkeitsbegrenzung auf der Autobahn ergab in der Simulation die besten Resultate. Der Beginn des Verkehrszusammenbruch konnte verzögert und die Erholung nach dem Verkehrszusammenbruch beschleunigt werden. Zudem konnte der Verkehrsfluss stabilisiert, der Durchfluss erhöht und der Anteil der Halte reduziert werden. Die totale Verlustzeit im Modell konnte auf der Autobahn um 30% und im Gesamtsystem (inkl. Einfahrtsrampen) um 12% reduziert werden. Die Auswirkungen der Verkehrsmanagementmassnahmen auf den Verkehr auf dem Hauptstrassennetz ist nur gering. Die beschriebene Steuerungsstrategie stellt unter den zu Anfang beschriebenen Rahmenbedingungen eine effiziente Variante dar.

Summary

This project is a natural next stage of earlier successfully completed projects for efficient traffic management schemes for Swiss freeways. Based on OFROU recommendations, we explore alternatives for developing the next generation of ramp metering strategy to address limitations of widely applied existing strategies, and substantially enhance the performance of the current traffic situation in the freeway system. Following a different approach, we develop a new coordinated ramp strategy with variable speed limits by focusing on densities and flows obtained by loop detector measurements.

While ramp metering is a widely-accepted strategy for congestion alleviation, in case of high demand inequity issues arise, as travelers at the on-ramps experience significantly higher delays than those in the mainline. Also, in case of short length on-ramps, long queues can spillback in the arterial network and create significant delays in urban streets. Both characteristics are highly present in Swiss freeway roads, which make the implementation of isolated metering not a very efficient solution in many cases. Given the Swiss high standards for travel time reliability and efficiency, there is a need for new traffic management strategies, which will allow freeways to move Swiss people at high flows and with small probability of breakdown. This research project seeks innovative and practical traffic control strategies integrating coordinated ramp metering and variable speed limit (VSL).

During the first part of the project, A1 freeway from Lausanne to Geneva was selected for the data collection. Given the limited data available from the loop detectors, two additional sources were utilized: data of manual counts at the arterials next to the on-ramps of Nyon and Coppet were collected by 10 EPFL MSc students and data from two high resolution cameras installed at the merge location of Coppet and Nyon ramps. The available dataset consists of five different types of source; mainline detectors (a single detector between two successive interchanges), manual counts at the interchanges (Nyon and Coppet), ramp detectors at three interchanges (Coppet, Nyon, and Gland), detectors from variable speed limit (VSL) system, ramp detectors, and the video camera located at Nyon and Coppet sites, covering the Geneva direction. Given that data from each source has different characteristics and different formats, a cleaning and mining process was initially developed. The results from different sources have been put together to select a representative congested day and to create the demand profile.

The second part of the project developed a dynamic zone-based coordinated ramp metering algorithm with variable speed limits considerations to treat all freeway and urban users in an equitable way. The whole freeway system is divided into zones, where the length of each zone is dynamic and is estimated in real-time. Within each zone the metering rates are chosen independently of conditions in other zones. The algorithm's goal is to keep the car density levels at all ramps below the congestion thresholds and not to allow low speeds to occur in the mainline, by constraining the ramp delays. The ramp rates become stricter when mainline density is close to the congestion threshold and the ramp rates increase when ramp waiting times are close to the ramp delay threshold. When it is not possible to keep both uncongested because of high on-ramp and mainline demands, the algorithm seeks to delay as further as possible the violation of both thresholds by utilizing the spare storage capacity of on-ramps in the proximity of the active bottleneck merge location.

The effectiveness of the new control strategies has been assessed by comparison with the no control case and other existing widely deployed algorithms through microscopic simulation for the A1 freeway site. The new metering strategies is deployed on a simulated network and implemented using the AIMSUN API module. Various measures of effectiveness were analyzed. The proposed coordinated algorithm with variable speed limits succeeds in delaying the onset of breakdown, accelerating system recovery after breakdown, and improving the overall freeway and ramp performances (through improved speeds and throughputs and reduced delays and stops). Under the new control strategy the total delays on the mainline decreased by about 30%, while the total system (freeway

and ramp) total delays decreased by about 12%. The effect of ramp metering in non-freeway drivers is small. This finding suggests that in this case the new strategy is very effective since it reduces not only ramp delay, but also total system delay without penalizing non-freeway users. The results clearly indicate that the new control strategy is very effective in keeping ramp queues below the maximum allowed and in reducing ramp delay time. Another interesting observation made by analyzing the simulation results is that the new strategy substantially reduces ramp queues compared with local ramp metering strategies.

1 Introduction

Metropolitan transportation networks have a hierarchical structure, which essentially consists of freeways and urban roads providing the interrelated infrastructure for mobility and accessibility. The freeway and the urban network are inherently coupled, but they have dissimilar traffic flow dynamics, which challenge the traffic control of mixed networks of two interconnected (urban and freeway) traffic control entities. Although integrating the two entities through an effective mixed control policy could enhance the network performances during heavy congestion conditions, lack of coordination among the urban and freeway network jurisdictions and/or limited means of traffic monitoring and data communication might impede such mixed traffic network ideal goal. To overcome such deficiency, cooperative decentralized or if possible centralized control schemes can be developed as potential solutions, which oblige us to inquire into the traffic dynamics and control of the freeway and urban network to model the mixed traffic network.

Freeways by design are expected to be free-flowing and provide a generally high level of service (LOS) to their users and to the communities which they serve. In recent years, however, it is common for freeway traffic to become highly congested, even to reach a stop-and-go state during peak periods. A study by OFROU (2010) showed that traffic in many Swiss freeways have increased more than 3 times in the last 30 years, e.g.in A1 freeway traffic increased from 20,000 to 90,000. It has been reported that ramp metering was able to reduce delay by 131 million person hours in 2002 worldwide. Of the various measures intended to alleviate freeway congestion, ramp control has been increasingly recognized as one of the most effective and viable strategies since its first deployment in the 1960s. In effect, the fundamental philosophy of ramp metering is to limit the entering traffic from exceeding the operational freeway capacity and to provide more efficient and smoother merging at the freeway entrance by breaking up vehicle platoons. The benefits of ramp control reported in the literature include improved use of freeway capacity, increased throughput and freeway average speed, alleviated congestion, reduced system travel time as well as environmental benefits (Arnold, 1998; Cambridge Systematics, 2001; Elefteriadou, 1997; Papageorgiou et al., 1997; Taylor et al., 1996, Geroliminis et al, 2011a).

Recently, a large effort for the development of Integrated Corridor Management (ICM) has been promoted by Highway Administration institutes, with many case studies around metropolitan areas worldwide (see for examples US, Netherlands, Australia and elsewhere). Most of these implementations and case studies perform scenario analysis and consider alternative routes under extreme events, e.g. accidents, while it is expected that a more formal optimization approach could lead to a better system performance. ICM framework consists of coordinated management of the freeway system along with the adjacent and connected local parts of the urban network. In freeways, ramp metering is the most commonly used controller to manipulate the flow entering the freeway from its urban surrounding roads. Local and coordinated control strategies were proposed and implemented for ramp metering. In local control strategies, the control law for an on-ramp is determined according to the traffic conditions downstream and upstream of the on-ramp. In coordinated strategies, the control law for multiple on-ramps is determined based on the traffic conditions in multiple areas including several on-ramps and sections in the freeway and the interactions among them. The coordinated ramp metering is in fact a multi-regulator controller as all ramp meters attempt to regulate the freeway traffic conditions near the desired densities. The ramp metering approach (even in the coordinated case) might not efficiently operate in case of downstream bottleneck restrictions, e.g. a high demand off-ramp queue spills back in the freeway which blocks mainline lanes. Also, in case a freeway ends inside a congested city center, ramp metering might not be able to increase the outflow. In these cases, the freeway and urban network should be controlled in an integrated manner.

Ramp metering has seen wide applicability as a tool to improve the operation of freeways. By breaking up platoons of vehicles and limiting the flow of vehicles entering the freeway, metering keeps the mainline flow in a more stable part of the flow-density fundamental diagram. This avoids the capacity drop and instability associated with higher vehicle densities and produces a system optimal solution. Fixed metering schemes are similar to fixed traffic signals, applying a control based on historical data with no adaptation for real-time conditions and have been proved inefficient for dynamic features of congestion. Local strategies set a metering rate based on current conditions on the freeway at the local position of merging area. These strategies are generally effective, but pose some equity problems as ramps close to a bottleneck will have strict metering, while those further away (which may have contributed more to the congestion) may not be metered at all. Coordinated strategies are often based on a local strategy, with the metering rate adjusted afterward to share queues between several ramps that feed into the same bottleneck. Local and coordinated strategies can also incorporate a queue limit to avoid queues spilling back from ramps onto arterial streets.

With the norm SN 640 807 “Rampenbewirtschaftung, Grundlagen”, the common guidelines and standards for the application and operation of ramp metering systems in Switzerland are defined and presented (2005). Additional extensions are provided to these guidelines with a recent project from ETH Zurich (VSS 2007/302). Also, project VSS 2003/302 studied qualitatively with engineering principles the effect of ramp metering in demand shift to secondary roads (Project Report 1223, 2008). In almost all cases isolated metering is applied in Switzerland. While isolated ramp metering has been proved beneficial in Switzerland for the few cases it has been implemented, it cannot cope with the increasing level of congestion and demand in Swiss freeways.

Isolated on-ramp metering has been proved to improve system efficiency and decrease overall vehicle hours travelled in the peak hour. Its main disadvantages that can have direct implications for the Swiss drivers are: (i) in case of high demand inequity issues arise, as travelers at the on-ramps experience significantly higher delays than those in the mainline and (ii) in case of short length on-ramps, long queues can spillback in the arterial network and create significant delays in urban streets. Both of the above characteristics are highly present in Swiss freeway roads, which make the implementation of isolated metering not a very efficient solution in many cases. Given the Swiss high standards for travel time reliability and efficiency, there is a need for new traffic management strategies,which will allow freeways to move Swiss people at high flows and with small probability of breakdown, with a field implementation in many different locations.

This research project seeks innovative and practical traffic control strategies integrating coordinated ramp metering and variable speed limit (VSL). The selected case study for analysis is A1 freeway at *Canton de Vaud* specifically the direction from Lausanne toward Geneva including three ramps; Gland, Nyon, and Coppet. A comprehensive field study was done for data collection utilizing manual counts, video, loop detectors, and *OpenstreetMap* data. The *impact assessment* of the proposed strategies performed with advanced simulation techniques. This is a necessary step to guarantee efficient performance of the algorithms when applied in the real field and estimate the optimal values of the parameters to optimize road performance. A micro-simulation model in *Aimsun* (a commercial traffic simulator package) has been developed and calibrated to replicate the traffic condition similar to the field data. Finally, different control strategies, e.g. local ramp metering, coordinated ramp metering, and integration of coordinated ramp metering and VSL has been developed and tested on the micro-simulation model. A detailed investigation on characteristics and performance of the control strategies for different levels of demand is curried out is carried out.

It is expected (as shown by the detailed analysis of this project) that the outcomes of a coordinated ramp metering wide implementation with variable limits in the Swiss freeways will have significant benefits both for the users of the system, but also for ASTRA traffic management group. The new strategy overcomes traditional problems of existing strategies which cannot reliably estimate freeway storage capacity leading to mainline congestion and ignore delays for ramp users. This project develops an advanced state of the art active traffic management scheme, which can be directly applied in Swiss freeways, with high standards of efficiency and reliability. More specifically the expected benefits after this work highlight that ramp metering can be utilized:

- To reduce delays for all the users in the system by an overage 8-12% (considering also the drivers that have to wait at the ramps);
- To provide equitable treatment of all drivers in transportation networks.
- To retain high speed conditions to mainstream freeway to the maximum possible extend (postpone freeway breakdowns and accelerate recovery times), while treating well ramp users by avoiding long queues to spillback to the city networks.
- To identify data needs, amount of sensors and optimal locations in freeway and ramps to efficiently observe level of congestion and successfully apply an active traffic management scheme.
- To alleviate freeway congestion; to improve freeway flow, traffic safety and air quality by the regulation of input flow to a freeway;
- To regulate the input demand of the freeway system so that a truly operationally balanced corridor system is achieved.
- To provide all the necessary recommendations and requirements for a successful deployment.
- To address practical issues regarding users' acceptance, integration in the existing operating schemes etc.

While these results are promising, a successful implementation of real-time automatic and active traffic management schemes relies heavily in the wealth of available data and existing equipment (loop detectors, changeable message signs, cameras etc.).

2 Literature Review

2.1 Ramp Metering Algorithms

Ramp metering algorithms can be mainly divided into three categories; fixed-time strategies (local & system-wide), local traffic responsive strategies and system-wide traffic responsive strategies.

1. Fixed-time control: Fixed time control strategies are implemented based on historical demand for particular times of day. They do not consider real-time measurements, and they are not adaptive systems. The objective criterion in the fixed time control case is to maximize number of served vehicles or total traveled distance considering the capacity constraints on the freeway and on the ramp. Nevertheless, as the metering rates are based on historical data, these systems are not able to produce efficient strategies in case of varying demands due to special events or incidents, and they are not able to adapt to traffic conditions on the freeway. Note that fixed-time control can be applied in either local or system-wide level, although system-wide fixed-time control is very rarely used.

2. Local traffic responsive control: Local control strategies compute ramp metering rate based on traffic conditions at the adjacent freeway section only. In contrast to fixed time control strategy, reactive ramp metering considers real-time measurements and computes metering rate based on downstream capacity. The primary reactive ramp control is demand-capacity strategy, which is described as follows;

$$r(k) = \begin{cases} q_{cap} - q_{in}(k-1) & if\ o(k-1) \leq o_{cr} \\ r_{min} & otherwise \end{cases} \qquad (1)$$

where q_{cap} is freeway capacity at downstream of ramp, $q_{in}(k-1)$ is the flow measurement at the previous time interval, $o(k-1)$ is freeway occupancy measurement at downstream of the ramp, o_{cr} is the critical occupancy value where freeway flow at downstream of ramp reaches its maximum, and r_{min} is the minimum allowed ramp metering rate. Basically, this strategy computes as high metering rates as necessary to reach capacity flow at the freeway section downstream of ramp. However, if $o(k-1)$ exceeds o_{cr}, ramp metering rate is reduced to the minimum allowed level to dissipate the congestion. This open-loop strategy is converted to a closed-loop policy, known as ALINEA, by Papageorgiou et al. (1991). The new feedback control law reads as follows;

$$r(k) = r(k-1) + K\big(o_{cr} - o(k-1)\big) \qquad (2)$$

where K is a regulator parameter, and ALINEA's performance is not very sensitive to its choice. Other local ramp metering strategies are reviewed in Papageorgiou and Kotsialos (2002) and Papageorgiou and Papamichail (2007).

3. System-wide (area-wide) traffic responsive algorithm: This refers to the control of a series of ramps in conjunction considering the interdependency between them. The aim of area-wide ramp control is to optimize the traffic flow over a freeway stretch, rather than a specific location. They can be divided into three groups regarding the way they are implemented (Zhang *et al.*, 2001).

- Cooperative algorithms: The ramp metering rate computed by local strategies is further adjusted in this method to avoid congestion at the freeway stretch. The adjustment of metering rates is mainly done using heuristics in an ad hoc way. Examples of these algorithms are HELPER (Lipp et al., 1991), Linked-Ramp (Banks, 1993), and HERO (Papamichail and Papageorgiou, 2008).

- Competitive algorithms: In these algorithms, ramp metering rate is calculated using both local and area-wide strategies, and the most restrictive one is implemented. This rate can also be further adjusted using some heuristics. Examples of competitive algorithm are Zone (Stephanedes, 1994), Bottleneck (Jacobson et al., 1989) and SWARM (Paesani et al., 1997) algorithms.
- Integral algorithms: In these algorithms, metering rates at multiple ramp locations are computed to optimize the objective function (e.g. total travel time, throughput of the section) which represents the performance of the whole freeway stretch. They can also consider system constraints such as maximum allowable ramp queue, bottleneck capacity, etc. This group of algorithms is the most appealing regarding the problem design. However, they call for a sophisticated design procedure, which is more demanding in computation. These algorithms can be implemented in a reactive way, considering the measurements from the previous time interval, or in a proactive way, considering demand predictions. Examples of integral algorithms are METALINE (Papageorgiou et al., 1990), fuzzy logic (Meldrum and Taylor, 1995) and MILOS (Ciarallo and Mirchandani, 2002).

Zhang *et al.* (2001) developed a ramp metering evaluation framework using microscopic simulation environment and compared the performances of 4 important ramp metering algorithms; ALINEA, Bottleneck, SWARM and Zone algorithms. Following findings are reported as the result of the analysis.

- *“Ramp metering reduces the total vehicle travel time up to 7% compared with no metering. The effectiveness of a ramp control algorithm depends on the level of traffic demand. As traffic demand increases, ramp metering tends to be more effective in reducing system travel time.*
- *No significant performance differences exist among ALINEA, modified Bottleneck, modified SWARM with 1 time-step-ahead prediction, and Zone algorithms under the tested scenarios.*
- *Modified SWARM with five-step-ahead prediction has the poorest performance among all tested algorithms due to the inaccuracy of the five-step-ahead prediction model. This indicates a good traffic prediction is the key to SWARM's performance.*
- *Coordinated ramp metering algorithms do not necessarily perform better than local control algorithms if some of their key parameters are not well calibrated. Well-tuned parameters are critical for the good ramp metering performance.*
- *Ramp metering performance and parameter values are non-linearly related. There is a broad range of parameter values over which ramp metering performance does not change significantly. Outside of this range, however, ramp metering performance deteriorates quickly.*
- *Ramp metering seems to be more effective under certain demand patterns than others.”*

Zhang *et al.* (2001) provides a classification tree for algorithms, displayed in Fig. 1. Note that although zone algorithm is classified as an isolated control method in Fig. 1, it is considered as a coordinated strategy in this study, as it considers traffic conditions in a freeway stretch rather than a specific location. The algorithms presented in Fig. 1 are reviewed in Zhang *et al.* (2001).

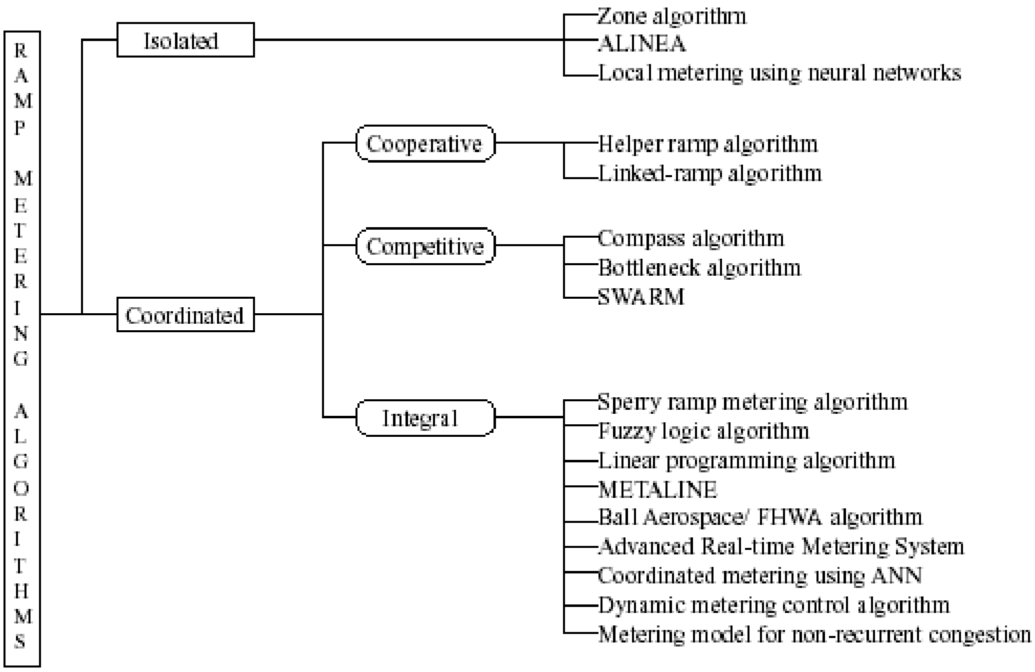


Figure 1 Ramp Metering Algorithms [Zhang *et al.*, 2001]

An extension to the above proposed control methods is the incorporation of breakdown probability models into the ramp metering strategy proposed by Elefteriadou *et al.* (2011). They develop a breakdown probability model for the merge areas as a function of freeway flow and ramp flow. This model is, then, incorporated in an existing ramp metering algorithm (e.g. COMPASS, stratified zone algorithm). Breakdown probability models can be used with current or predicted traffic volumes, depending on the type of the algorithm used. Elefteriadou *et al.* (2011) tested this approach in a microscopic simulation environment and concluded that the new approach has the potential to improve the performance of existing ramp metering algorithms by delaying or preventing flow breakdown and by increasing freeway throughput.

Although ramp metering algorithms have, in general, compact structures, a real-world ramp metering system consists of a combination of algorithms designed to handle various conditions. For instance, Highways Agency (2007) lists seven algorithms needed for their ramp metering operation system.

- *Ramp metering algorithm:* The core algorithm that produces ramp metering rates based on local or area-wide traffic conditions on the freeway.
- *Data filtering algorithm:* Filtering algorithm detects and removes outlier flow, speed and occupancy observations from raw data collected by detectors. The success of filtering algorithm is critical to the performance of ramp metering system.
- *Switch on-off algorithm:* This algorithm basically switches the ramp metering system on or off based on traffic conditions on the freeway and a pre-defined flow, occupancy or speed threshold.
- *Queue override algorithm:* It monitors the queue size on the ramp and releases the vehicles from the ramp to clear the queue that may spillback to the arterials.
- *Queue management algorithm:* This algorithm attempts to keep queue length on the ramp at a pre-defined desired level by monitoring proportional occupancy measurements. This algorithm is implemented to minimize the action of queue override function.

- *Arbitration algorithm:* This algorithm collects the output from ramp metering, queue management, queue override and switch on-off modules, and determines the final allowed inflow rate from the on-ramp to the freeway. Arbitration algorithm always selects the highest allowed inflow rate and passes it to the release algorithm.
- *Release algorithm:* This algorithm sets traffic signal durations based on the allowed flow rate computed by the controller. There are various signal policies that can be implemented in this step: one-car per green, two-cars per green or traffic-cycle realizations.

2.2 Ramp Metering Status in the US

Benefits of ramp metering reported in literature include system-wide travel time savings, improved safety and reduction of fuel consumptions and vehicle emissions. However, there are no standard evaluation criteria to quantify these benefits. In addition, it is difficult to evaluate certain disbenefits in particular (e.g. diversion of travelers to the arterials). Early ramp metering applications in Chicago, Detroit, Los Angeles, Minnesota and Seattle areas have been very successful and have led to the extension of ramp metering systems to other metropolitan areas in US. Table 1 contains a list adapted from ITSA (1995) and Gan *et al.* (2011) with some updates to reflect more recent implementations.

Table 1 Ramp Metering Systems in US
[ITSA, 1995; Bogenberger *et al.,* 1999; Gan *et al.* 2011, Houston TranStar 2012]

State	Area	Number of Meters
Arizona	Phoenix	132
California	Fresno	47
	Los Angeles	808
	Orange County	278
	Sacramento	19
	San Bernardino	51
	San Diego	134
	San Francisco	96
Colorado	Denver	54
Florida	Miami	22
Georgia	Atlanta	8
Illinois	Chicago	113
Michigan	Detroit	50
Minnesota	Minneapolis	416
Nevada	Las Vegas	70
New Mexico	Albuquerque	2
New York	New York	86
Ohio	Cincinnati	4
	Columbus	17
Oregon	Portland	135
Pennsylvania	Allentown	14
	Philadelphia	16
Texas	Houston	89
Utah	Salt Lake City	32
Virginia	Arlington	26

Washington	Seattle	148
Wisconsin	Milwaukee	126

Ramp Metering Development plan (RMDP) 2011 prepared by California Department of Transportation reports that there are 2460 existing ramp meters throughout the state, which accounts for 60% of all existing ramp meters in the US. RMDP 2011 indicates that state of California plans to implement 1715 new ramp meters within the next 10 years.
The ramp metering system in Minneapolis / St. Paul area was first implemented in the 1970s as a fixed-time control strategy by Minnesota Department of Transportation (MnDOT). This system was converted to a local traffic responsive system and, later, to an area-wide traffic responsive control system using Zone algorithm. In 2000, an empirical experiment on ramp metering was conducted in Minneapolis-St. Paul area (Cambridge Systematics, 2001). Traffic flow and safety impacts were investigated by disabling 430 ramp meters for six weeks. The results indicated 9% reduction in freeway throughput, 22% increase in travel time, 7% decrease in freeway speed and 26% increase in the number of crashes. MnDOT implemented stratified zone metering strategy (Xin *et al.*, 2004) in 2002 to dissolve the congestion on the freeway but also to minimize the waiting times on the ramps. Michalopoulos *et al.* (2005) evaluated the stratified zone algorithm in a microscopic simulation environment, and concluded that the algorithm produced less on-ramp delays compared to the previous zone metering algorithm, while the freeway delays increased with the implementation of the new algorithm. However, the algorithm presented clear improvements over the no-control case regarding freeway delay, freeway speed and number of stops.

Washington State Department of Transportation (WsDOT) developed Bottleneck algorithm (Jacobsen *et al.*, 1989), a competitive area-wide ramp control strategy, and implemented it in Seattle central business district starting from 1981. WsDOT conducted a six-year evaluation study, which indicates that travel time decreased by 48%, mainline flow increased by 62-86%, and crash rate decreased by 39%. WsDOT implemented fuzzy logic control (Meldrum and Taylor, 1995) later in 1999, considering the improvements over the existing Bottleneck algorithm. Taylor and Meldrum (2000), a study evaluating the fuzzy logic algorithm, reported an 8.2% decrease in occupancy and 4.9% increase in flow compared to local ramp metering and similar mainline performance with less queue delay on ramps compared to the Bottleneck algorithm.

SWARM (Paesani *et al.*, 1997) was first developed by the National Engineering Technology Corporation, under a contract with the California Department of Transportation (Caltrans). The first field implementation of the algorithm was in Orange County for 6 weeks with no quantitative evaluation. Moreover, the system did not appear to operate properly. Later the implementation and evaluation of SWARM was more successful in Los Angeles and Ventura Counties, California, in the late 1990s. The benefits of the new SWARM algorithm compared with the previous ramp-metering operations were evaluated during the morning peak periods on a freeway corridor that contains 20 controlled on-ramps. The evaluation revealed an 11% increase of the main-line speed, a 14% decrease of the travel time, and a 17% decrease of the freeway delay. Moreover, the queue lengths at the nine busiest on-ramps increased by more than 40%.

The global mode of SWARM operates on an entire freeway stretch based on forecast densities at the bottleneck location. The density prediction is done by performing a linear regression on a set of short term historical data and applying a Kalman filtering process. A parameter, T_{crit}, denotes the forecasting time span, which is usually several minutes. The excess density is then the difference between the predicted density at T_{crit} and a pre-determined threshold density representing the saturation level at the bottleneck. This excess density is converted to the (current) required density to avoid congestion at T_{crit} by reduction in volume at each detector station:

required density = current density – (excess density/T_{crit})
volume reduction = (local density − required density) * (no. of lanes) * (distance to next station).

SWARM algorithm has also been tested in Portland metropolitan area by Oregon Department of Transportation (ODOT). Ahn et al. (2007) study the implementation during a 2-week pilot study on a 7 mile long freeway corridor and report the benefit of the new SWARM system as compared with the fixed-time algorithm regarding the savings in delay, emissions and fuel consumption, and safety improvements on and off the freeway. The analysis shows that the percentage of communication failures was below 2% at most locations with the fixed-time strategy, whereas the failure percentages with SWARM were much larger, such as exceeded 10%. In addition, the VMT increased marginally (0.8%) with the SWARM operation, which indicates that the demand remained nearly independent of the ramp metering control deployed in the field (at least for the short term). However, surprisingly, SWARM increased the VHT and the average travel time by 6.0% and 5.1%, respectively, corresponding to a significant increase of 34.7% in total freeway delay. Empirical evidence suggests that this deterioration resulted from high metering rates at most of the on-ramps, resulting in lower travel times on on-ramps and increase in freeway delays. Currently, SWARM is under development and refinement by Delcan, the company which first developed the algorithm (Chu *et al.*, 2009). While promising in principle, SWARM algorithm have not been significantly better than local strategies due to the difficulty in accurately predicting future conditions in the freeway and the ramps.

Chu *et al.* (2009) reports that there are three major real-world ramp control systems deployed in California.

- San Diego Ramp Metering System (SDRMS), deployed in Sacramento, Fresno, San Bernardino and Riverside, and san Diego areas
- Semi-Actuated Traffic Management System (SATMS), deployed in Los Angeles and Orange County
- Traffic Operations System (TOS), deployed in the Bay Area

These systems can be operated under traffic responsive metering control or pre-timed metering control. SATMS is based on demand capacity control, while SDRMS and TOS are based on occupancy control. Even though ramp metering algorithms have simple structures, these real-world ramp metering systems are complicated because of the necessity to handle various conditions.

There are various studies that evaluate ramp metering implementations in the state of California. The evaluation study on I-580 indicates that installation of ramp meters over an 18 mile long section of freeway led to 30% reduction in travel time (Kimley-Horn and Associates, 2008). Metropolitan Transportation Commission published the fact sheet that presents the benefits of ramp metering implementations; 80% of evaluated freeway segments exhibit 30% or greater delay reduction (MTC, 2011).

Ramp metering system, along with an isolated control strategy, has been installed in Denver (Colorado) on I-25 freeway in 1981. HELPER (Lipp *et al.*, 1991) algorithm was first introduced in 1984 in the same area. Evaluation results indicated that if isolated ramp control is able prevent the breakdown, HELPER has little benefit. However, if not, cooperative control was found to be very effective in dissolving congestion.

METALINE (Papageorgiou *et al.*, 1990) was tested in Milwaukee (Wisconsin) area, in 1997. Although the field results indicated improvements over local ramp control strategies, its deployment has been stopped (Bogenberger and May, 1999).

COMPASS algorithm was first implemented on the Queen Elizabeth Way in Toronto, Canada, in 1975. Ramp metering system can be operated under automated competitive control strategy or can be manually regulated from traffic control center. Local metering rates are computed using an ad hoc look-up table with various levels for each ramp, while global rates are computed using off-line optimization procedure based on area-wide traffic conditions. No evaluation study, to the authors' knowledge, exists related to the implementation of COMPASS algorithm.

In overall, ramp metering reduces congestion, decreases travel time and increases freeway throughput by managing the ramp flow and improving the efficiency of the merging area. This results also in fewer accidents, which in turn may cause significant delays in the freeways. As there are no standard evaluation criteria to assess the benefits of ramp metering systems, it is extremely difficult to compare performance of various algorithms described above, unless one develops an evaluation platform using a simulation environment (Zhang *et al.*, 2001; Chu *et al.*, 2009). In addition, there are few studies in the literature that attempt to put evaluation results together for numerous field implementations. Table 2 summarizes such an evaluation study from six locations in the US (Piotrowicz and Robinson, 1995).

Table 2 Benefits of Ramp Meters [Piotrowicz and Robinson, 1995]

		Speed (mph)		**Changes in (%)**		
State	**Area**	**Before**	**After**	**Travel Time**	**Accidents**	**Flow**
Colorado	Denver	43	50	-37	-50	19
Michigan	Detroit	-	-	-	-50	14
New York	Long Island	29	35	-20	-	-
Minnesota	Minneapolis	34	46	-	-27	32
Oregon	Portland	16	41	-156	-43	-
Washington	Seattle	-	-	-91	-39	62

Kang and Gillen (1999) also reviewed numerous ramp metering implementations and summarized the impacts of ramp metering strategies on system performance. A part of this review is presented in Table 3.

Table 3 Evaluations of Ramp Metering Systems [Kang and Gillen, 1999]

Location and Agency	***Site Description***	***Results***
Austin, Texas Texas Department of Transportation	Three ramp meters installed in 1997 on I-35 northbound	- Throughput increased by 7.9% - Speeds increased by 60%
Houston, Texas Texas Department of Transportation	I-10 freeway in 1996	- Total daily estimated travel time savings of 2,875 veh.h
Denver, Colorado Colorado Department of Highways	5 ramp meters on I -25 Evaluated in 1981-1982 HELPER algorithm	- Speeds increased by 58%. - Emissions dropped by 24% - Accidents dropped by 5% - Flows on area arterials increased from 100vph to 400vph, no degradation on surface street conditions
Detroit, Michigan Michigan Department of Transportation	Six ramp meters installed in 1982 on I-94 eastbound	- Speeds increased by 8%. - Accident dropped by 50%
Long Island, New York New York Department of Transportation	Sixty ramp meters installed in eastbound Long Island Expressway Evaluated between 1987-1990	- Travel times dropped from 26 min to 22 min - A motorist using a metered ramp saved 13% in travel time. - No significant change in throughput

Portland, Oregon		
Oregon Department of Transportation	I-5 freeway in 1981 16 meters in fixed-time are evaluated	- Speeds increased from 16-40 mph to 41-43 mph - Fuel consumption reduced by 540 gallons/day - Accidents dropped by 43%

2.3 Ramp Metering Status in Europe

Despite the accelerated ramp metering deployment in Europe in the last decades, only few hundred of on-ramps in few European countries are equipped with ramp metering technology where all installations employ only local algorithms. Furthermore, there is no freeway in Europe with ramp metering installation in most of its on-ramps. In addition, motorway-to-motorway metering is non-existent in Europe. Thus, there is a huge potential for motorway traffic flow improvements, if available state-of-the-art ramp metering strategies would be applied in a coordinated way. (Nearctis deliverable report 8, 2010)

A European Union funded research project, European Ramp Metering Project (EURAMP) has been conducted and completed in 2007. The first step of the project is the design and simulation testing of various ramp metering algorithms. The second step is the field implementation of different ramp metering strategies. Demonstration sites are A6 motorway (Paris, France), A28 and A2 motorways (Utrecht, Netherlands), A94 motorway (Munich, Germany) and Ayalon Highway (Tel Aviv, Israel). Evaluation results indicate that all test sites, except Utrecht, indicate travel time benefits. In Utrecht, ramp delays are more significant than travel time improvements achieved on the mainline. Among several control strategies used, coordinated ramp metering provided the best results. On the other hand, 1-car per green or 2-car per green strategy is used in Utrecht, which may lead to significant ramp delays.

2.3.1 Ramp Metering Status in the UK

The first ramp metering system in England has been installed on M6 J10 roadway in 1986 (Highways Agency, 2007). The first widespread deployment of ramp metering on the highway network was started in 2005 with the aim to deploy 30 ramp metering systems by the end of 2007. These ramp metering systems are implemented on the M1, M5, M6, M42, M56, M60, and M62 motorways located in the West Midlands and the North of England.

The operational evaluation of ramp metering installation has indicated benefits to the travelling vehicles on the mainline of the motorway in terms of travel time savings, increased speeds, increased flow, and more stable traffic conditions. The overall increase in peak period mainline flow and speed after the implementation of ramp metering are reported as between 1% and 8% and between 3.5% and 35%, respectively. In many cases, ramp metering has delayed the onset of flow breakdown and/or recovered earlier from the flow breakdown. The mainline travel time savings during peak periods is reported up to 40%. With daily 13% average travel time saving across all sites, the economic assessment indicates that ramp metering installation results to First Year Rate of Return of 48%. It is worth to note that ramp metering has not been successful at all sites. For instance, mixed results were obtained from ramp metering on the M27 and M3 motorways in Southern England, which has been stopped there. As of 2011, there are 88 ramp metering sites on England’s motorway network. (Nearctis deliverable report 7, 2010)

2.3.2 Ramp Metering Status in France

METALINE (Papageorgiou *et al.*, 1990) and ALINEA (Papageorgiou *et al.*, 1991) were introduced in Paris, in 1990 and early 1991. Both control strategies were tested during the morning peak period for 10 days, which resulted in higher mainline speeds for both. In the framework of the PDU (Plan de Déplacement Urbain) program and according to the results obtained in the EURAMP project, the authorities decided the renewal of the existing ramp metering system to consider the possibility of real-time control of several candidate on-ramps (Nearctis deliverable report 7, 2010). A field evaluation is done on the generalized ramp metering strategy on the East part of Île-de-France motorway network using ALINEA strategy. The implementation started in February 2008 on 17 on-ramps with heavy peak period congestions. The obtained results indicated a positive impact of ALINEA on the traffic, which the total time spent (veh·h) on the mainstream plus the on-ramps and the total travel distance (veh·km) are between 3% to 15% and 1% to 8%, respectively. The overall collective benefit is evaluated to be equal to 13.5 M€/year for the 17 on-ramps field test.

Another field test was done to develop, test, and evaluate the traffic impact of four ramp metering strategies: No control, ALINEA, VC_ALINEA (Variable Cycle ALINEA), and Coordination (CORDIN). The field test site was located in the south of the Île de France motorway network, 20 km-length A6W, which includes 5 consecutive on-ramps fully equipped with loop detectors and traffic signals. Each on-ramp is equipped with 2 detector loops, one at the signal stopline for on-ramp volume measurements, and the second one at the upstream of the on-ramp for the queue override strategy. In addition, the freeway is equipped with detectors stations (each 500 m) for traffic volume, occupancy and speed measurements. In the following, two ramp metering strategies (VC_ALINEA and CORDIN) are introduced.

The basic formula of VC_ALINEA requires computing the split ratio as the control variable instead of the green duration. The split is defined as $\alpha = G/C$, where G is the green time and C is the cycle time. The VC_ALINEA control law is:

$$\alpha(k) = \alpha(k-1) + K\,[\hat{o} - o_{out}(k-1)]$$

where K is a predefined parameter, ô, and o_{out} denote the desired and current occupancies. Similar to ALINEA, the split (α) is constrained by the minimum and maximum cycle durations. Similarly, the CORDIN strategy is based on ALINEA, in which the coordination is coded to a systematic manner to find first the location of an active congestion (Master on-ramp) and second to modify all upstream control values of ALINEA. The correction of ALINEA control values can be done by adjusting a few parameters.

The aforementioned strategies have been applied over the period from the mid-September 2006, until the end of January 2007. By scrutinizing the collected data, days with major detector failures, uncommon traffic patterns, and significant incidents or accidents are discarded. It was reported that ALINEA in comparison with the no control case decreases the total time spent by 10%, decreases the total travel distance by 2%, and increases the mean speed by 5%. Further, VC_ALINEA decreases the travel time spent and total travel distance by 12% and 5%, respectively. In addition, the CORDIN strategy resulted to 12%, 0% and 11% decrease of travel time spent, total travel distance and mean speed, respectively. For environmental analysis, fuel consumption of vehicles during activation of each ramp metering method is studied. In comparison with the no control case, the changes of -8 %, -5%, -8 % were reported for ALINEA, VC_ALINEA and CORDIN, respectively. The emission indices are also reduced for all strategies. For safety analysis, a risk model based on the traffic measurements (occupancy and flow) is considered, which was calibrated and validated both on the ring road of Paris and on A6W. The obtained results reveal improvement of 20% for all other strategies compared with the no control case. The results of the cost benefit analysis, with respect to the investments and the maintenance cost of the ramp metering system, indicated a collective benefit of 2.4 M€, 2.44 M€ and 3.5 M€ per year for ALINEA, VC_ALINEA and CORDIN, respectively. (Nearctis deliverable report 7, 2010)

2.3.3 Ramp Metering Status in the Netherlands

In 1989, the first ramp metering system in the Netherlands was installed on the A10 mo-

torway, with reported positive evaluations. There are 50 ramp meters operating as of 2006, with the implementation costs of 150000 euros for a one-lane onramp controller and 175000 euros for a two-lane controller including outside equipment. The A10 motorway is the ring road around Amsterdam with connections to the nation-wide motorway system of The Netherlands. The A10 is a busy motorway with up to 93.000 vehicles per day in 1994 and frequent congestion occurrences. In June 1994, three new local ramp metering systems have become operational. Taale and van Velzen (1996) report the analyses of two metering strategies on A10: Rijkswaterstaat and ALINEA. The former is a feed-forward strategy assigning the remaining capacity of motorway to the onramp traffic. The Rijkswaterstaat (RWS) strategy can be summarized as follows.
The ramp control system switches on when i) the flow on the motorway or on the on-ramp or the sum of both flows exceed certain predefined values, ii) the speed upstream or downstream the onramp drops below a certain value. Afterwards, the number of vehicles allowed to enter the motorway is:

$$r_k = C - I_{k-1}$$

where r_k is the number of vehicles allowed to enter at time interval *k*, *C* is the capacity of the motorway downstream the on-ramp, and I_{k-1} is the measured flow upstream the on-ramp in the previous time interval. The cycle time of the metering system is then calculated:

$$t = \frac{n}{r_k} \times 3600$$

where *t* is the cycle time (second) and *n* is the number of lanes on the on-ramp.

The evaluation results show no significant difference in flows. However, ALINEA increases speeds considerably such that during the peak periods the average minimum speed has increased approximately from 30 km/h to 50 km/h. Moreover, with the introduction of ramp metering a 19% reduction of delays has been achieved for both the motorway and the on-ramps. For the Rijkswaterstaat strategy, however, traffic conditions in terms of delays and speed have worsened with respect to the no ramp metering situation.

Taale et al. (1996) examined filed implementation of 3 different ramp metering strategies (RWS, ALINEA, and Fuzzy) at The A12 motorway from The Hague to Utrecht. The output of fuzzy strategy is the cycle time and the inputs are: speed upstream the on-ramp, speed downstream the on-ramp, and the existence of a queue on the onramp. The input variables are divided into a number of fuzzy sets, e.g. very low, low, medium, high and very high. In the first step (fuzzification), the measurement of an input variable is transferred to degrees of membership for those sets. Depending on the degrees of membership, some fuzzy rules are triggered (fuzzy reasoning). These rules have the form:

IF *speed upstream = medium* AND *speed downstream = low* THEN *cycle time = long*.
The switching on of the fuzzy strategy is when the calculated cycle time exceeds a certain threshold and switching off is when the cycle time drops below another threshold. The results of the assessment show that the fuzzy ramp metering strategy was performing better than the other strategies: the capacity of the bottleneck increased (RWS=4048 (veh/h), ALINEA=4000 (veh/h), and Fuzzy=4256 (veh/h)), giving a better throughput, higher speeds, and shorter travel time (RWS=6.0 (min), ALINEA=6.2 (min), and Fuzzy=3.9 (min)). However, fuzzy strategy shows a safety problem that it switches on and off too often.

Taale and Middelham (2000) investigate the manner of driver traffic law compliance at onramps. They report that in case of bottleneck occurrence, about 6% of the drivers ignores the red light, whereas in case of no bottleneck this increases to about 15%. However, where a traffic camera is installed; only about 3% of drivers risk ignoring the red traffic signal. In addition, they state that with ramp metering the percentage of rerouting from the onramps to other roads is noteworthy.

2.3.4 Ramp Metering Status in Germany

Ramp metering has been implemented in Rhine-Ruhr area, Munich and Hamburg, in Germany. Germany has noted that ramp metering prevents significant speed drops at merge locations and leads to a reduction in accidents (German Ministry of Transportation, 2005). Moreover, the number of congestions is reduced by around 50%, the number of severe accidents (person injured or severe damage) is reduced by 25%, and particularly the speed on the through lanes is increased by 10%. As of September 2012, there are around 100 on-ramps on motorways in Nordrhein-Westfalen, Germany equipped with ramp metering control.

2.4 **Ramp Metering Status in Australia**

A coordinated traffic responsive ramp control strategy, HERO (HEuristic Ramp metering coOrdination) (Papamichail and Papageorgiou, 2008), was implemented by VicRoads at 6 consecutive inbound on-ramps on the Monash freeway, in Melbourne, Australia. HERO objective is to target the critical occupancy for throughput maximization, which recent studies demonstrate that is more robust and effective than targeting a predefined capacity value. HERO adjusts local ramp metering rates computed by ALINEA based on real-time measurements of traffic conditions along the freeway stretch. HERO applies the co-ordination by appropriate setting of minimum ramp queue lengths that should be created and maintained at specific ramps. The principal methodology of HERO is summarized as follows:

i. HERO identifies potential active bottleneck of mainstream. The nearest ramp upstream of the bottleneck is regarded as the master on-ramp.
ii. To delay or avoid the mainstream congestion and queue control of the master on-ramp, HERO increases the storage space by employing the upstream located slave on-ramps.
iii. The formed cluster of on-ramps (master and several slaves) is dissolved when the master on-ramp queue or the mainstream occupancy at the bottleneck become sufficiently low.

The Monash freeway is a six-lane dual roadway carrying more than 160,000 vehicles per day and experiences long periods of congestion between 3 to 8 hours a day. The evaluation undertaken by VicRoads for the pilot project shows a 4.7% increase in average flow (on top of the previous system) and a 35% increase in average speed at morning peak, and a 8.4% increase in average flow and a 58.6% increase in average speed at afternoon peak. Evaluation study also indicates that results produced by HERO are better than local ramp metering strategies and are close to sophisticated optimal control schemes, which require demand prediction. It is worth to mention that HERO was also field-implemented in a 20-km stretch of the A6 freeway in the south of Paris, France, in 2006, although in a simplified form due to the lack of real-time on-ramp data. Nevertheless, results indicated a clear improvement over the uncoordinated ALINEA case.

2.5 **Variable Speed Limit**

Early work in the Netherlands demonstrated a homogenization effect, which greatly increased the stability of the system (Smulders, 1990, Hoogen and Smulders, 1994). This increased stability also reduces the number of accidents (Lenz *et al.,* 2001). Other works have shown that traffic breakdowns can be prevented by controllers, which move the system to an optimal density (Chien *et al.,* 1997), as well as the effect of VSL in eliminating or reducing speed of shock waves (Hegyi *et al.*, 2005b).

Hegyi *et al.* (2005a) developed a coordinated ramp metering and VSL control in a macroscopic model. They and Papamichail *et al.* (2008) suggest that this type of coordination is well-suited for situations where ramp metering alone is unable to prevent breakdowns.

Variable speed limit (VSL) studies can be distinguished into two groups. The first focuses on the homogenization effect to improve traffic safety, while the second emphasizes the reduction of flow to prevent traffic breakdown (Hegyi *et al.*, 2005b).

The main idea in homogenization is that traffic safety can be improved by reducing the speed differences. This approach usually employs speed limits that are higher than the critical speed (corresponding to the critical density). Therefore, this approach does not limit the traffic flow, but only slightly reduce the average speed and increase average density. VSL implementations that aim for homogenization effect result in more stable and safer traffic flow, but they do not indicate any significant improvement of traffic volume (Hoogen and Smulders; 1994). Recent reports from the Dutch experiment indicate an improvement of air quality and safety, but they have similar findings regarding the effects on speed and flow (Hegyi *et al.*, 2005b).

Traffic breakdown prevention approach employs speed limits that are lower than the critical speed to limit the inflow to the jammed area. By resolving the bottleneck locations, higher traffic flow can be achieved. Several control methodologies have been tested to apply new speed, such as multilayer control (Li et al., 1995) and optimal control (Alessandri et al., 1999). Other studies use a simple control logic in which the switching between the speed limit values is based on traffic volume, speed or density measurements (Zackor, 1979; Hoogen and Smulders, 1994; Hardman, 1996).

3 Data

3.1 Analysis

A1 freeway from Lausanne to Geneva was selected for the field experiment to test the developed methodology. Given the limited data available from the loop detectors, two additional sources were utilized: (i) data of manual counts at the arterials next to the on-ramps of Nyon and Coppet were collected on two Tuesdays, April 23 and April 30 by 10 EPFL MSc students with the coordination of RGR engineer, Adil Hussain-Khan and (ii) two high resolution cameras were installed at the merge location of Coppet and Nyon ramps and collected data for two consecutive weeks April 18-May 3. The available dataset consists of five different types of source; mainline detectors (a single detector between two successive interchanges), manual counts at the interchanges (Nyon and Coppet), ramp detectors at three interchanges (Coppet, Nyon, and Gland), detectors from variable speed limit (VSL) system, ramp detectors, and the video camera located at Nyon and Coppet sites, covering the Geneva direction. Figure 2 presents a map of the case study showing data collection stations, and Figure 3 depicts snapshots from the video processing software Autoscope. The data from each source has different characteristics and different formats. Therefore, they have been treated differently in the data cleaning and mining processes. The results from different sources have been put together to select a representative congested day and to create the demand profile in the detailed microscopic simulation model. Details of each step are given in the following subsections.

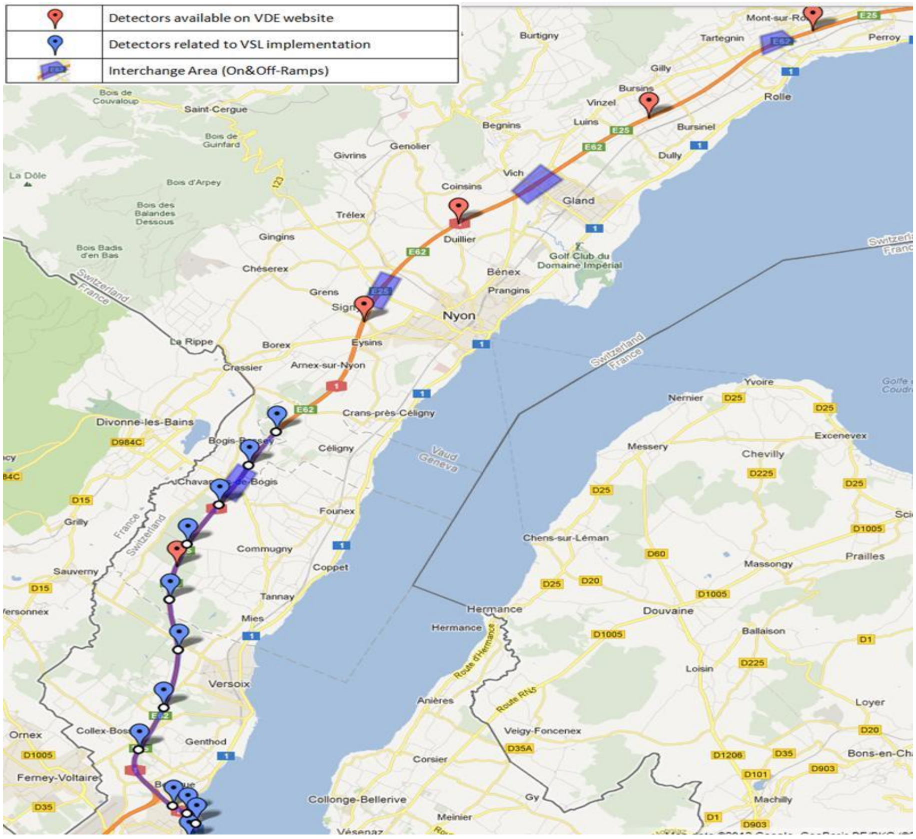


Figure 2 Detector Stations on A-1 Freeway

Figure 3 Snapshots of processed video data collection with Autoscope

3.2 **Cleaning**

Mainline Detectors

This data was already grouped by day in separate files and had fields separated by standard delimiters. The metadata, which appeared in the middle of the set every two hours and one footer line, had to be removed manually before processing.

Manual Counts

Chronograph time (synchronized by both groups before proceeding to the locations) had to be converted to clock time. Since some of the counts were grouped in one-minute intervals and others were done by traffic light cycle, the aggregation into simulation intervals was also done manually.

Ramp Detectors

In the Gland data, metadata was removed and nonstandard delimiters (spaces and ';') were replaced by tabs. The Coppet and Nyon data had headers and footers to be removed. The figure below illustrates the snapshot of the corresponding Matlab structure file.

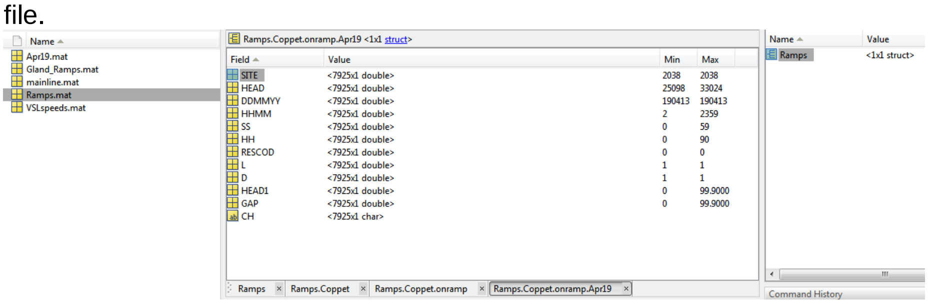


Figure 4 Matlab data structure

VSL data
The VSL files contained several different datasets: 6 minute and 1 hour counts, data from Lausanne and Geneva directions, and data for the left, right, and both lanes. These datasets had to be separated for processing, so a Java function was written to extract rows that contain data for both lanes, in the Geneva direction, at 6 minute intervals. The same function can, of course, be used to extract other sets from the same file. 1min data was not possible to be collected and this might happen at a later stage (discuss with RGR).

3.3 Mining

Mainline detectors
The raw data was imported into Matlab. These are loop detector readings, so each row represents the passage of one vehicle. This was aggregated into one minute flow counts and speed averages by lane and saved into structures indexed by location, date, and type (flow or speed). One-minute dataset has been used to create the demand profile in the microscopic simulation model. The data is further aggregated into 6-minutes intervals to match the format of VSL data.

Manual Counts
The manual counts were primarily used to identify arterial demand and to calibrate the simulation model. Signal information from manual counts is incorporated in the microscopic simulation model. Also, the model is calibrated to match the real queue sizes on the signalized arterials.

Ramp Detectors
The ramp data comes from loop detectors located on the on- and off-ramps, similar to the mainline detector data. The raw data was imported into Matlab, aggregated to one minute flow counts, and saved into structures similar to the mainline data.

VSL data
The VSL data was imported into Matlab. It was already aggregated into 6-minute intervals, so no further processing was needed.

Camera data
With the help of Minnesota Traffic Observatory (directed by Prof. John Hourdos) we utilized Autoscope software to automatically estimate speed and flow measurements for a critical day. The location of the cameras was not in an ideal location and Autoscope results included some estimation errors. We manually observe the videos to identify the onset and offset of congestion for the 2 ramps. Figure 2 shows how the Autoscope Software performs.

3.4 Visualization

Mainline detectors
Initially, plots of one-minute flow and speed by lane were created. These included all four lanes (both directions) and were useful to identify the directions since this information was not included in the metadata.

VSL data
Since the location of all detectors was given by milepost, the six-minute speed readings were represented as a contour plot. This contour plot was expanded to include the mainline detectors, also plotted according to their milepost location.
Speed data from mainline and VSL detectors have been merged to create speed contour plots and to identify a representative congested day. Figure 3 presents the resulting speed contour plots and allows us to observe the congestion level on different days. As can be clearly seen, the most congested day within the study period is April 22nd. However, traffic conditions observed on this specific day do not seem to be recurring; the congestion level observed on other days is quite light compared with April 22nd. This is because of an accident that occurred on the freeway, which cannot be considered in our

analysis. Therefore, April 19th is selected as the representative day, considering its compliance with average traffic conditions on the freeway. Note that, on April 19th, an active bottleneck starts at the Coppet interchange, and it propagates back to Nyon, but it does not reach Gland. Only 6 out of the 14 days experienced some level of congestion with significant decrease in the freeway speed. Our coordinated ramp metering strategy at three interchanges is expected to produce favorable results, considering the distance between them and the length of the congested region. An additional scenario for the date of April 22nd can be created to test the performance of the algorithm during accident conditions (to be discussed with the Committee).

3.5 Integration into Aimsun

The Aimsun model stretches from the Échangeur du Vengeron near Geneva to just beyond the Rolle interchange. The primary goal of the model was to have accurate traffic behavior on the Geneva direction of the Autoroute A1 and on the arterial streets at the Coppet and Nyon interchanges, where the manual counts are collected. No attempt was made to calibrate vehicle flows in the Lausanne direction or on the arterial streets at the Gland and Rolle interchanges and these should be ignored.

Figure 5 clearly indicates April 19th to be one of the most congested days, so it is considered as the representative day in the model. Data from April 19th was extracted from mainline, ramp, and VSL detectors. Manual counts were only available for April 23 and 30. April 30th was used because conditions were similar to the ones on April 19th. Note that on April 22nd, a non-recurrent severe congestion condition can be observed that is consistent with a reported accident.

The simulation period is broken into 12 intervals: 6:30-7:00 (one interval), 12 minute intervals between 7:00 and 9:00, and 9:00-9:30 (one interval). Flow in each of these periods was extracted and converted to vehicles/hour. The demand was coded into Aimsun using traffic states. That is, vehicles entering from exterior links need to be defined as well as turning percentages at every intersection. Vehicles enter the freeway upstream of Rolle according to the flows observed at the Rolle detector. The off-ramp detector flows are used to calculate "turning probability", the percentage of vehicles taking the exit. The on-ramp detector flows are used to adjust the arterial demand.

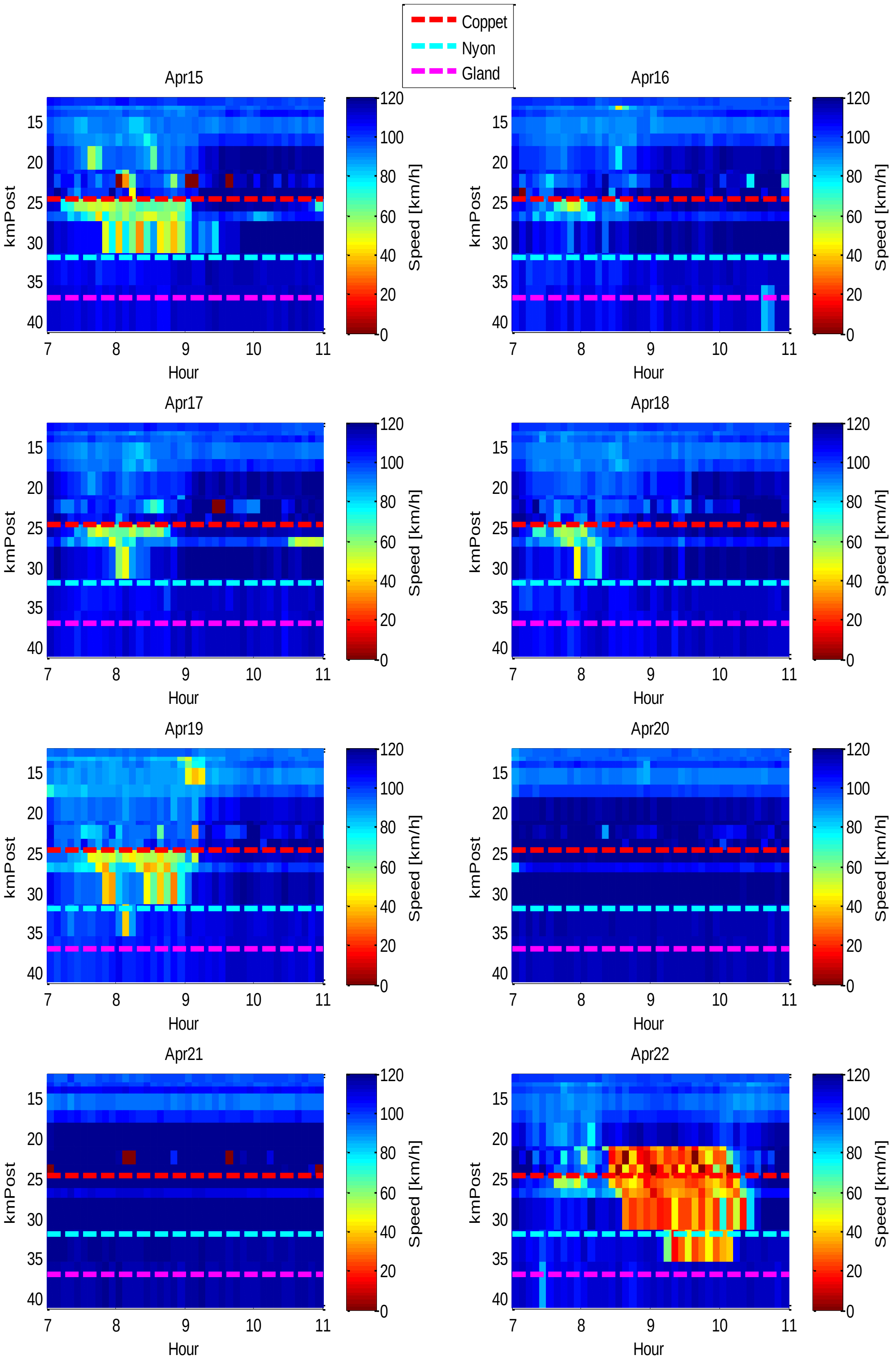


Figure 5 Speed Contour Plots

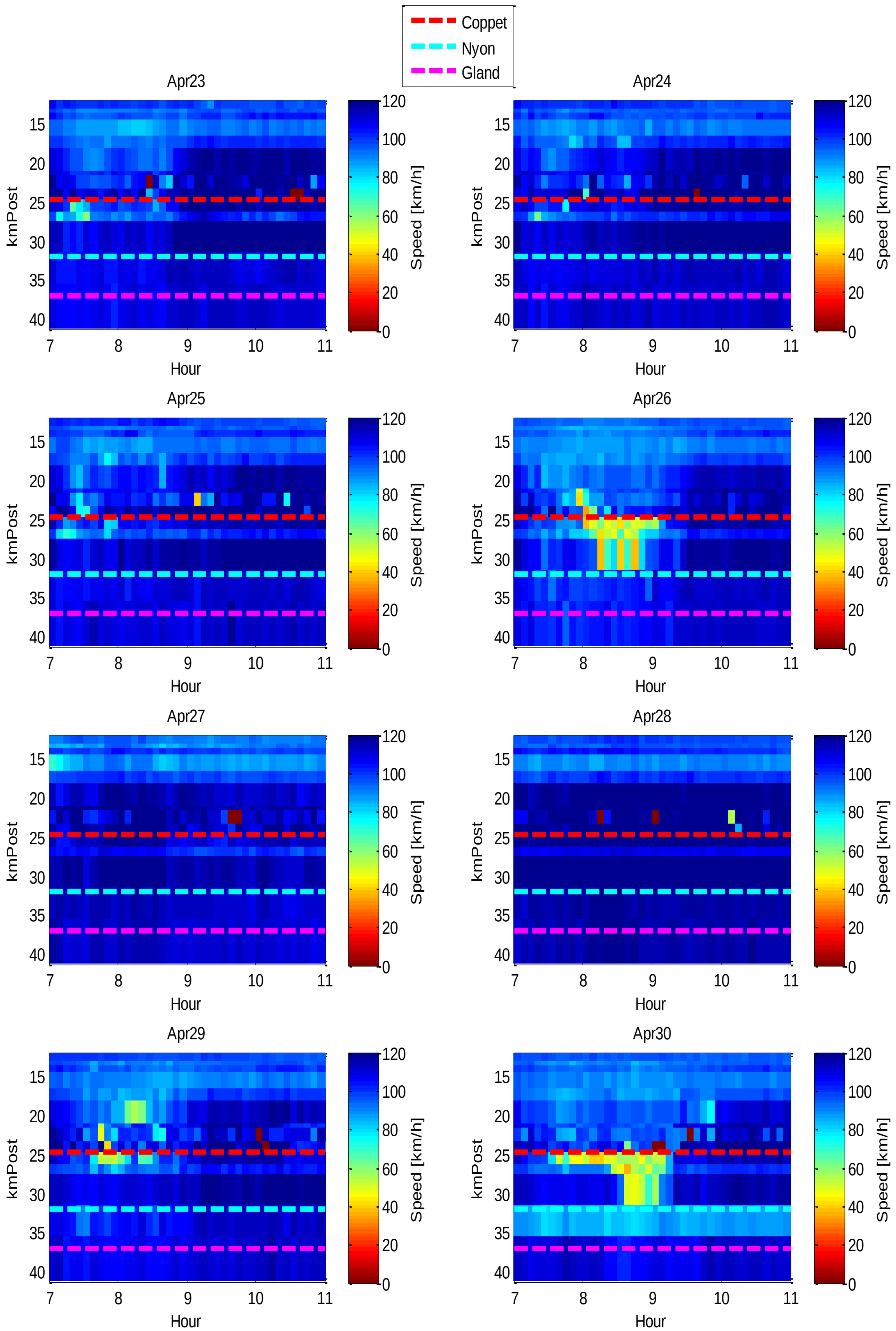


Figure 5 Speed Contour Plots (continued)

Arterial flows and signal timings are taken from the manual counts on April 30th. One exception is the signal at the intersection of Route de Divonne and Route de Bogis-Bossey, which is an adaptive signal in the simulation. The signal timing and turning percentages were set according to the manual counts, but the vehicle flows to and from the freeway were changed to match April 19th detector counts. Select turning movements are shown in the table below. Where turning movements were unknown, an equal probability was assigned to each choice. This is the reason why some vehicles can be observed turning on to the Lausanne direction of the freeway during simulation.

Table 4 Turning movements(percentages) obtained from manual counts, adjusted to match April 19 ramp flows

	Coppet				***Nyon***			
	West		***East***		***West***		***East***	
Time	***A1 Genève***	***Straight***	***A1 Genève***	***Straight***	***A1 Genève***	***Straight***	***A1 Genève***	***Straight***
06:30	65	35	52	48	48	52	45	55
07:00	45	55	62	38	53	47	51	49
07:12	47	53	49	51	56	44	53	47
07:24	50	50	67	33	51	49	50	50
07:36	50	50	54	46	48	52	56	44
07:48	43	57	58	42	53	47	41	59
08:00	48	52	53	47	41	59	49	51
08:12	57	43	64	36	45	55	42	58
08:24	58	42	50	50	33	67	30	70
08:36	49	51	36	64	38	62	35	65
08:48	53	47	49	51	29	71	26	74
09:00	42	58	38	62	29	71	26	74

4 Calibration

The first step of calibration adjusted ramp and mainline flows and driver behavior to better approximate the conditions observed on the freeway mainline. Merge behavior in the microscopic simulation is adjusted using the cooperation percentage of the travelers and the video records from the study site. Mainline traffic conditions within space and time can be best compared using speed contour plots. Both qualitative (bottleneck shape on speed contour plots) and quantitative (mean absolute error) measures were used to evaluate calibration results. The key parameter values are given in Table 5.

Table 5 Key Aimsun Parameters

Parameter	Value
Maximum desired speed – median	115 km/h
Maximum desired speed – range	90-130 km/h
Compliance with regulation	100%
Cooperative merging	100%

After mainline calibration was finished, the arterials were considered. Queue lengths at the intersection with Geneva direction ramps were counted as part of the manual counts. At Nyon, the signal with the Lausanne direction ramps was modified to match the other signal (whose timing was known), and the two were offset to pass vehicles through both signals on one green phase. This was enough to match queue lengths at Nyon (i.e. variable between 10-15 vehicles in both real counts and simulated results) and the mean absolute error for the entire simulation improved as well. At Coppet, the same signal coordination strategy did not work as well. After some testing, an offset was selected that does not coordinate the signals. This leads to small queues forming on the bridge (as observed in reality) and produces the best results in terms of mean absolute error. Figure 6 presents the speed contour plots constructed using the speed data taken from the real detectors on the freeway and the detectors located in the same position in the microscopic simulation model. Although the resulting speed values at the detectors are not exactly the same, the shape of the bottleneck and the congestion pattern are quite similar in the reality and in the detailed microscopic simulation model.

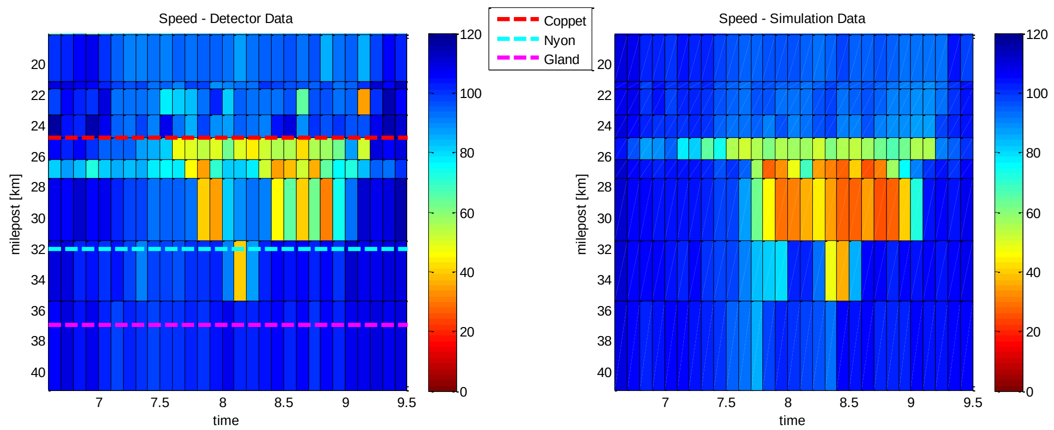


Figure 6 Calibration Results

In both reality and the micro-simulation, the bottleneck that starts to form at Coppet interchange area around 7:40 creates a queue that reaches the interchange area at Nyon. The downward shockwave speed, the rate at which the queue size increases or congested speeds move backwards, is very similar in both cases. The bottleneck starts to get smaller with an upward shockwave speed and it completely disappears at Coppet interchange area around 9:05.

Queue size at the signalized arterials is another crucial factor, which has to be similar in reality and in the model. Although ramp meters always improve the conditions on the freeway, they may create excessive queues at the on-ramps, which may block the arterials connected to them. This project aims to improve the conditions on the freeway without negatively affecting the conditions on the arterials. Therefore, the calibration of queue sizes plays an important role in our analysis. Figure 7a depicts a snapshot from the microscopic simulation model (roundabout in Coppet). The queue size from the manual counts is quite similar to what we observe in Figure 7a.

Figure 7b provides another snapshot from Coppet merge area. Although the mainline is congested, the vehicles do not show unreasonable behavior (i.e. going till the end of the shoulder lane and waiting to merge). Lane changing cooperation parameter embedded in AIMSUN allows us to calibrate merging behavior and to avoid unreasonable merge behavior.

a.

b.

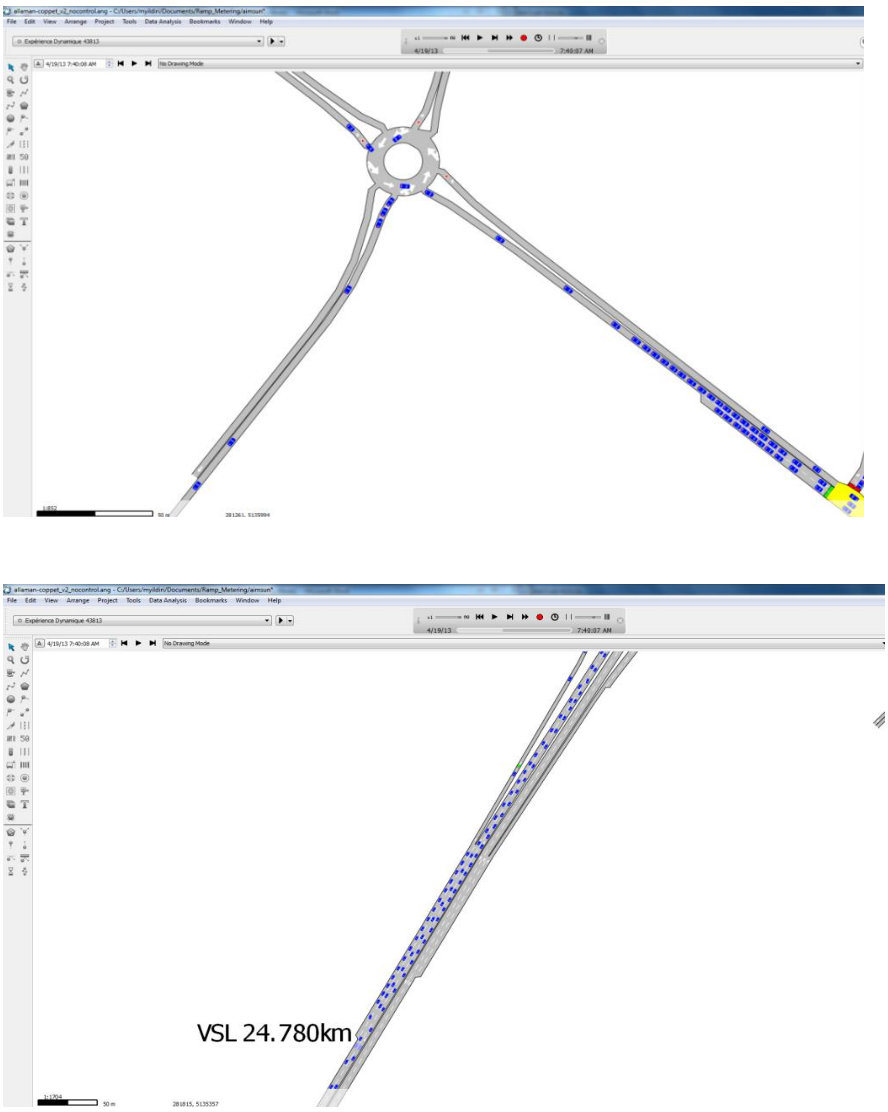


Figure 7 Queue in Coppet Arterials and On-Ramp

The capacity of freeway sections is defined as the maximum flow possible at a specific location. A bottleneck is a location where the full performance level (capacity) of an entire system cannot be achieved due to an abnormality at a single or multiple components of the system. The performance at one location thus brings down the performance of the entire system. An active bottleneck is a bottleneck whose performance is not affected by any other bottlenecks occurring downstream, and has free flow conditions downstream and congested conditions upstream. In other words, active bottleneck refers to the traffic conditions where the discharge rates measured downstream of a queue are not affected by conditions from further downstream. While the maximum possible flow (capacity) from an active bottleneck was traditionally considered a fixed value for a given location, there are many recent studies that suggest that the outflow from the bottlenecks diminish once queues start forming upstream of that location or once traffic breakdown occurs. This phenomenon is well known as 'capacity drop'. Hall and Agyemang-Duah (1991) and Banks (1991) first suggested that discharge flow at bottlenecks diminish once queues start forming upstream of the location, thus marking the onset of congestion. Thus, the congested capacity of the bottleneck can be distinguished from the bottleneck's free flow capacity, with the difference being termed as the capacity drop, ranging between 5 and 15%. Recently, many researchers have tried to identify the causes of capacity drop by looking at microscopic phenomena. Lane changing maneuvers, vehicles entering a merge at low-speed and heterogeneous lane behavior have been considered to enlarge the capacity drop phenomenon (e.g. Cassidy and Ahn, 2005). One -of the reasons is that the aforementioned phenomena generate variations between different levels of saturated traffic states at merges that prevent the system to reach the full freeway capacity before the breakdown.

Unfortunately capacity drop phenomenon is not captured in microscopic simulation models where car following models have been applied. To capture this effect in the micro-simulation, we observe the traffic conditions at the potential active bottleneck location and when the breakdown occurs, we increase the minimum headway between the vehicles that go through the jammed area. The minimum headway between the vehicles is calibrated to match the flow values downstream of the active bottleneck after the capacity drop. Figure 8 compares the measurements from a detector at downstream of the bottleneck with the measurements at the same location from the micro-simulation. We apply the calibrated scenario in two different ways; with and without capacity drop phenomenon. Figure 8 clearly shows that flow measurements are overstated in the scenario where the capacity drop phenomenon is not considered. Although it is not a perfect match, the addition of capacity drop phenomenon improves the flow estimation at this location and makes traffic dynamics more realistic. This simple analysis indicates the importance of capacity drop phenomenon; the success of freeway control management schemes is highly correlated with the prevention of traffic breakdown and so capacity drop phenomenon.

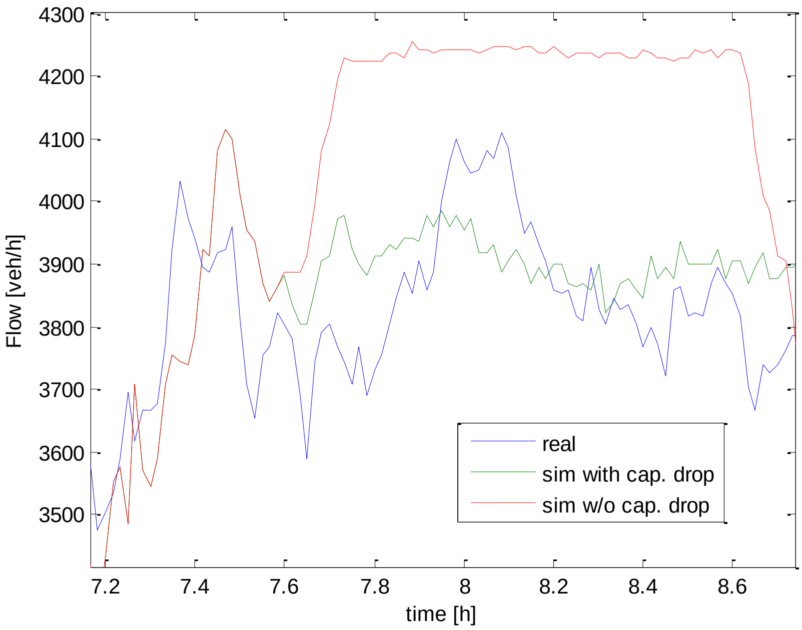


Figure 8 Flow measurements downstream of active bottleneck

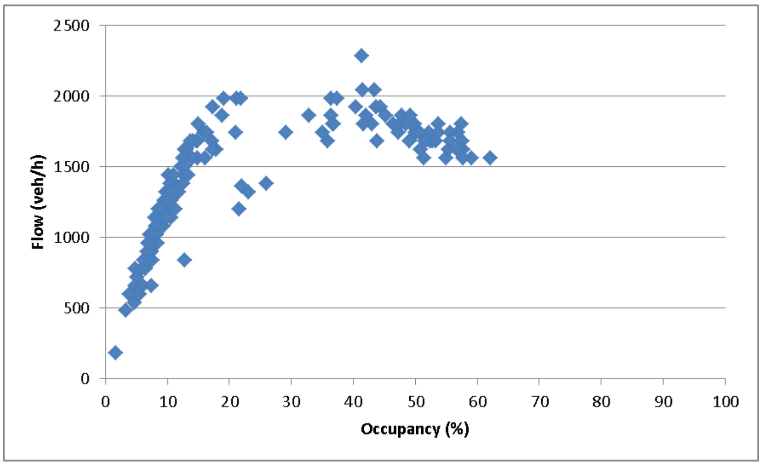


Figure 9 Fundamental Diagram without Capacity Drop

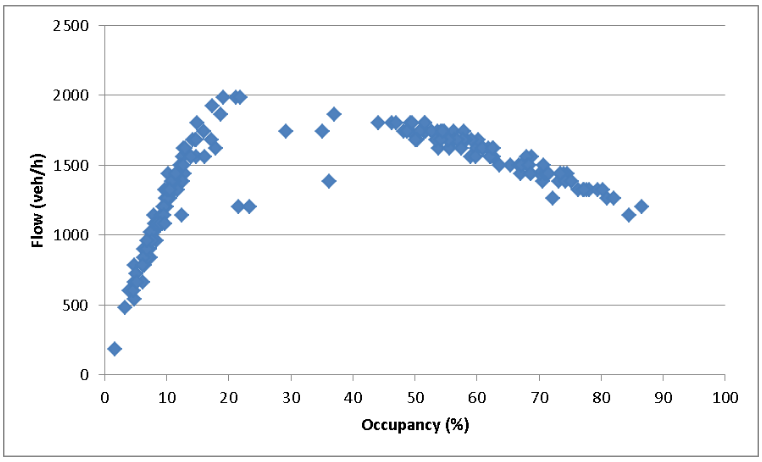


Figure 10 Fundamental Diagram with Capacity Drop

5 Methodology

5.1 Coordinated Ramp Metering

In [Geroliminis, et al. 2011], a dynamic-zone-based algorithm is proposed that divides the whole freeway system into zones that in each zone, the metering rates are chosen independently of the conditions in other zones. The length of each zone is dynamic and is estimated in real time that mainly depends on: 1) the level of congestion on the mainline; 2) the demand and queue lengths at individual on-ramps; and 3) the location of the active bottleneck(s). The location of an active bottleneck is either at freeway merges, where there is an additional inflow, or in areas where the capacity changes (e.g., a change in topology). An active bottleneck is defined as a location with heavy congestion that is not affected by conditions further downstream, i.e. conditions are congested upstream of the bottleneck and uncongested (or at capacity) downstream of the bottleneck.

We propose an alternative version of the algorithm for ramp metering in the A1 freeway between Gland and Coppet, Switzerland. The algorithm sequentially identifies the metering rates for each section. The section is a segment of the freeway that contains one on-ramp and one off-ramp. When freeway traffic is free flowing and on-ramp demands are low, there is no need for a coordinated algorithm. A coordinated algorithm is used when there is a series of high-demand ramps upstream from an active bottleneck, or there are two closely spaced active bottlenecks and the downstream one is propagating upstream or when there are long queues in one of the on-ramps that propagate in the arterial system.

We now provide the definition of a zone. A zone comprises an active bottleneck location (or a location that is a threat for an active bottleneck if demand conditions continue to be the same) at its downstream end and the upstream sections that are influenced by the bottleneck/threat. Note that the condition in A1 freeway seems as a single zone where the Coppet on-ramp is the active bottleneck and a congestion propagation threat for the Nyon and Gland upstream on-ramps. The associated on-ramp of this downstream bottleneck is the *controlling ramp* for this zone. All rates in the other ramps will be estimated to postpone the occurrence of the breakdown at the controlling ramp. The algorithm's goal is to keep the car density levels at all ramps below the congestion thresholds and not to allow low speeds to occur in the mainline by constraining the ramp delays. The ramp rates become stricter when the mainline density is close to the congestion threshold, and the ramp rates increase when the ramp queues are close to the ramp full queue threshold. When it is not possible to keep both uncongested because of high on-ramp and mainline demands, the algorithm seeks to delay the violation of both thresholds as much as possible. If both on-ramps and mainline congestion thresholds are violated, then the algorithm will give priority to the on-ramps to avoid huge penalties in the arterial system.
The metering rates are decided based on the following criteria:

1) In normal conditions (i.e. no other constraint is active), the ramps are controlled with an ALINEA controller that can be interrupted with a queue-override criteria. ALINEA ramp metering strategy is a simple feedback controller strategy that determines the metering rate of the on-ramp in such a way to maintain the occupancy downstream of the merge location at an ideal threshold, o_d. The value of this threshold is usually chosen as 90-95% of the critical occupancy that maximizes the flow for the fundamental diagram (flow-occupancy) of the loop detector location. The practical location of loop detector should be very close to the place of active bottleneck that based on numerous field observations is downstream of the merge area. The ALINEA metering rate at time step t+1 is estimated as

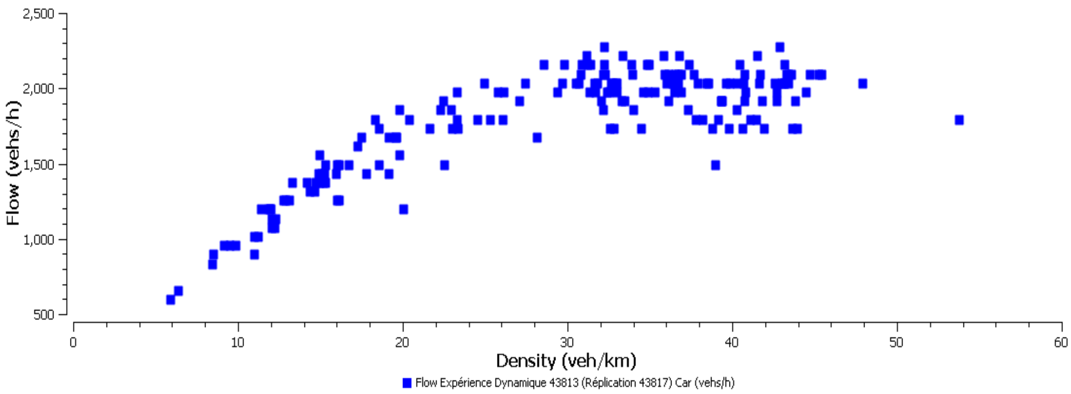
$$r(t+1) = r(t) + K(o(t) - o_d)$$

where *K* is a control regulator and $o(t)$ is the occupancy value at the previous time interval (interval is usually 20sec-1min). Later the value of $o_d$for different ramp locations will be further discussed.

2) A queue-override is integrated within the ramp metering strategy to avoid situations where the queue of vehicles in ramp spillbacks to the urban area. Thus, ALINEA is active when the queue at the on-ramp is below a threshold value (40-70% of the on-ramp length, which should be calibrated carefully). Otherwise the queue-override activates the maximum release rate at the on-ramp.

3) In addition, to overlook outlier traffic states the queue-override should be activated after a prescribed interval. I.e. if the queue length on the on-ramp is consistently higher than the queue size threshold for the prescribed interval then the queue-override is activated and the metering rate is changed to the maximum. After a careful calibration the prescribed interval is chosen as 5 minutes.

4) Abrupt alternation in the metering rate could create stop and go shockwaves in the merge area that degrades the flow of the freeway. To avoid sudden changes in the metering rate, a maximum rate jump is defined such that the difference between $r(t+1)$ and $r(t)$ should be smaller than that.



The “slave” ramps (Nyon and Gland) follow the traffic condition in the master ramp (Coppet) by manipulating the metering rate. The goal of the coordinated strategy for the master ramp is to postpone the congestion occurrence as much as possible (override ramp queue threshold or mainline critical density). This is achieved by balancing the mainline congestion and all other ramps delays. Note that in A1 case study, Coppet is always treated like the critical bottleneck and Nyon and Gland ramp-meters are the follower of the bottleneck.

The key idea of the coordinated ramp metering is how to set the desired occupancy, o_d, for every ramp. As mentioned before, the desired occupancy for the Coppet should be around 90% of the critical occupancy of the fundamental diagram. We choose 35% based on the values of the corresponding fundamental diagram. For slave ramps, the desired occupancy should be selected such that the associated flow of that occupancy plus the flow of the master ramp does not exceed the freeway capacity. Assuming the uncongested part of the fundamental diagram is a linear function and based on historical data of the ramp flow, the desired occupancy at slave ramps can be estimated. Based on several calibration and fine-tuning efforts, we choose $o_d = 10\%$. Note that with this setting (strict metering at slave ramps), we explicitly provide a relative equity among the ramps as supported by the results.

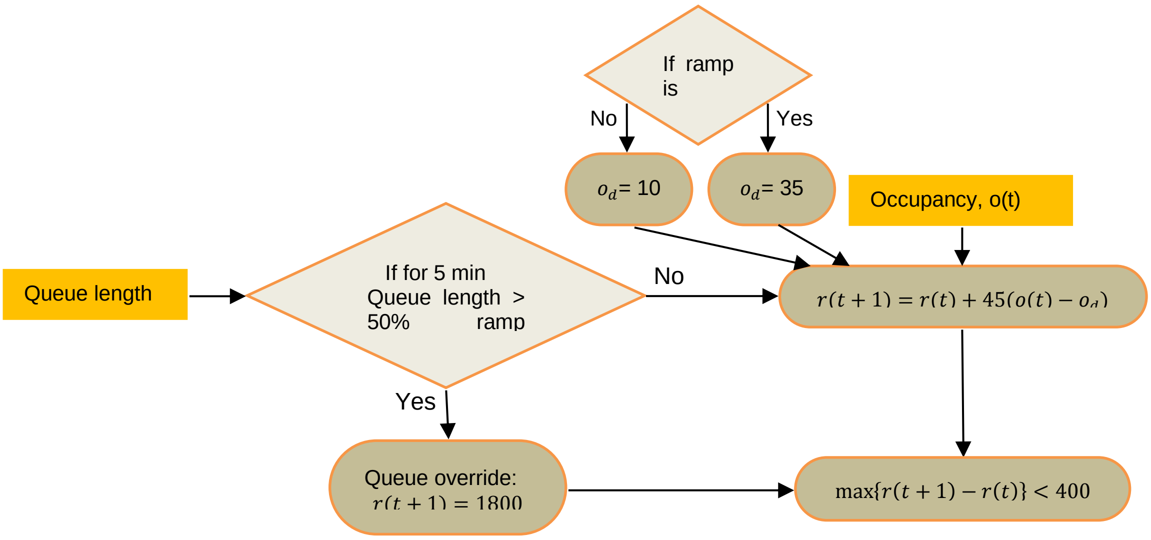


Figure 11 Flowchart of Coordinated ramp metering method

5.2 Bottleneck and Zone Identification

While the original expectation from freeways was to allow uninterrupted freely flowing traffic at all times with maximum level of service, they are known to often become congested in recent times. Congestions on road networks are caused due to the formation of Bottlenecks. A bottleneck is a phenomenon where the full performance level (capacity) of an entire system cannot be realized due to an abnormality at a single component of the system. The performance at one location thus brings down the performance of the entire system. An 'active' bottleneck is a bottleneck whose performance is not affected by any bottlenecks occurring downstream, and has free-flow conditions downstream.

The specific case study has a well-defined active bottleneck (Coppet), which operates as the Master (controlling) ramp meter, and two slave (or controlled) ramp meters (Nyon and Gland) that support the Master one with the objectives of equity and avoidance of ramp queue violation. Nevertheless, in potential large-scale field implementations of future ramp metering strategies the location and activation of bottlenecks might not be a trivial task. Master and slave ramp meters need to be identified in real-time and their interactions should determine the number of controlled meters for each Master. The state conditions identify the problematic locations that can be expected to become the active bottleneck(s). The zone identifies the associated sequence of sections that get affected by a given active bottleneck (or are expected to get affected by a potential active bottleneck before it is actually formed). Thus, the definition of zones also relies on the identification of the active bottleneck locations and threats. Usually a zone would have congested / near congested location(s) at its downstream end and 2-3 uncongested sections at the upstream end.

To identify the controlling ramps and the zone length when conditions are near or at congestion, we start from the most downstream location of the freeway and move upstream by analyzing each location individually at each step. We then use the following rules to mark a merge as the controlling location. Each zone has only one controlling section/ramp at its downstream end and all the upstream ramp rates are calculated as a function of the controlling one.

To identify the most problematic location, we define the net inflow between the two locations i and j , i.e., Mt(i, j) , which is given as the sum of on-ramp volumes minus the sum of off-ramp volumes for all ramps between the two locations. This justifies whether the demand at the upstream problematic location is higher or lower than the demand at the downstream location, thus representing the gain of vehicles within the given section for the specified interval. This variable will help in choosing the critical bottleneck, which will define the metering rates in the coordinated strategy.

For clarity, we adopt a naming convention for the sections such that the sections are numbered from 1 to *N* (*N* being the total number of sections along the freeway) starting at the downstream end of the stretch (section *j* has section *j-1* located immediately downstream of itself). We then first estimate the state of all sections, $S_t(j)$ for all *j*=1, 2, 3… *N*.The 3 possible states can be congested (state 2), semi-congested (stae 1) and uncongested (state 0). Once the bottleneck threat state levels are defined for the sections, we then define the controlling nature of the bottlenecks and hence also identify the controlling active bottlenecks. The bottlenecks are marked controlling or non-controlling according to the following sequential rules:

If section *j-1* is not controlling, and $S_t(j)$ = 1 or 2, then mark *j* as controlling.

If section *(j-k)* is controlling and $S_t(j)$ = 1 for *k*<3,
then, if $M_t(j, j-k) > 0$, mark *j* as controlling
else, mark *j* as non-controlling
If current state = 2, then mark *j* as controlling.
If none of above, then mark *j* as non-controlling.

Once the controlling ramps are identified, the zones are implicitly obtained as the complete lengths between any 2 controlling ramps with the controlling ramps marking the downstream end of each corresponding zone. Thus, we ensure that the downstream end *(i)* is a controlling bottleneck (either a single congested / near congestion section, or a series of sections in the congested / near congestion state) and (ii) has the highest state value among all sections within the zone (we cannot have a non-controlling section in state 2 if the controlling section of this specific zone is at state 1). We also ensure that the upstream end is uncongested since it is just downstream of another bottleneck that defines the boundary for the upstream zone. Since the zone definition comes from the definition of the state level condition for a merge location, and from the bottleneck type for the location, both of which are dynamic, the zone definitions themselves are also dynamic with time. Figure 12 shows an example of zone partitioning (blue cells are the controlling ramps and red squares the zones).

Rolle	Gland	Nyon	Coppet	Vengeron
0	0	0	1	0
0	0	0	1	0
0	0	0	1	0

(a) Uncongested State

Rolle	Gland	Nyon	Coppet	Vengeron
0	1	1	2	0
0	1	1	2	0
0	1	1	2	0

(b) Congested State

Figure 12 A figurative summary depicting Zone Identification

The above is a figurative depiction of how zones are identified. A hypothetical stretch of freeway is taken where flow of traffic is from left to right. In the first step, each section is assigned a state level (0,1 or 2). The state 2 bottlenecks are then highlighted as the high-priority locations. Starting at the downstream end, zone boundaries are then created based on the state information available for each section. The final step shows the final zone boundaries in place with the controlling merge locations highlighted for each zone.

5.3 **Variable Speed Limit System**

An important control measure for traffic flow on freeways is variable speed limit (VSL) in response to the traffic conditions. In most cases, VSLs are mandatory and strictly enforced to increase the driver compliance in the corresponding freeway sections. The main target in the currently installed VSL systems is to improve traffic safety through speed reduction and speed homogenization, which are correlated with a decrease in accident probability. Current installations employ simple rule-based control logics (e.g. preselected thresholds of flow, occupancy or speed) to activate VSL. These thresholds are usually selected in an ad hoc way. Hence, the potential impact of VSL systems on traffic flow efficiency is not yet exploited in practical applications.

VSL systems are implemented for two reasons; enhanced traffic safety through homogenization effect and preventing/delaying the traffic breakdown by reducing or delaying the flow to the potential active bottleneck location. This study focuses on the second approach and employs VSL to prevent the breakdown. This approach focuses on potential active bottleneck locations and employs speed limits in the upstream sections in order to limit the inflow and avoid high densities in the jammed area. Note that the traffic breakdown triggers the capacity drop phenomenon at the active bottleneck location and causes 5-10% reductions in the capacity flow. This approach, by resolving or delaying the bottlenecks, can result in higher flows at the jammed area.

Most of the models in the literature use a speed limit model, which represents the impact of VSLs on the fundamental diagram. However, there are several models, which contradict with each other, and this issue has not been sufficiently investigated with real data. Figure 13 presents three major speed limit models (flow-density relation) used in the literature. The impact of VSL on the critical occupancy and the capacity flow is identified in a different way in each model.

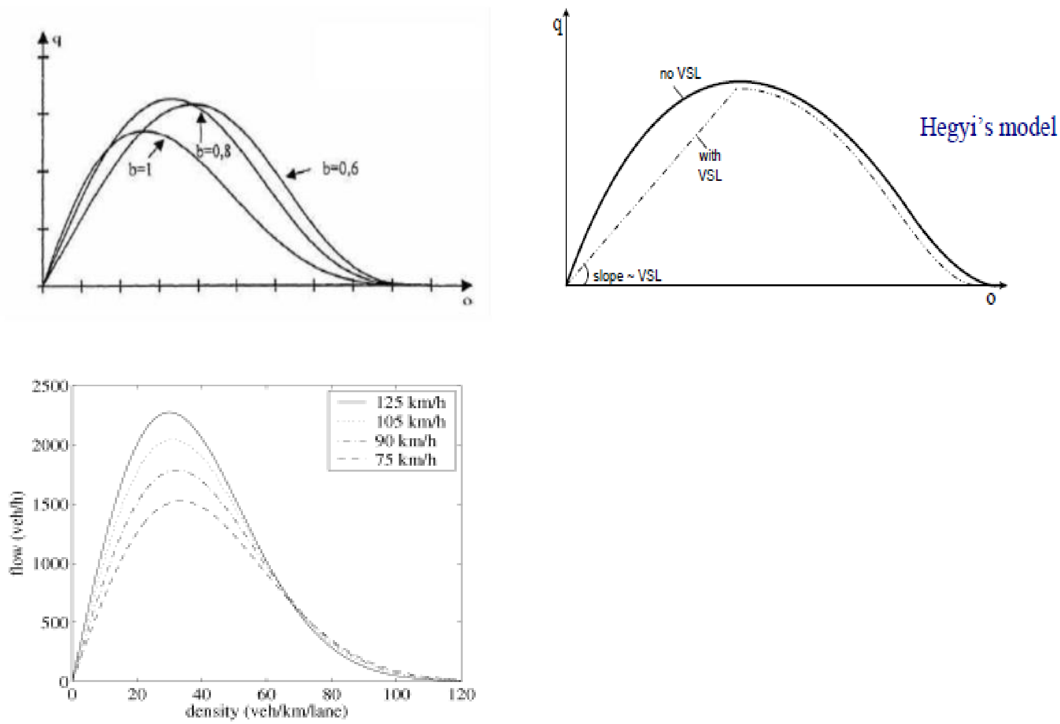


Figure 13 Speed Limit Models

This study does not use a macroscopic traffic model; therefore we do need to identify the impact of VSL on the aggregate traffic parameters (i.e. fundamental diagram). Actual vehicles in the micro-simulation reduce their speeds according to the posted speed determined by the VSL system. A decrease in the speed limit is usually accompanied by a decrease in the flow in the above speed limit models. However, this effect is not observed in the modeled microscopic simulation environment. By enforcing a lower speed limit, VSL strategy can only delay the incoming demand to the jammed area in the microscopic simulation environment. Although this might still help delay the breakdown in the active bottleneck location, the effect of VSL is expected to be more significant in a real-world application. Note that VSL strategy in this framework cannot be very useful to resolve an already formed bottleneck, but it might improve traffic conditions by delaying the breakdown.

Figure 14 presents the VSL system configuration in the study site. Considering the historical data and the demand profile, the interchange at Coppet has been identified as the potential active bottleneck location. The aim of the VSL strategy is to prevent very high densities at the potential active bottleneck location. VSL system is idle at the beginning (speed limit is the currently posted limit), and it tracks the flow measurements at the mainline detector close to Nyon interchange and the on-ramp detector at Coppet (see Figure 8). Although a small portion of the demand at the mainline detector exits the freeway at Coppet, the addition of these two incoming demand measurements is a very accurate proxy for the density at the active bottleneck location. Whenever the sum of these two incoming demand measurements exceeds the specified threshold, VSL system gets activated and variable message signs (VMS) located throughout the section between Coppet and Nyon start to post the new speed limit. VSL section is defined as the 5-km long upstream section starting from Coppet interchange.

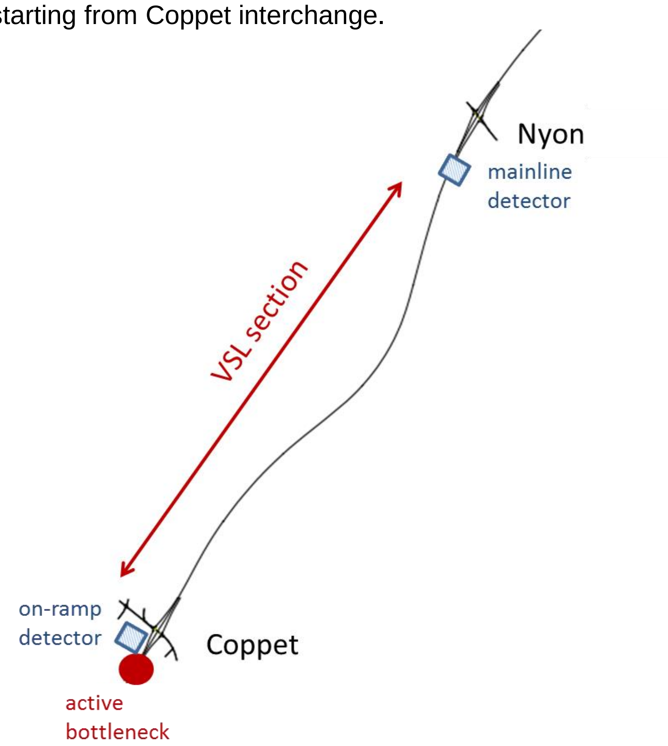


Figure 14 Setup of VSL system

Figure 15 presents a flowchart, which explains the methodological framework of the VSL system. There are two performance measures that are considered in VSL system; sum of the incoming demand measurements at Coppet on-ramp and Nyon mainline, and occupancy measurements at Coppet mainline (active bottleneck location). The former parameter is important in the sense that it represents a good proxy for the anticipated density at the active bottleneck location. The latter indicates the traffic breakdown at the potentially jammed area. Note that VSL system in the microscopic simulation environment is not able to permanently decrease traffic flow (while the opposite is suggested by the above speed limit models) and so to resolve a traffic breakdown; it can only delay the occurrence of breakdown. However, in this work, VSL is kept active for safety reasons after the occurrence of breakdown as well. After the formation of queue due to the active bottleneck, VSL guarantees that vehicles encounter the shockwaves at the tail end of the congested section at a lower speed. In fact, the microscopic simulation model that we employ in this work is an accident free environment where safety measures are not well defined. To connect safety with VSL and make valid conclusions under congested conditions, a real field test is needed. Our analysis highlighted that VSL working together with ramp metering is able to produce more equitable and less congested situations. Conclusions related to the improvement of safety are beyond the scope and the ability of this project (given the constraints of the simulator). Note that a real world VSL implementation may require a step-by-step speed reduction technique (e.g 20 km/h) to avoid sudden reaction of drivers. The VSL can be also activated for other reasons on which this work does not provide any conclusion.

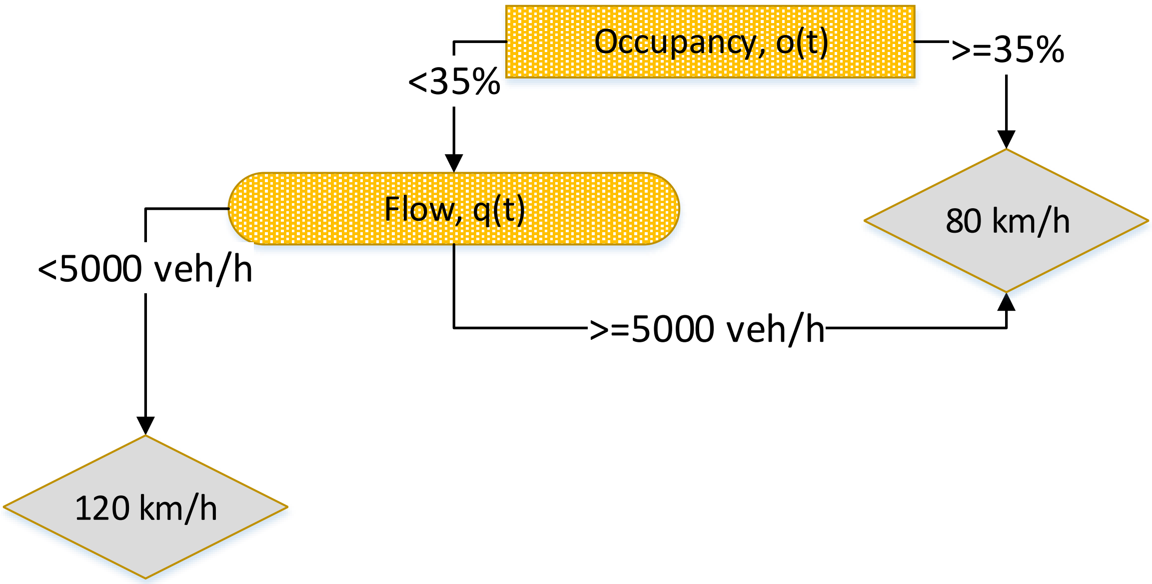


Figure 15 Abstracted Flowchart of VSL System

VSL system is idle at the beginning and keeps track of the flow measurement at two detectors presented in Figure 14 and occupancy measurement at the potential active bottleneck location. If the sum of flow measurements exceeds 5000 veh/h (signaling a very high density at the jammed area) while the bottleneck is not developed yet (i.e. occupancy is less than 35%), VSL system acts in a proactive way and starts to post new speed limits (80 km/h). VSL system remains delays the inflow to the jammed area until the breakdown occurs at the active bottleneck location. Beyond this point VSL is not very useful, because, due to the reasons explained above, it can only delay the inflow to the jammed area, and it does not reduce the number of vehicles that reach jammed area. However, considering the safety reasons, VSL is kept active until the bottleneck dissolves or the occupancy falls below 35%. Note that ramp meter at Coppet on-ramp is inactive throughout the period where VSL is active. First of all, a regulated inflow at Coppet on-ramp can deteriorate the proxy for high density values, the sum of flow measurements at detector locations. Second of all, the detector measurements from the study site show a very high inflow from the Coppet arterials to the freeway, which makes the metering very difficult at Coppet on-ramp area. Therefore, as an alternative to ramp metering, the breakdown is delayed at the jammed area by delaying the mainline flow as long as possible, and ramp metering gets activated right after deactivation of VSL system.

New posted speed limit, and flow and occupancy thresholds are the parameters that can be calibrated depending on the study site. In this study, a careful sensitivity analysis on the microscopic simulation results yielded the parameters presented in Figure 15.

6 Results

The developed strategy is tested through AIMSUN microscopic simulator on a 30-km segment of A1 freeway (Geneva direction), starting from the Rolle interchange and ending at Echangeur du Vengeron near Geneva. This section includes 4 entrance ramp and 4 exit ramps. 3 ramps (Coppet, Nyon and Gland) are metered. The upstream and downstream boundaries are uncongested. For the purpose of this study, only one peak period is tested, specifically the morning peak on April 19th, 2013, between 6.30AM and 9.30AM. The analysis is performed for the demand calibrated in previous steps of the project by utilizing data from the field experiment. Four different strategies are evaluated and compared with the No Control case: (i) ALINEA local coordinated strategy, (ii) ALINEA with queue constraints for all 3 ramps, (iii) the coordinated ramp metering strategy developed in chapter 4 and (iv) combined coordinated ramp metering with variable speed limits (VSL). The results are presented in table forms (to quantify the change in the travel times and delays for each section of the site) and in figures that summarize the physical characteristics of the strategy with the time of the day. To evaluate the performance of the algorithm, a scenario with 10% demand was also investigated. The measures of effectiveness selected for the preliminary assessment are:

1) average delay (in min/km) on the mainline, ramps, and arterial areas (freeway and ramps);
2) system delay (in veh-h);
3) average number of stops on the mainline, ramps, arterial areas and entire system;
4) average speed on the mainline, ramps, arterial areas and entire system;
5) mean queue size on ramps;
6) maximum queue size on ramps;
7) time-series and contour plots of speed and density for the freeway sections.

Given that traffic has stochastic characteristics and conditions are not identical from day to day, the simulation results averaged over 5 replications, are summarized in Table 5. The average delay for each of the 3 ramps, the mainline freeway and the arterial system associated with each ramp are presented here. System delays and total travel time for the whole network are also shown. Average delay is a useful estimator for small areas where trip lengths are similar but would be biased towards shorter trips on the system level. Therefore, the preferred system measure is total delay. This is computed from section statistics, which is important because it does not depend on the number of completed trips that occur in each strategy. Even if demand is the same in all scenarios, due to high congestion a number of vehicles does not finish their trips. Note that the pre-determined performance measures of AIMSUN do not provide a reliable description of the system, as they do not consider engineering principles. By considering all these performance measures, a clear picture for the influence of each strategy to different users and locations of the system is carefully studied. Note that average speed measurements from the whole network (column 'system' in Table 5) is the average speed for all vehicles that have left the system. This is calculated using the mean journey speed for each vehicle. However, it does not consider the effect of virtual queue or the vehicles waiting at the network entrance, which becomes significant in some scenarios. Therefore, the most accurate performance measure that can be extracted from the micro-simulation and that we can rely on is the total time spent or total delay in the network.

The initial results for system delay show a 3% improvement with Alinea with Queue strategy, a 10% improvement with the Coordinated strategy, and a 12% improvement with Coordination and VSL. A surprising observation is that the Alinea strategy is about 3% worse than the No Control case. We further investigated this to identify the reason. It is apparent that in case of metering the queue size on the ramps would increase. With careful inspections, we find out that in case of Alinea the ramp queue at Coppet is so high that that it spills back and blocks the urban roads. This deteriorates the urban area and system travel time extensively and leads to a net loss for the system even though the mainline improvement is the best of all scenarios. Therefore, Alinea is not the best choice for ramp metering in case of mixed urban and freeway networks, specifically when there are conflicts among the origin and destination of different groups of vehicles. It can provide good system performance when the effect of the urban traffic is negligible.

To overcome the shortcoming of Alinea, we propose to utilize Alinea with queue constraint, i.e. *Alinea w/Q*, in which when the ramp queues reach to a predefined threshold, the Alinea ramp meter go into queue override, discharging vehicles at the maximum rate. In this way, the arterial system is taken into consideration during the control stage and it creates a more equitable strategy. Through extensive trial and errors, we found that the threshold about 50% of the ramp size yields the best outcomes.

However, the disadvantage of Alinea w/Q is that there is relatively little storage capacity on the Coppet ramp and high entering demand during the study period. This means that metering at Coppet is only active for short periods before the queue override goes into effect, and as a result Alinea w/Q offers only a small improvement over the No Control case. By distributing the demand that has to be metered among three on-ramps, higher benefits on the mainline can be achieved before the queue constraints are activated. The Coordinated + VSL strategy introduces a reduced speed limit of 80 km/h between Nyon and Coppet which is activated in the onset of congestion. This reduces the flow, creating more gaps for vehicles entering at Coppet to merge and slowing the shockwave.

Table 6 Summary of the results

		Ramp			Area			System	
		Coppet	Nyon	Gland	Coppet	Nyon	Mainline	Total	% change
Average delay (sec)	No control	18.05	2.87	1.65	321.74	33.51	737.66	1230.12*	-
	ALINEA	65.40	9.54	6.14	780.10	34.55	356.52	1270.72*	3.30%
	ALINEA w/Q	49.42	9.26	4.92	288.92	34.12	709.20	1192.83*	-3.03%
	Coord.	71.01	66.95	91.62	368.78	35.96	515.23	1104.81*	-10.19%
	Coord+VSL	66.47	62.72	91.22	331.28	36.88	521.36	1077.67*	-12.39%
Average number of stops	No control	0.06	0.01	0.01					
	ALINEA	0.72	0.19	0.09					
	ALINEA w/Q	0.66	0.19	0.07					
	Coord.	0.56	1.40	1.76					
	Coord+VSL	0.65	1.27	1.64					
Average speed (km/h)	No control	48.00	59.68	61.78			87.62	76.10	
	ALINEA	35.93	54.08	57.89			100.01	75.49	
	ALINEA w/Q	29.75	53.88	58.03			88.15	76.78	
	Coord.	29.50	36.42	36.30			93.32	78.34	
	Coord+VSL	29.98	37.31	36.18			95.05	78.84	
Average queue size (veh)	No control	0.93	0.01	0.02					
	ALINEA	10.57	0.67	0.44					
	ALINEA w/Q	5.60	0.57	0.28					
	Coord.	11.34	8.69	12.56					
	Coord+VSL	9.96	8.08	12.36					
Max queue size (veh)	No control	23.20	4.80	5.20					
	ALINEA	67.20	31.20	21.40					
	ALINEA w/Q	37.60	23.00	14.00					
	Coord.	66.60	65.00	62.00					
	Coord+VSL	66.40	63.00	62.60					

*units of these values are given in vehicle hours

The comparison of the ALINEA w/Q local strategy and the coordinated strategy indicates some noticeable differences. Ramp delays are more equitable in the coordinated case (note that Gland on-ramp has almost zero delays in the ALINEA w/Q strategy). Also, mainline delays are significantly reduced using the storage capacity, which was idle in the upstream ramps. We have to mention that if the arterial delays were omitted from the consideration (as it is done in most simulation analysis) ramp metering improvements would be much higher.

Figure 16-20 show speed contour plots that correspond to different scenarios of the same replication. Similar plots for the other four replications are available in the appendix. Each cell represents one minute on the x-axis and approximately 500m on the y-axis. This allows us to identify congested areas in the freeway. For example, in the No Control plot (Figure 16), the mainline congestion reaches a maximum extent of 5km around 8:00. With Alinea (Figure 17), most of the congestion disappears, although low speed values can still be observed at the interchange locations due to merging and minimum flow allowed in the metering rate. In Alinea w/Q (Figure 18), the congested area around Coppet slightly decreases compared with No Control. This is the impact of the queue constraint. When occupancy starts to increase on the mainline in the onset of congestion, metering is applied at Coppet. This action improves the mainline, but the ramp quickly fills up due to the high flow rate, triggering the queue constraint. The meter now goes into queue override and discharges all the vehicles on the ramp onto the mainline. This platoon of vehicles will have difficulty finding enough gaps to merge into, causing mainline vehicles to brake or merge into the left lane to make space. The maximum extent of the congested region is 4.5km upstream of Coppet. Alinea w/Q does provide some benefit in the offset of congestion, however, as the demand on the ramp is lower and metering can be used to help the mainline return to an uncongested state. With Coordination (Figure 19), the phenomenon of queue overrides is greatly reduced. The extent of congestion is much less than No Control, reaching a maximum extent of 2.5km from Coppet. The statistics show a reduction of around 30% in mainline delay. The effect of VSL is clearly visible in Figure 20 as the block of slower speeds at the onset of congestion. This strategy achieves a similar reduction in mainline delay with less metering (and by extension, less delay at Coppet and Nyon ramps and Coppet arterial roads).

Figures 21-25 show ordered (the one chosen by the controller of the ramp) and actual flow (the real flow of vehicles that actually entered the freeway). No Control (Figure 21) is provided for reference, to show what the entering flow on each ramp looks like. We see that flow on all three ramps is quite variable from one minute to the next. This occurs in part because all three intersections are signalized, so a green light for the left turn movement discharges a platoon of vehicles onto the ramp. This means that even a relatively light ramp metering strategy would help by breaking up the platoons of vehicles created by the arterial signals. In Figure 22 (Alinea), we see that minimum flow is imposed at Coppet from 7:30 to 8 and briefly at Nyon within the same time period. For the rest of the simulation period, there is no restriction. Gland is not metered at all. Alinea w/Q (Figure 23) activates metering at Coppet many times throughout the simulation, but can only maintain this for 1-2 minutes before the queue override is activated. The behavior at Nyon and Gland is similar to regular Alinea.

With Coordination (Figure 24), the controller is allowed to ignore the queue constraint at Coppet for 5 minutes after activation. This produces multiple activations with minimum flow during the simulation. Each time, the queue override kicks in after 5 minutes. Metering rates at Nyon and Gland show a smooth behavior because of the step limits defined in the algorithm. Although queue constraint gets activated in the on-ramps of Gland and Nyon due to the low values of desired occupancy, developed strategy is always limited by the defined step limits and does not produce sudden changes in the metering rate. However, the algorithm is still able to avoid the spillbacks to the arterials, as the demand from Gland and Nyon is not too high. Figure 25 (Coordination+VSL) shows similar behavior to Coordination alone. The use of VSL slightly delays the first activation of metering at Coppet (by about 10 minutes) but otherwise the algorithm is the same so we would expect similar behavior.

Figures 26-30 show the queues for the three ramps. The measure is actually number of vehicles on the ramp, so they are not necessarily stopped. Figure 26 (No Control) shows that queues do form on the ramp, even without metering. This occurs late in the simulation (8:15-8:45), and only at Coppet. The plots for Nyon and Gland suggest that vehicles are free-flowing for the entire simulation. In Figure 27 (Alinea), we observe that the Coppet ramp queue plateaus around 65 vehicles. In fact, the queue is probably larger than this, but this method of data collection is unable to count the length of a queue that has spilled back beyond the ramp itself. There is a brief buildup of queue at Nyon (7:30-7:45) but the ramp does not spill back on to the arterial. (Capacity at Nyon is around 70 vehicles.) Figure 28 (Alinea w/Q) shows a significant queue on the Coppet ramp between 7:30 and 9. The spike around 8:30 represents a situation where the controller is in queue override but the queue continues to build because congestion on the mainline makes it difficult to discharge vehicles. Queues at Nyon are very similar to Alinea. Figure 29 (Coordination) shows similar queue profiles at the three ramps, indicating that the controller is working as expected. All three ramps go into queue override multiple times during the simulation. Figure 30 (Coordination + VSL) shows the delay in initial activation previously seen in the ordered-actual plots. Otherwise, the performance is similar to Coordination.

Table 7 shows the maximum extent of the mainline congestion in the base and +10% demand cases. The same information is presented visually in the speed contour plots. The average extent of congestion along the freeway stretch can be calculated using the spatiotemporal congested area that can be observed in speed contour plots and the congestion duration. However, as the start and end times of congestion vary from one scenario to another, we believe it is not an accurate performance measure. We suggest the reader refer to the total delay values in the mainline to see an equivalent and accurate performance measure. On the other hand, the maximum extent of congestion defines the potential congested sections in the freeway in its worst case.

Table 7 Extent of Congestion, Replication 44601

Extent of congestion	base	+10%
No control	5 km	8 km
ALINEA	1 km	1.5 km
ALINEA w/q	4.5 km	8 km
Coord.	2.5 km	4.5 km
Coord+VSL	2 km	6.5 km

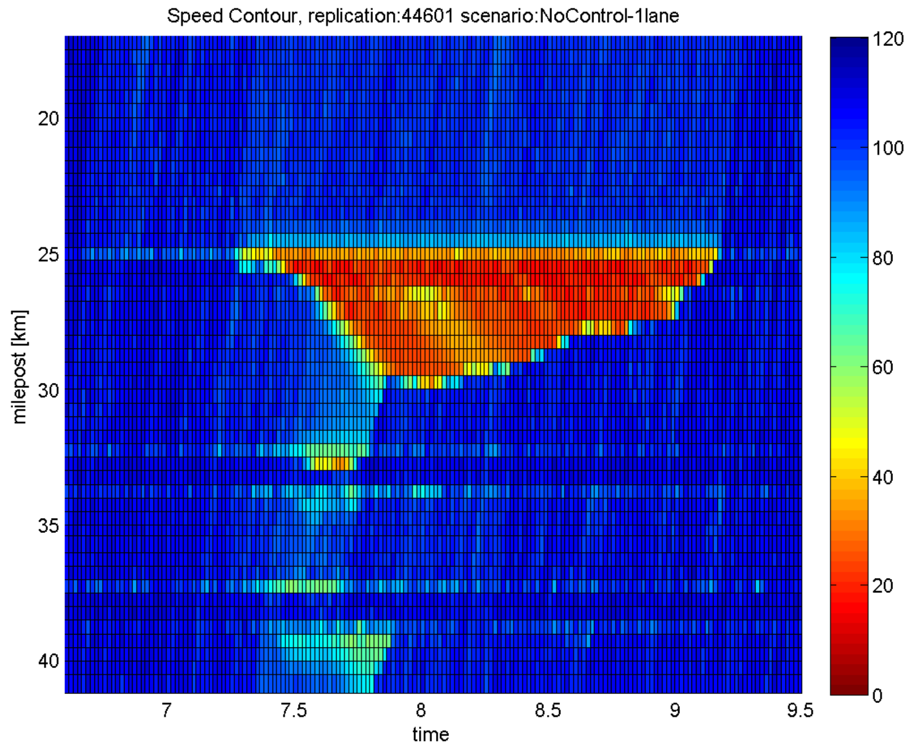


Figure 16 Speed Contour Plot, No Control

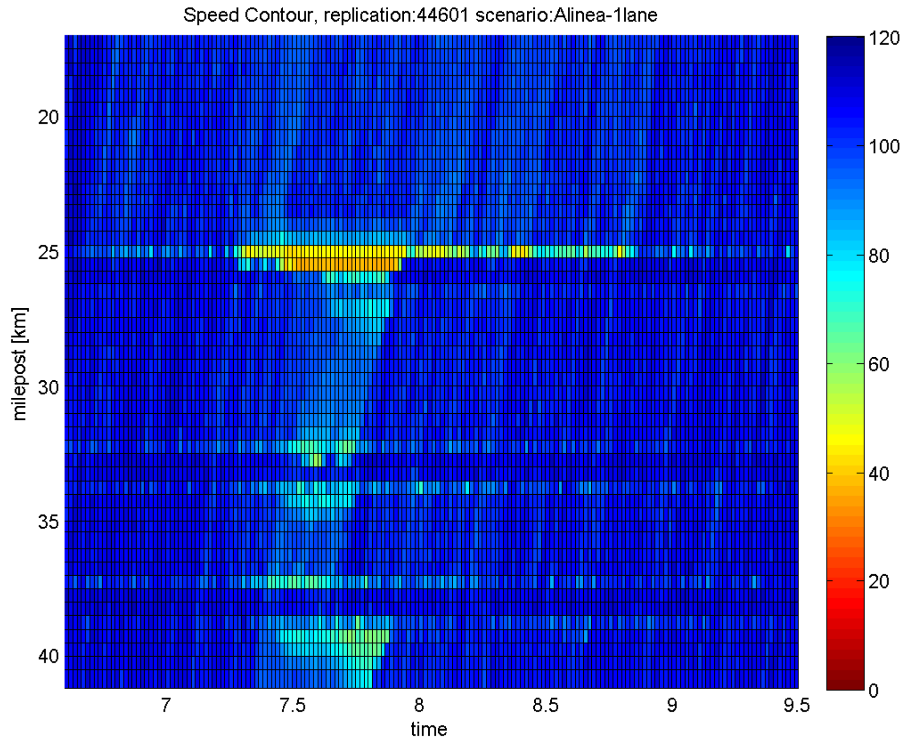


Figure 17 Speed Contour Plot, Alinea

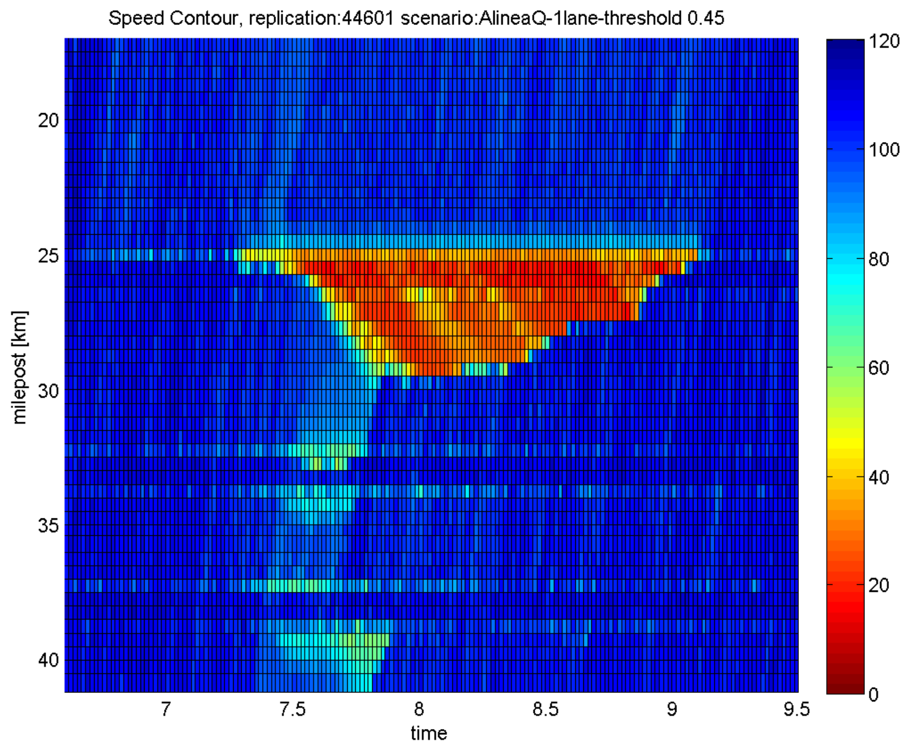


Figure 18 Speed Contour Plot, Alinea w/Q

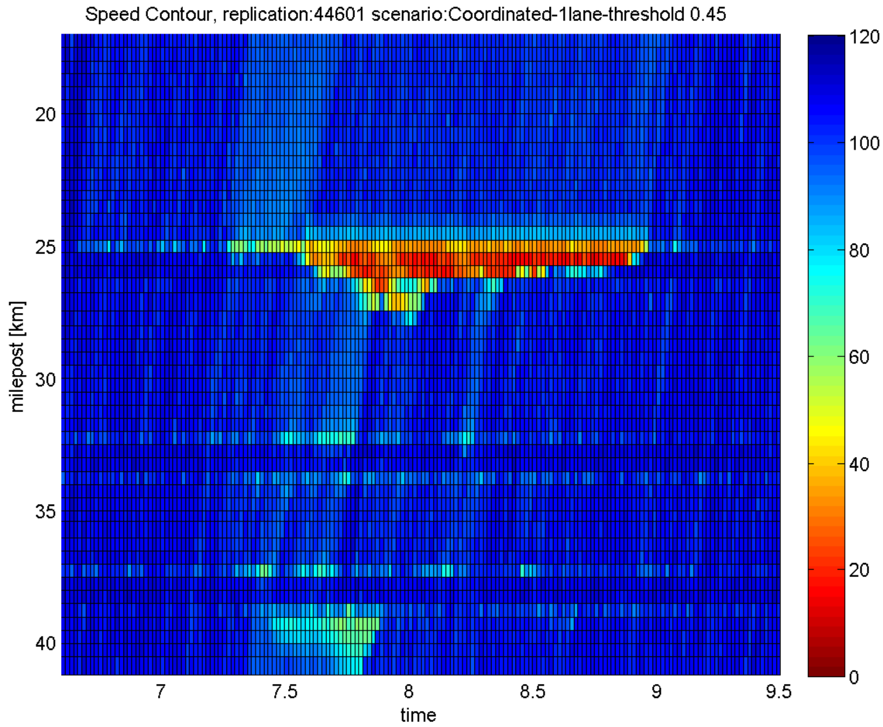


Figure 19 Speed Contour Plot, Coordination

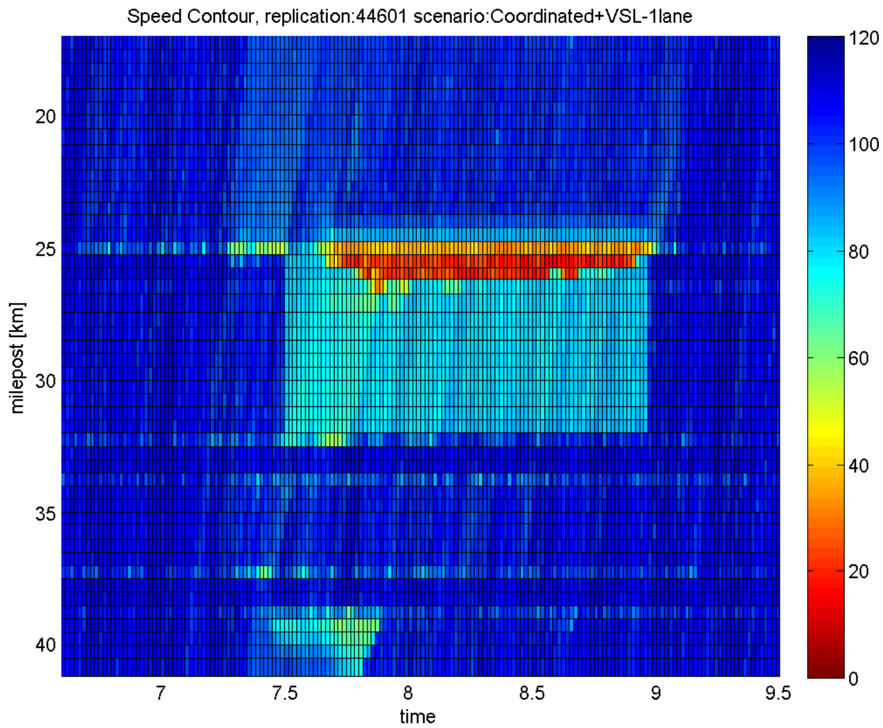


Figure 20 Speed Contour Plot, Coordination + VSL

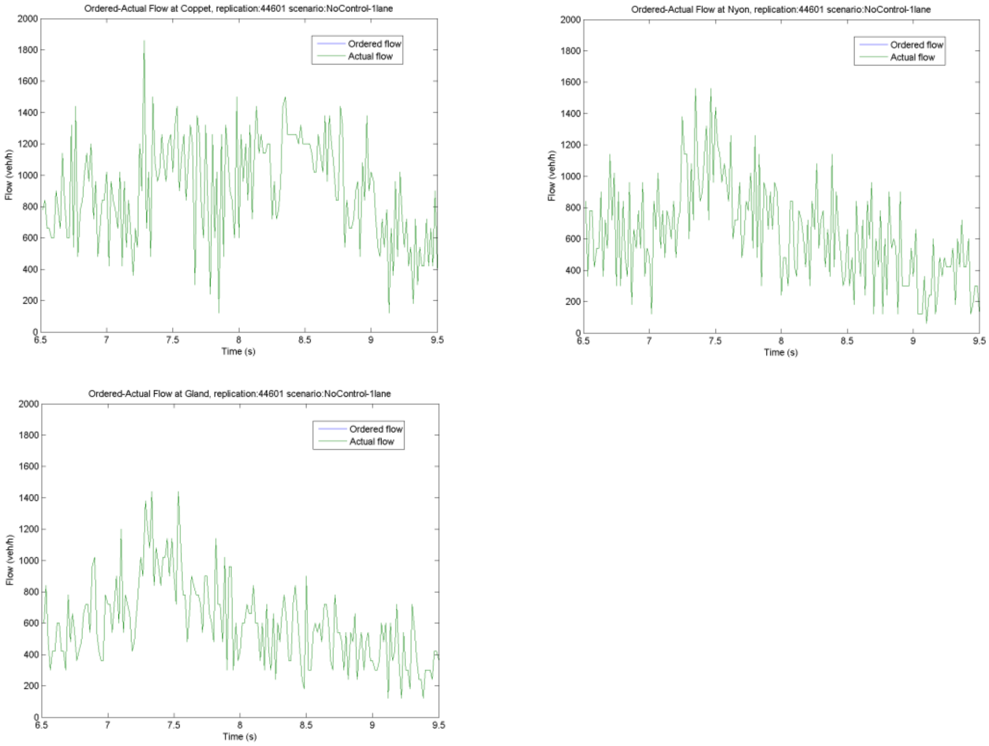


Figure 21 Actual Flow, No Control

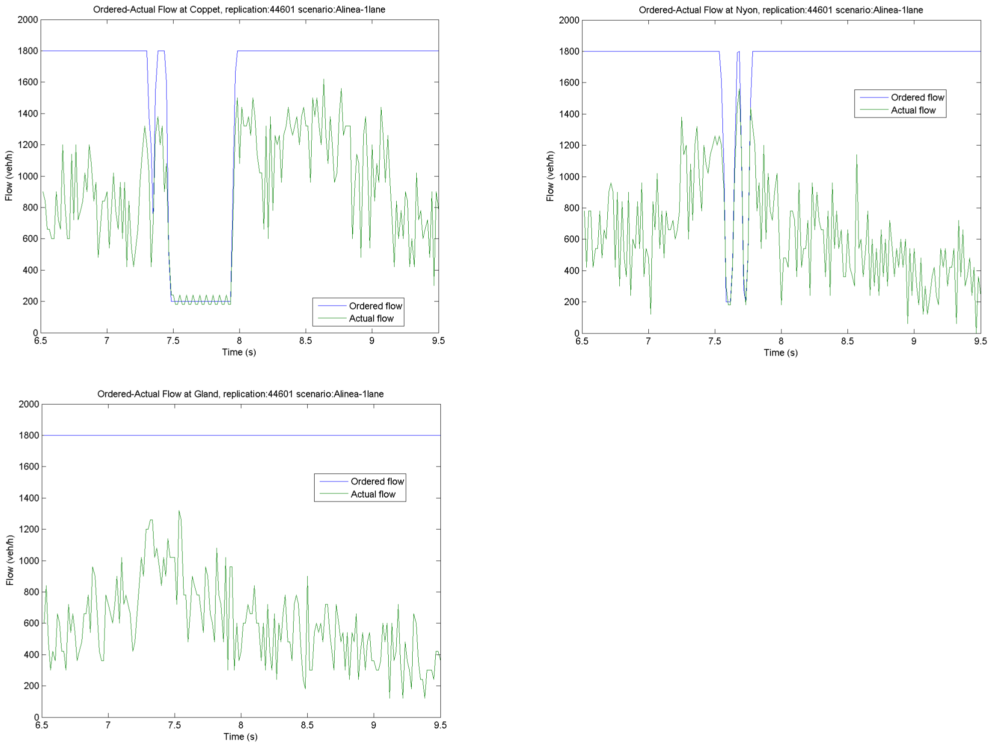


Figure 22 Ordered-Actual Flow, Alinea

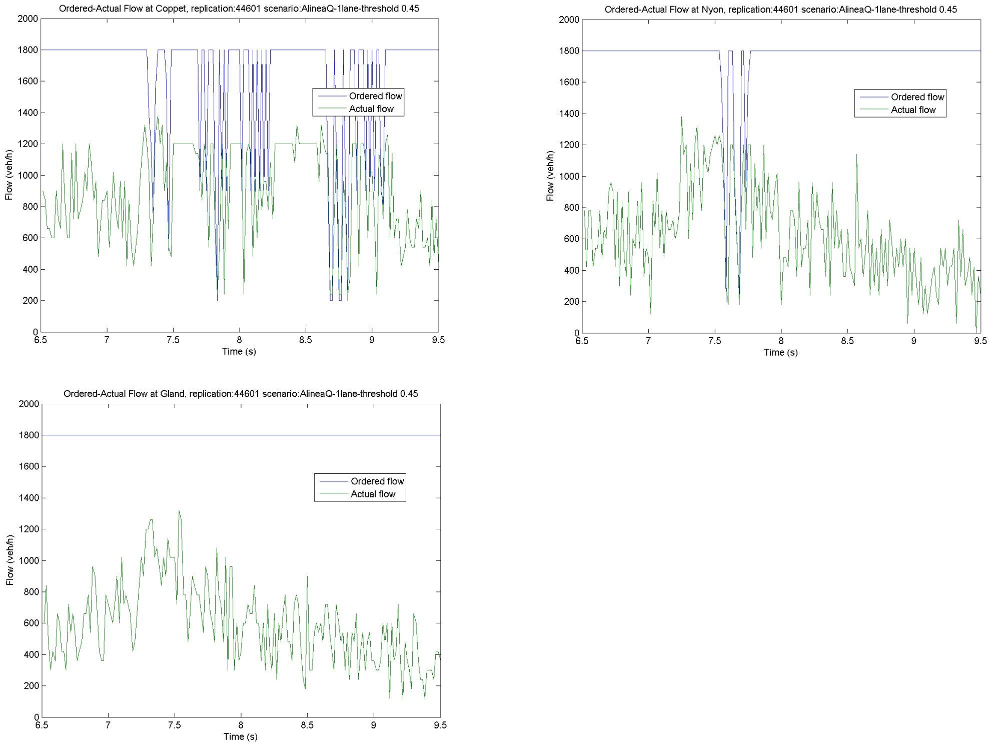


Figure 23 Ordered-Actual Flow, Alinea w/Q

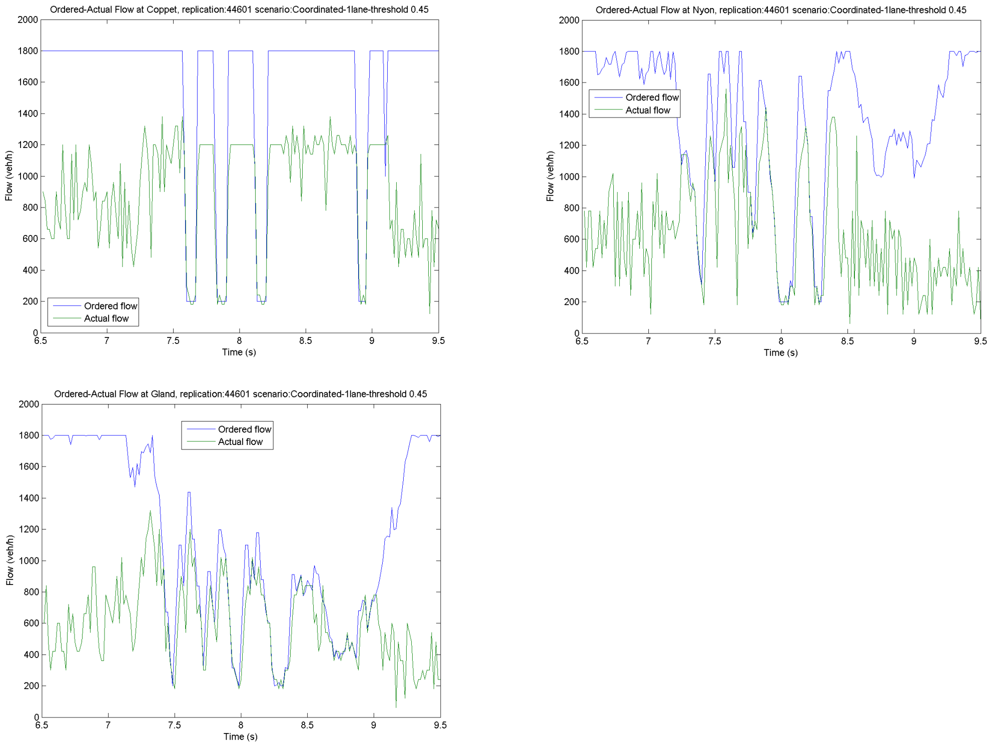


Figure 24 Ordered-Actual Flow, Coordination

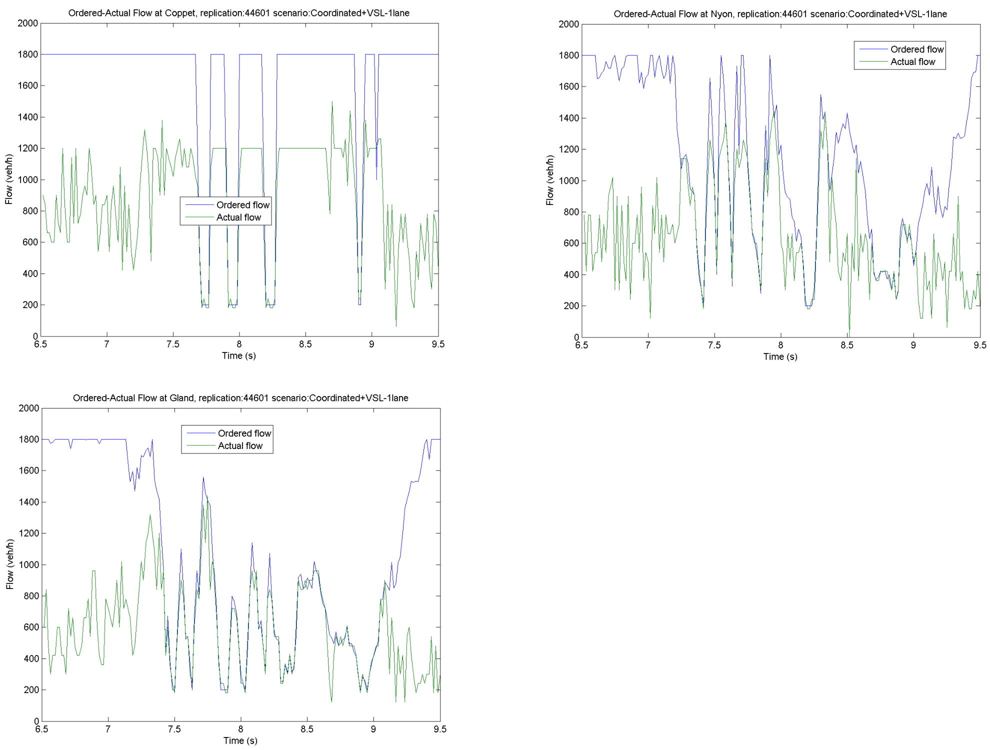


Figure 25 Ordered-Actual Flow, Coordination + VSL

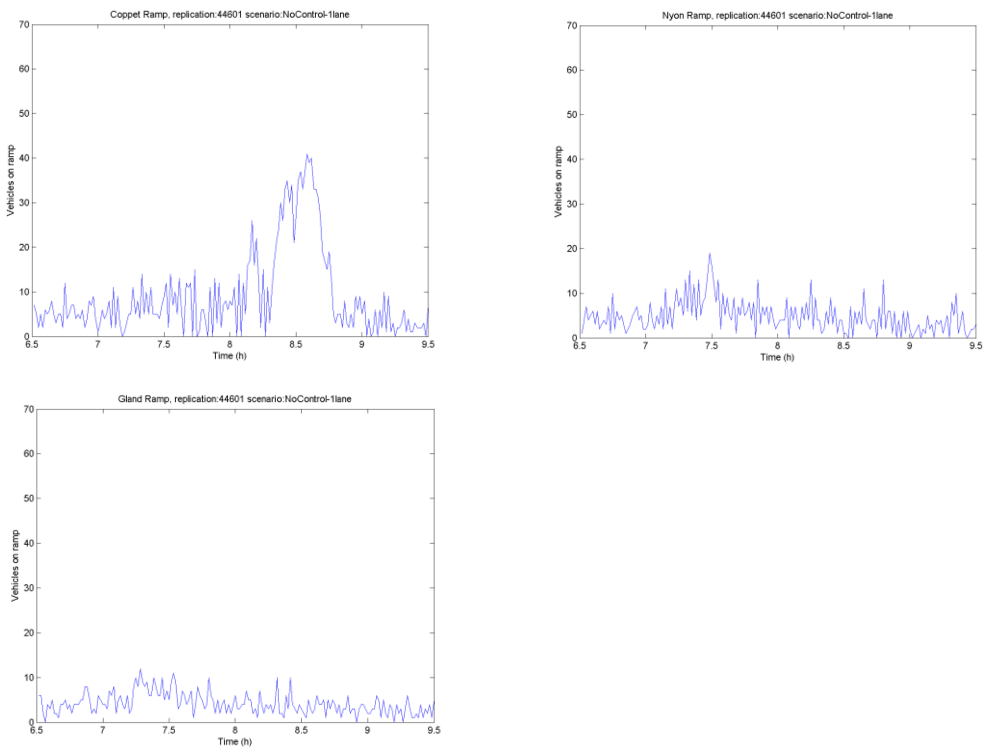


Figure 26 Ramp Queues, No Control

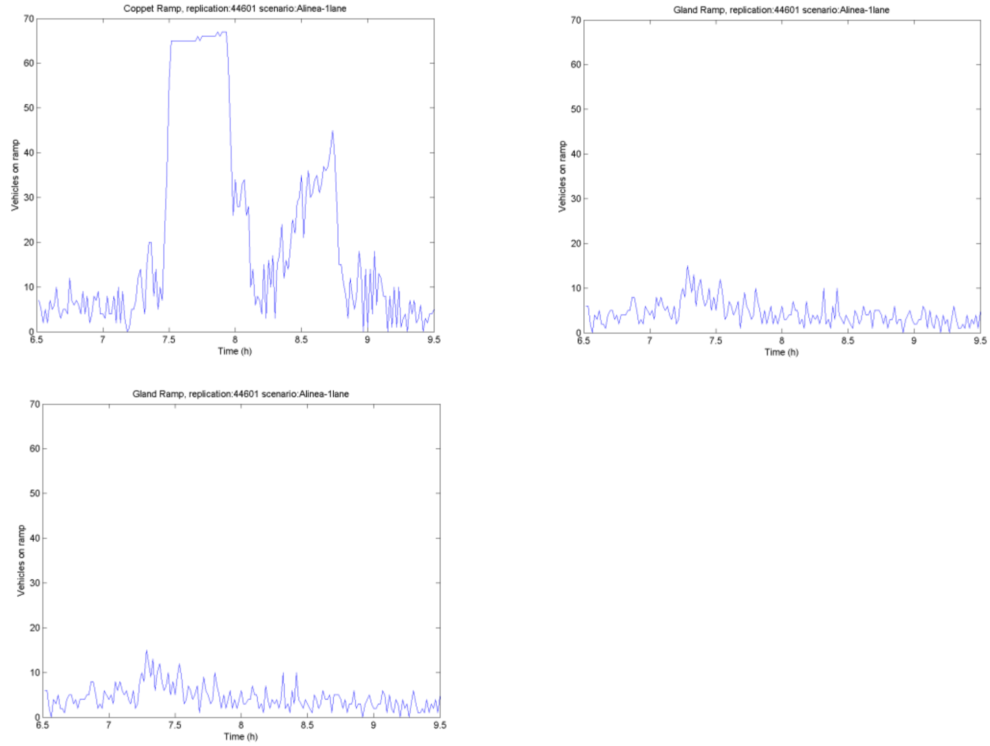


Figure 27 Ramp Queues, Alinea

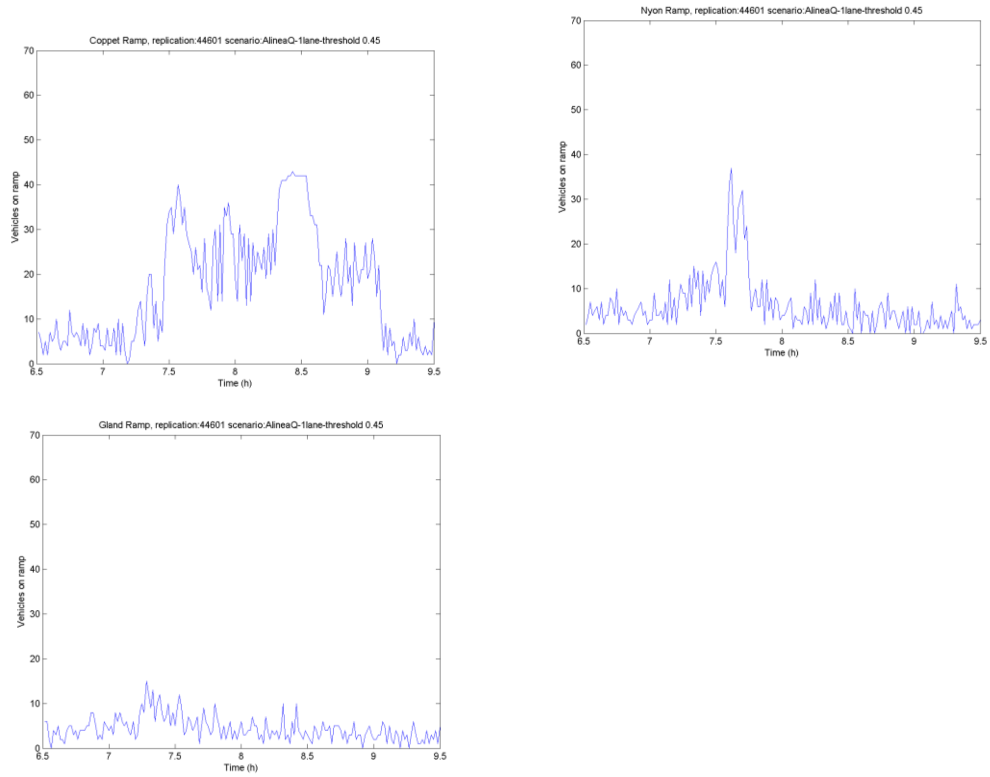


Figure 28 Ramp Queues, Alinea w/Q

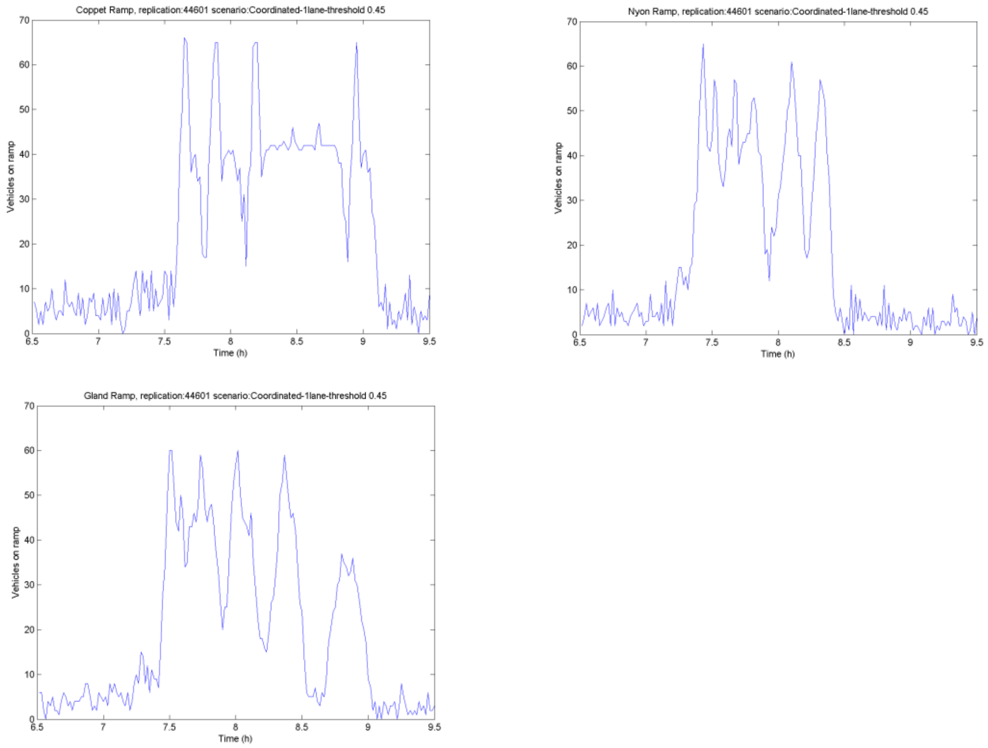


Figure 29 Ramp Queues Coordination

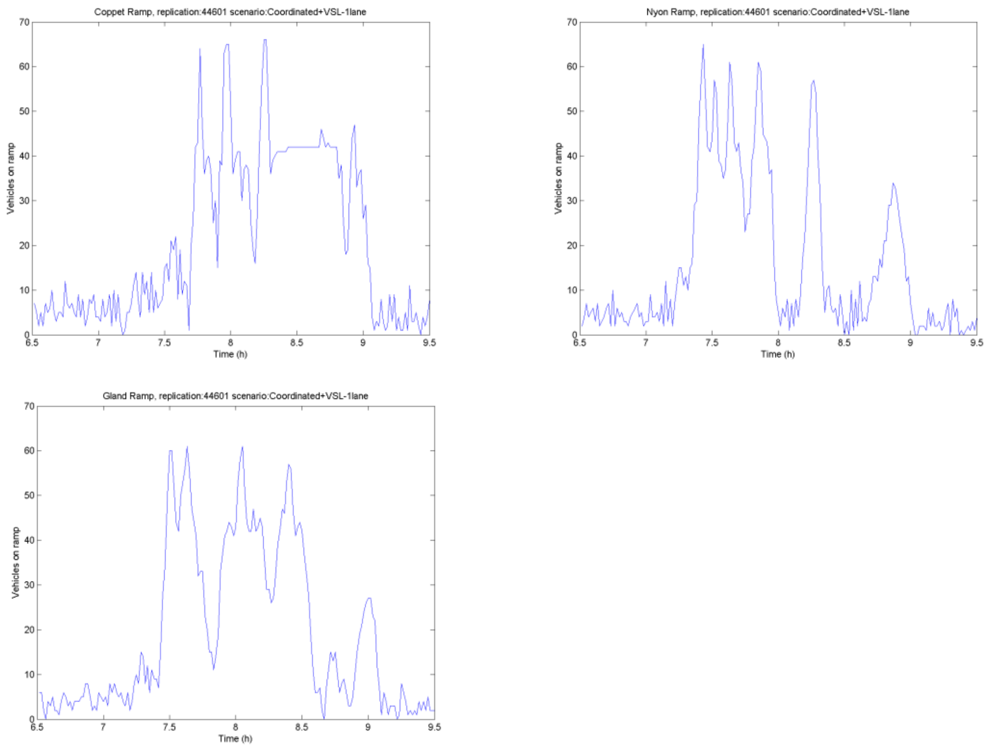


Figure 30 Ramp Queues, Coordination + VSL

6.1 **Equity**

Another dimension to consider is equity. Ramp metering, by definition, uses control to move from user equilibrium to system equilibrium. The result is better overall, but it may not be better for every individual user. Ramp metering generally penalizes short freeway trips and benefits long trips. We provide the following plots, Figures 31-35 looking at de-

lay and Figures 36-40 looking at the travel time of various origin-destination pairs as a way to look at the winners and losers of each scenario.
Figures 31 and 36 (No Control) show that mainline (vehicles originating upstream of Gland and going to Geneva), Gland, and Nyon all have the same shape. The bottleneck is at Coppet, so these three groups experience the same delay. Coppet vehicles, on the other hand, are the ones causing the bottleneck but only experience about half the delay as the other groups. Figures 32 and 37 (Alinea) show that the delay experienced by the Coppet group is extreme from 7:30-8:30. The other three groups are more or less equal. Figures 32 and 38 (Alinea w/Q) look similar to No Control. The Coppet group experiences a little more delay, especially around 8:30, but still less than the other groups. Figures 34 and 39 (Coordination) show a much more equal distribution of delay. The oscillations up and down are the result of individual ramps going into queue override (so a vehicle which arrives at the right moment could get the reduced travel time on the mainline without the wait at the meter). Figures 35 and 40 are similar to Coordination, except that mainline group is much better off from 8:15-8:45 and the Gland group is penalized more than Co-ordination. The reason for this is not clear, but it is possible that by delaying the start of ramp metering, VSL allows metering at Gland to continue for longer before reaching the queue constraint.

Table 8 contains the maximum wait time at each ramp in the different scenarios. According to this metric, Alinea is the most inequitable scenario, while Coordination has similar delays for the three ramps. In other areas that have implemented ramp metering (most notably the Minneapolis-St. Paul area), a maximum wait time is part of the control and may be more restrictive than the queue constraint.

Table 8 Maximum Wait Time at Ramps

	90^{th} Percentile Wait Time [sec]		
	Coppet	Nyon	Gland
No Control	8	6	3
Alinea	611	16	5
Alinea w/Q	99	16	5
Coordinated	197	206	270
Coordinated+VSL	75	165	313

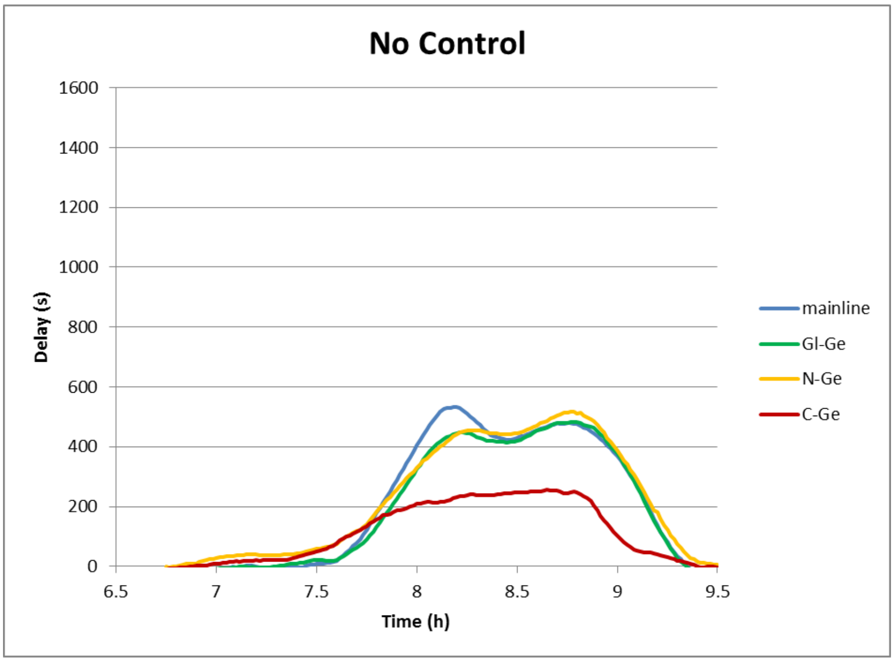


Figure 31 Delay, No Control

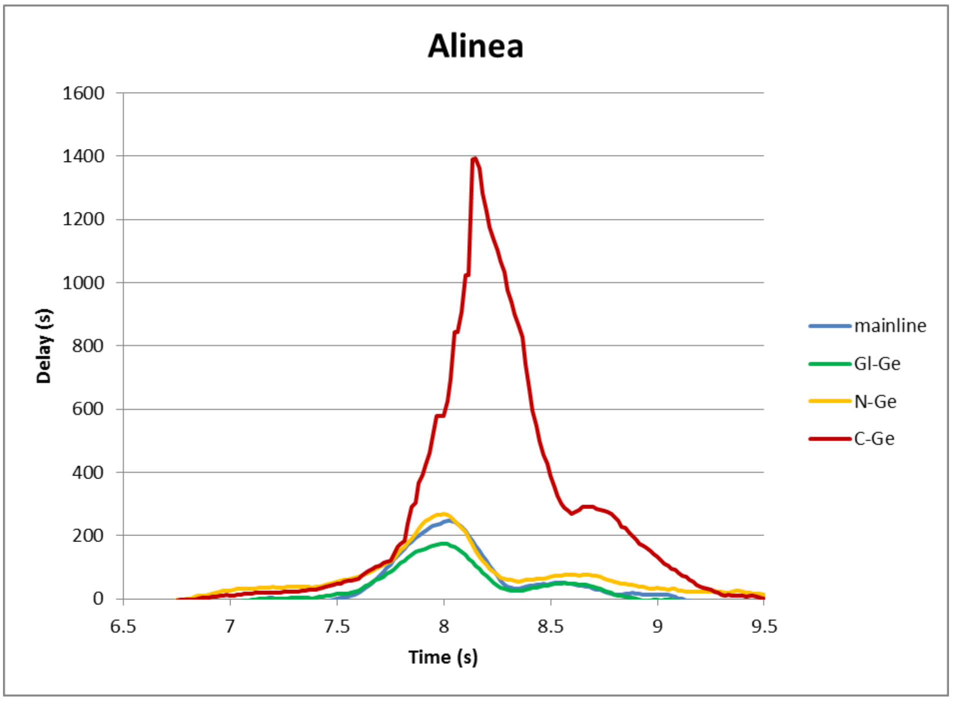


Figure 32 Delay, Alinea

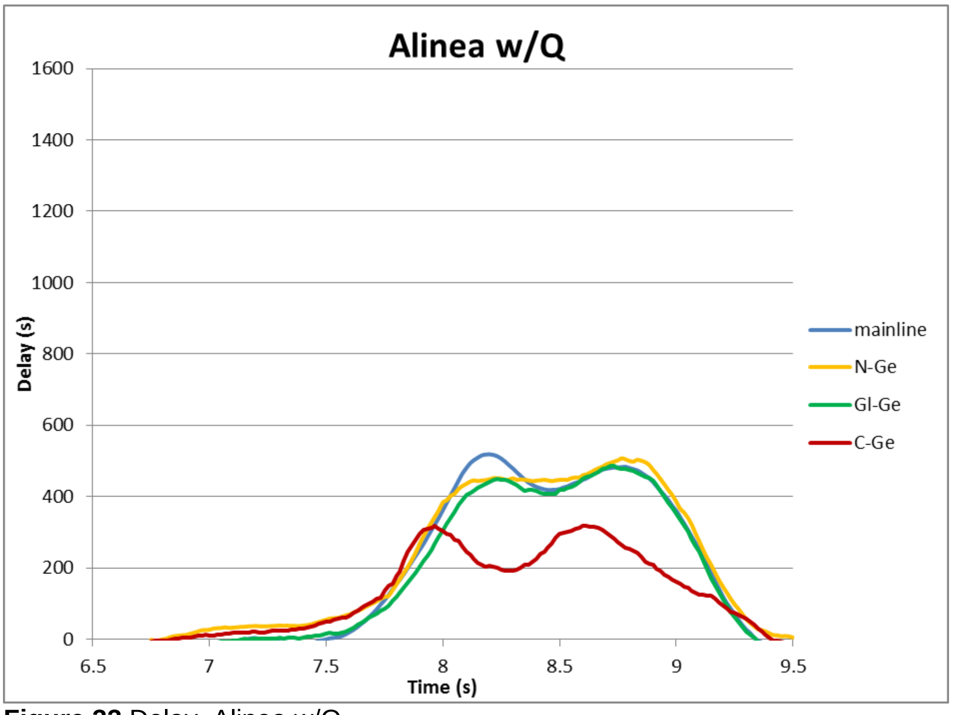


Figure 33 Delay, Alinea w/Q

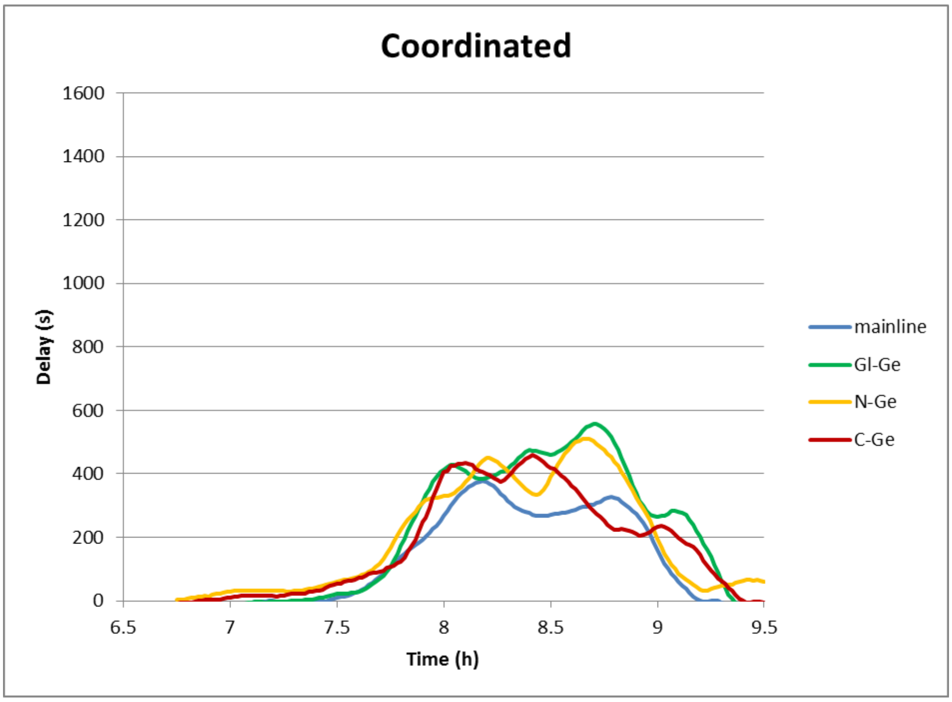


Figure 34 Delay, Coordinated

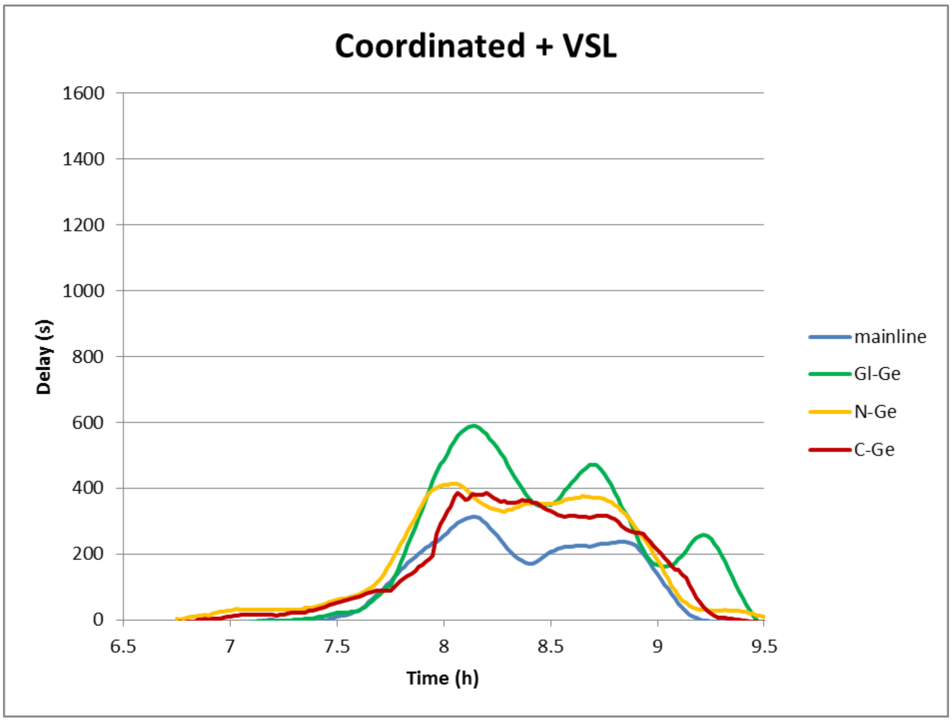


Figure 35 Delay, Coordinated + VSL

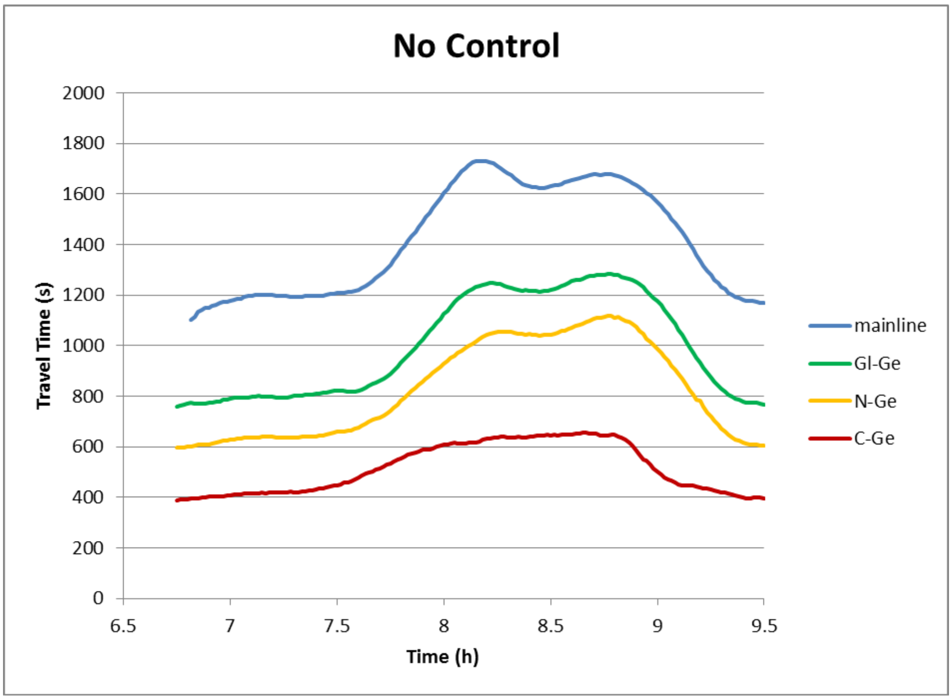


Figure 36 Travel Time, No Control

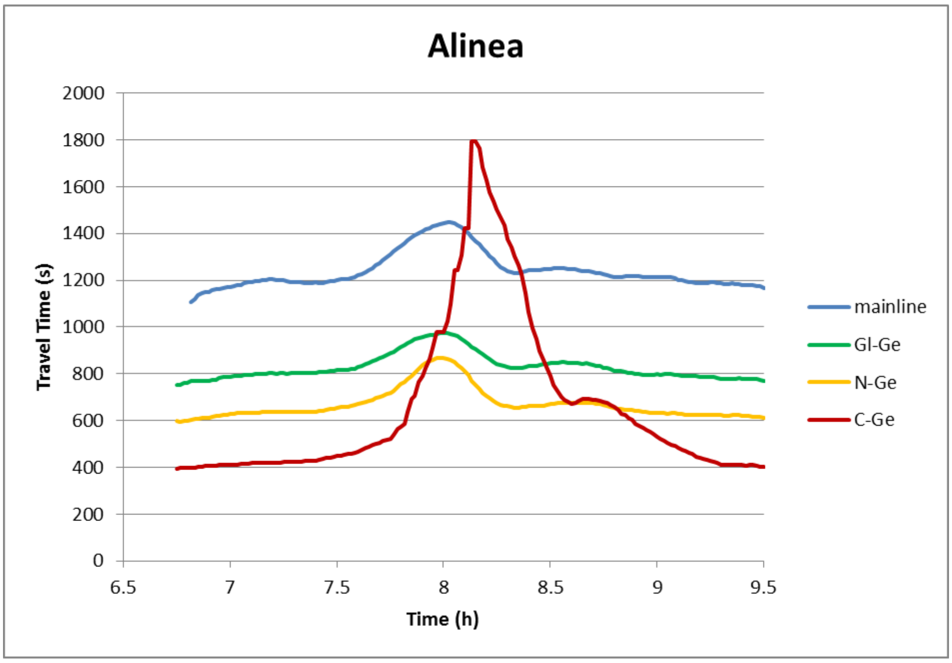


Figure 37 Travel Time, Alinea

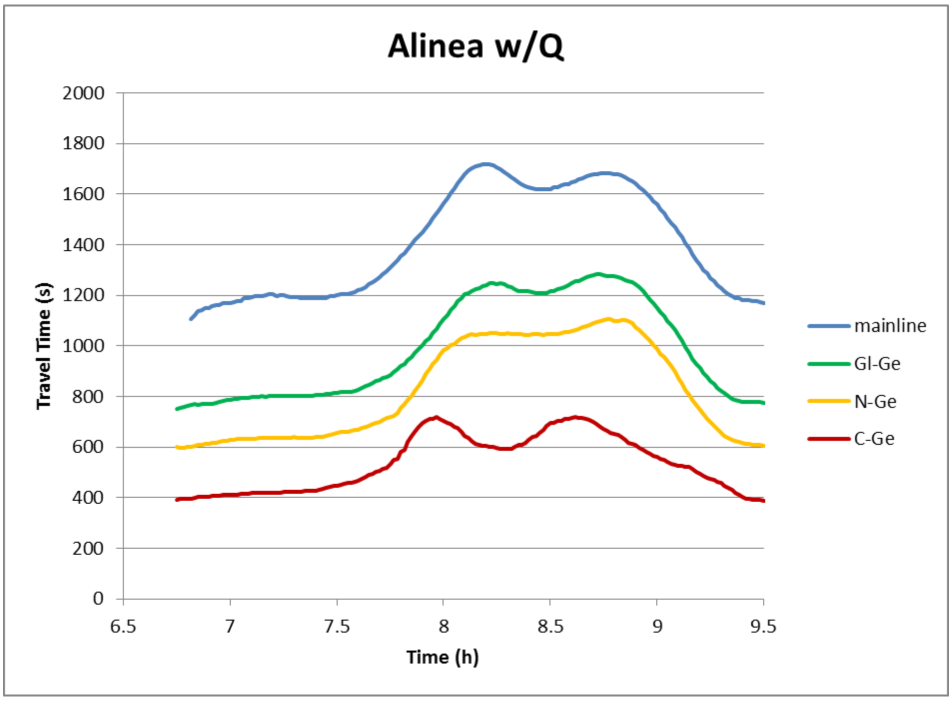


Figure 38 Travel Time, Alinea w/Q

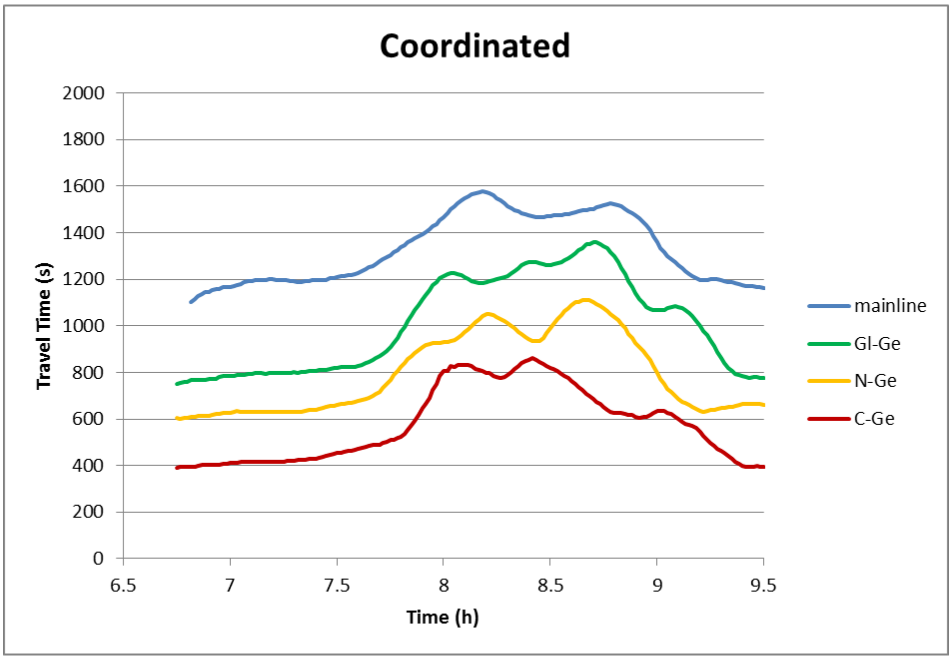


Figure 39 Travel Time, Coordinated

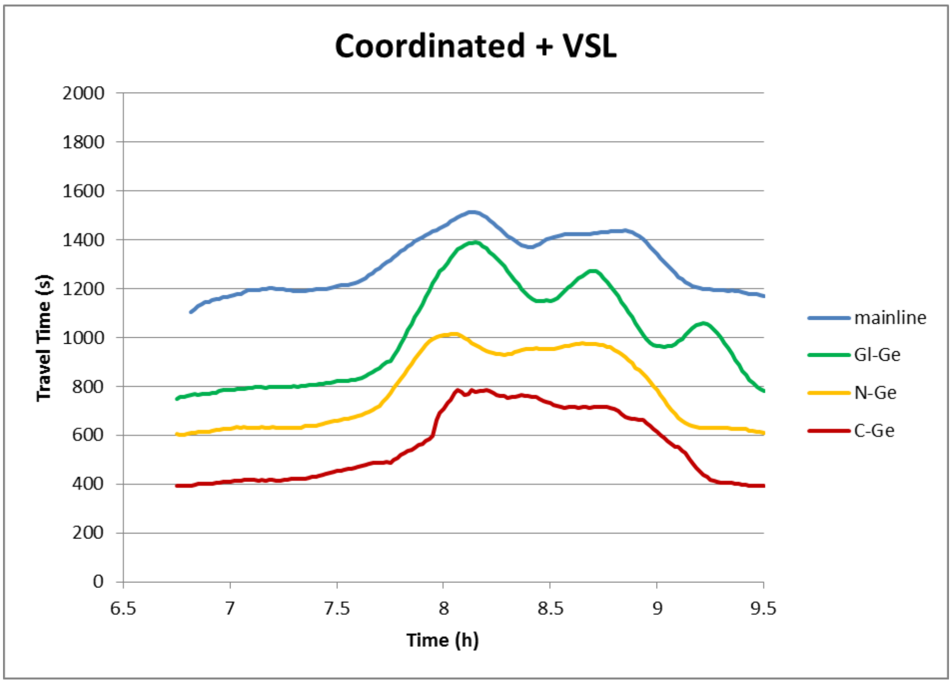


Figure 40 Travel Time, Coordinated + VSL

6.2 Sensitivity Testing

The above results, which we will refer to as the base case, are all simulations of the real traffic demand observed on 19 April 2013. This day was the best available in the set of detector data and manual counts collected in April 2013. However, traffic demand experiences both day-to-day stochasticity as well as seasonal variations. Any field implementation of ramp metering would need to perform well under a range of traffic conditions (although manual intervention might be needed for cases like construction and incidents). Therefore we include this section on sensitivity testing to see how the algorithms respond to changes in traffic demand.

Loop detector data was available for the period 1/1/13-1/10/13, covering approximately 9 months. This included the four detectors near Coppet, Nyon, Gland, and Rolle. We took a simple measure, adding the flows registered at the four detectors from 6:30-9:30 every day. Figure 41 presents this measure across 9 months. Weekdays and weekends are clearly visible, as well as seasonal variation (low traffic in summer, reaching a minimum the first week of August). A zero value means that data for one of the four detectors is missing (which is the case for several weeks in May and June). We take 20,000 as a threshold, since all non-holiday weekdays are above this level, and produce a sorted graph (Figure 42). The value for April 19 is 36,400, placing it in the middle of this group, slightly above the median. Based on these graphs, it seems reasonable to produce test cases with -10% and +10% demand (32,760 and 40,040, respectively, using this measure). We emphasize that the results from these cases are intended for sensitivity analysis only. These cases are *not calibrated to real data*, meaning that the simulation results are not accurate enough. These control strategies may perform better in reality under similar conditions.

First, we look at the -10% demand case. It is important to note that even in the base case congestion is relatively light compared to freeways in the US, France, and other countries where ramp metering is currently in use. This case is also uncalibrated (to real data) so results may not be as reliable. The weekdays with the lightest demand (represented by this case) may not need ramp metering at all if the system performance is acceptable without it. This could be accomplished with an activation condition separate from the ramp metering control logic. We observe that the total travel time for No Control, Alinea w/Q, Coordinated, and Coordinated + VSL are all approximately the same (less than 1% variation). Although there is no systemwide improvement from any of the ramp metering cases, there are shifts in delay within the system. Mainline delay is reduced by around

20% with Alinea, Coordinated, and Coordinated + VSL, while delays on the ramps and the Coppet arterial network increase. Although the system travel time is the same, these results show a change in utility which favors the mainline through traffic over the vehicles entering at the ramps in the corridor (as well as some 'collateral damage' to arterial traffic at Coppet). This may be desirable anyway, as a consistent policy of prioritizing mainline through traffic over entering traffic at these ramps would have the effect of encouraging the use of other modes and alternate routes.

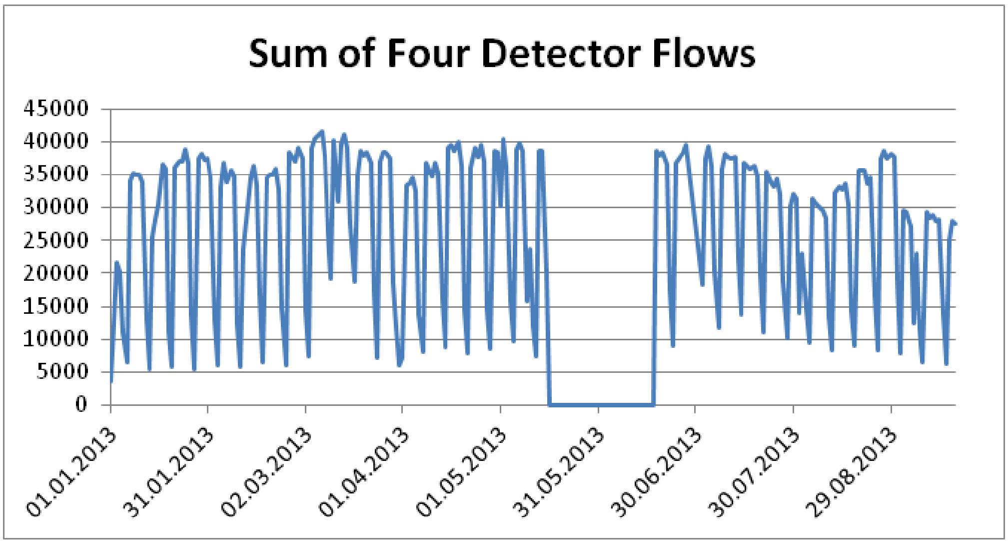


Figure 41 Detector flows by date

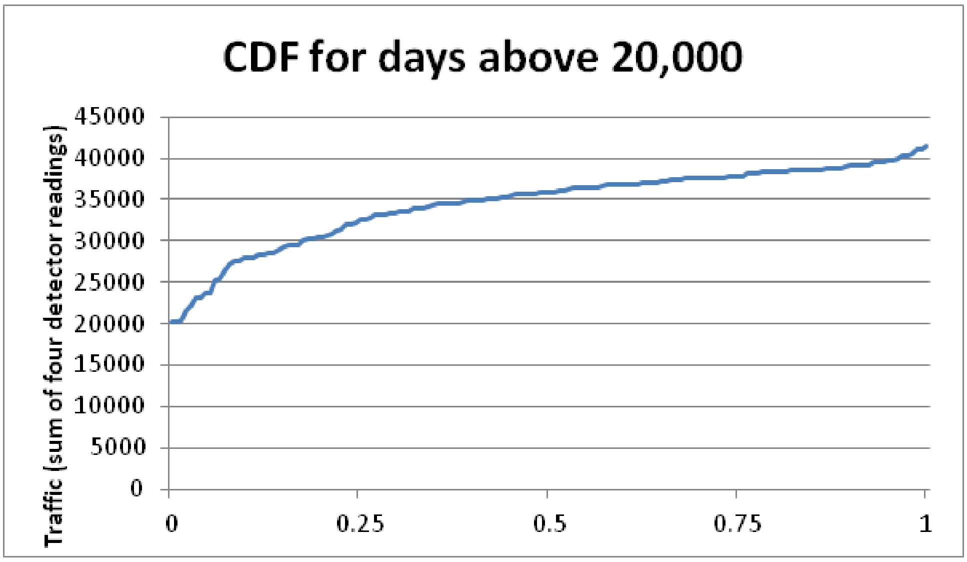


Figure 42 Sorted detector flows

Like the -10% demand case, system delay and travel time with +10% demand are essentially the same (less than 1% variation) for No Control, Alinea w/Q, Coordination, and Coordination + VSL. The Alinea strategy is very effective at reducing mainline delay (66% reduction), but results in a system performance that is worse overall (5% increase in total travel time) due to the impact on the Coppet arterial roads from queue spillback from the ramp. Alinea w/Q offers little improvement over No Control because the increased demand means that the queue constraint is reached even faster than in the base case. Coordination and Coordination + VSL both produce a 25% reduction in mainline delay, although this improvement is balanced out on the system level by the increase in delay on the three ramps as well as the Coppet and Nyon arterial roads. Similar to the -10% case, we caution that this scenario is uncalibrated so the results may not be as reliable as the base demand.

The same statistics for an alternate +10% demand case are shown in Table 9. Speed contour plots for the +10% case are available in the appendix. This time, there is an improvement systemwide with a reduction in total travel time of around 4% for both Coordinated and Coordinated + VSL. For this case, the queue constraint has been removed in Gland, leading to high ramp delays there but better performance for the system as a whole. The reduction in mainline delay is 45% with Coordination and 46% with Coordination + VSL, compared to 25% with the Gland queue constraint. These results suggest that, while the queue constraint in Gland should probably be used in normal conditions to maintain equity between different users, it could be removed in heavy congestion to improve the system. In reality, drivers wishing to use the ramp at Gland also have the options of taking arterial roads to Nyon and using the ramp there or taking arterial roads all the way to their destination. These options are not considered in the simulation, but could reduce the effective delay for a driver at Gland below the value listed in this table.

Table 9 Alternate control case for +10% demand

		Ramp			Area			System	
		Coppet	Nyon	Gland	Coppet	Nyon	Mainline	Delay (veh.h)	% change from No Control
Average delay (sec)	No control	25.46	5.08	7.33	604.25	57.07	1356.42	2261.95	-
	ALINEA	100.20	22.01	16.53	1839.83	84.54	463.65	2526.77	11.71%
	ALINEA w/Q	62.36	23.57	15.21	577.14	71.21	1346.88	2270.69	0.39%
	Coord.	80.14	78.37	256.30	828.74	72.77	750.64	2121.88	-6.19%
	Coord+VSL	78.86	74.26	264.68	813.92	65.65	738.47	2098.28	-7.24%

7 Sensor placement for a potential field test

The existing sensors in the study site are not sufficient for a direct field implementation. The sensors should allow for a direct estimation of the various variables and parameters that are embedded in the coordinated ramp metering and variable speed limit strategy. More specifically loop detectors are required in the on-ramps to facilitate the estimation of queues, such that at least two detectors at two extremes of the ramp are needed to provide an accurate estimate of the number of vehicles in the ramp. The arterial sensors should be able to communicate with the ramp metering central controller the level of congestion in arterials to guarantee smooth traffic conditions of all conflicting movements in the area. Mainline loop detectors are needed to estimate more accurately the level of congestion in the proximity of the merge. The existing sensors while allow for an accurate estimation of congestion, they are located in quite some distance from the merges, which will significantly delay propagation of shockwaves, the activation and the deactivation of the strategies. Specifically, to monitor the traffic condition of the merge area and observe the traffic breakdown, a loop detector downstream of the merge area (in proximity of end of the acceleration lane) is essential. For the successful implementation of the variable speed limit strategy more frequent sensors are required in the freeway intersection upstream of the active bottleneck. VSL signs are also required to provide information to the users for the desired speed, for example every 500 meters. Driver adaptation to these dynamic speed limits should be investigated during the field test. Figure 43 presents the location of sensors for a successful implementation. While the recommendation of specific types of sensors is beyond the scope of the project, there are some new type of sensors (still with electromagnetic field measurement) that tend to replace loop detectors and operate with WiFi technology and are easy to be installed without strongly influencing traffic conditions. Note that an important feature of all sensors is that they need to transfer the measured variables in real time in a central controller that will calculate the desired metering rates and speed limits.

Figure 43 Detector Stations on A-1 Freeway

The following is a list of new detector locations:

Detector Name	Description of Location
Gland ramp inflow detector	Approximately 40m from centerline of Avenue du Mont Blanc
Gland ramp outflow detector	Immediately downstream of ramp meter
Gland mainline detectors (2)	20m downstream of merge point (left and right lanes)
Nyon ramp inflow detector	Approximately 45m from centerline of Route Blanche
Nyon ramp outflow detector	Immediately downstream of ramp meter
Nyon mainline detectors (2)	20m downstream of merge point (left and right lanes)
VSL gantries	Between Coppet and Nyon. 1km spacing would require 7 gantries plus an additional sign downstream of Coppet merge point to end speed restriction.
Coppet ramp inflow detector	Approximately 40m from centerline of Route de Divonne
Coppet ramp outflow detector	Immediately downstream of ramp meter
Coppet mainline detectors (2)	20m downstream of merge point (left and right lanes)

8 Conclusions

A new coordinated, traffic-responsive ramp metering algorithm with variable speed limits (VSL) considerations has been designed for Swiss freeways based on density measurements, rather than flows. Our test results based on detailed micro-simulations indicate that the feedback coordinated algorithm succeeds in (i) delaying the onset of breakdown, (ii) accelerating system recovery when ramp metering is unable to retain uncongested conditions in the mainline due to the violation of maximum allowable ramp waiting time and (iii) improves freeway and ramp performance compared with the no control case and state-of-the-art ramp metering algorithms.

The main results/conclusions of the project that are described in details in the previous sections are;

- The developed strategy of coordinated ramp metering with variable speed limits is able to reduce delays for all users in the system by an average of 8-12% (considering also the drivers that have to wait at the ramps);
- Equitable treatment is provided for all drivers in transportation networks and no users are unduly penalized by the control strategy.
- The developed strategy retains high speed conditions on the mainstream freeway to the maximum possible extent (postpone freeway breakdowns and accelerate recovery times), while treating ramp users well by avoiding long queues and spillback to the city networks.
- Data needs, amount of sensors and optimal sensor locations in freeway and ramps to efficiently observe level of congestion and successfully apply an active traffic management scheme are described
- The combined strategy regulates the input demand of the freeway system so that a truly operationally balanced corridor system is achieved.
- Recommendations and requirements for a successful deployment are provided.
- To study the effects of varying traffic demand patterns, occurrence of incidents, detector malfunctions, and other relevant issues, additional sites should be selected for testing. This additional testing will allow more in-depth evaluation, parameter optimization, and potential improvements for the new strategy. A field test implementation of the resulting control strategy, is essential for refinements before a large scale deployment in the Swiss freeway network, as simulations invariably include untested assumptions.

Simulation results for the morning peak of the Coppet bottleneck of A1 freeway (direction Geneva) are very promising. This is a challenging case study due to the short length of on-ramps and also a considerable amount of traffic that utilizes the arterial network without entering the freeway. The developed coordinated strategy was successful in treating equitably most of the users in the system and distributing the delays and queues in all on-ramps under consideration. While a field test can shed more light in the potential delay savings for the car users, this analysis showed that with the current scenario (or even with scenario of higher demand), delay savings are in the range of 8-12% for the whole system (including the additional delays for non-freeway users). This improvement is in the range of 100-150veh-hours of travel for only the morning peak of one active bottleneck with 3 on-ramps. From a conservative and approximate analysis shown in figure 42, this strategy can be active and beneficial 100-150 days a year, which could result in about 15,000 veh-hours of delay savings for Swiss travellers for only one bottleneck.

The cost of implementation of a ramp metering strategy with variable speed limits is quite small compared to the construction of new infrastructure and can be a useful alternative or a complementary strategy in many cases of active bottlenecks. Careful consideration should be given to space constraints especially when the ramps are in the proximity of the city centers. The developed strategy showed that is capable of redistributing the queue sizes according to the available storage and avoid strong spillbacks in the arterial network.

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Annexes

Appendix

I.1 Calibration Figures

I.1.1 No Control Case

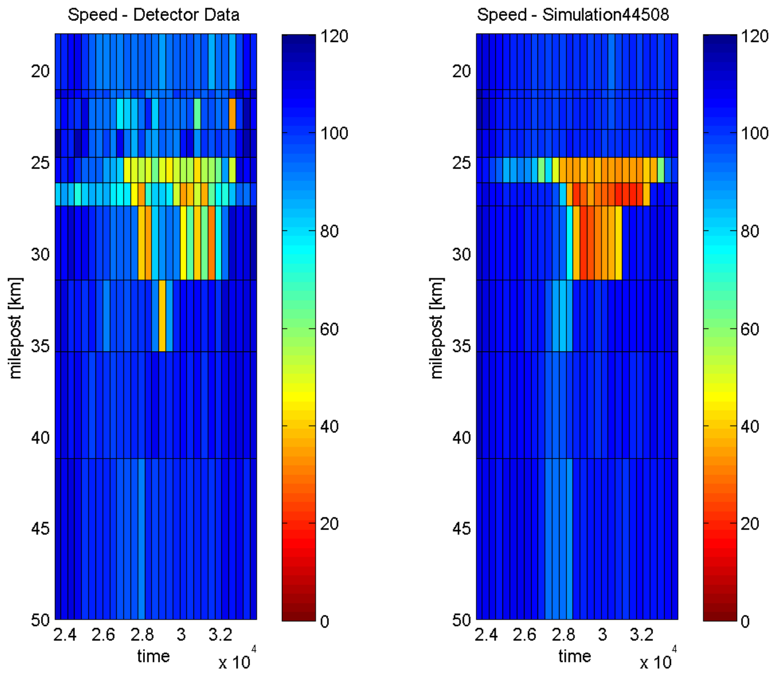


Figure I.1.1.1 Calibration for replication 44508

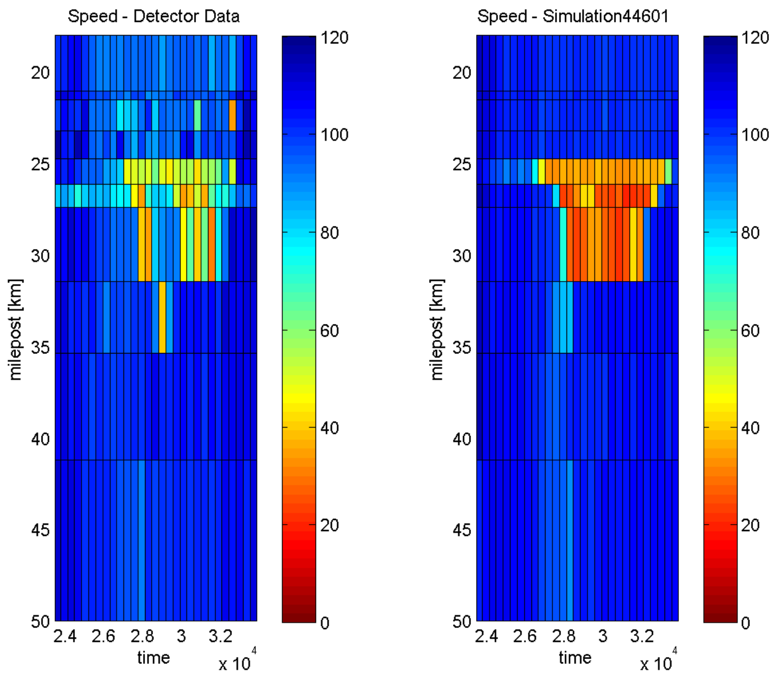


Figure I.1.1.2 Calibration for replication 44601

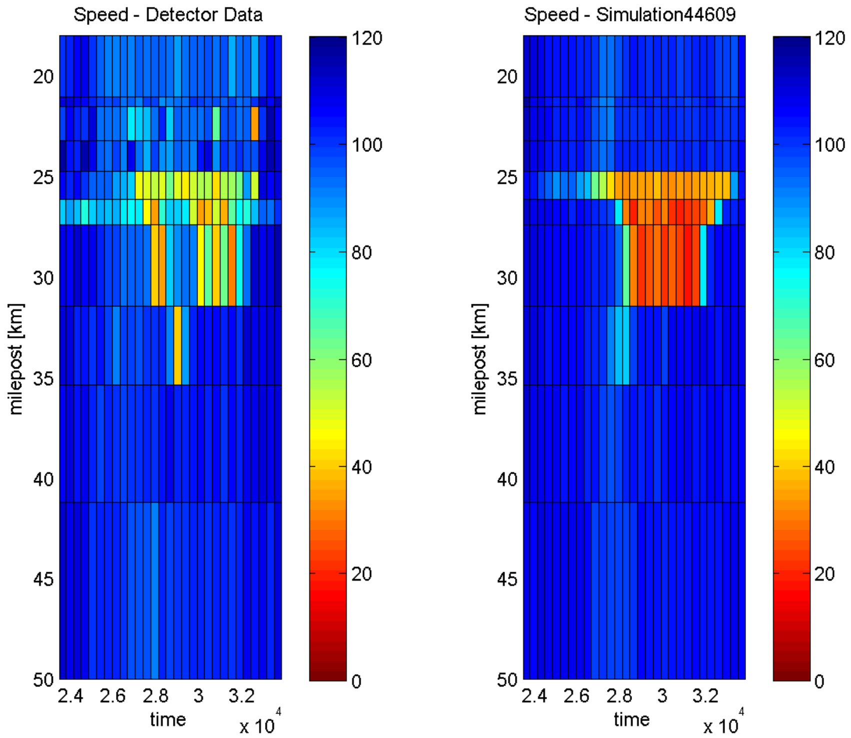


Figure I.1.1.3 Calibration for replication 44609

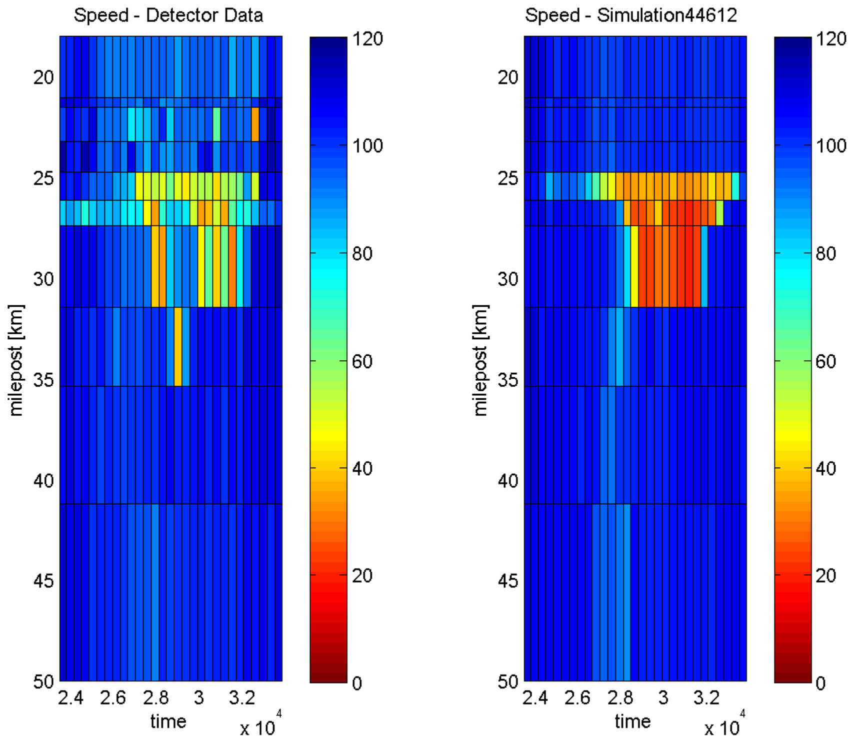


Figure I.1.1.4 Calibration for replication 44612

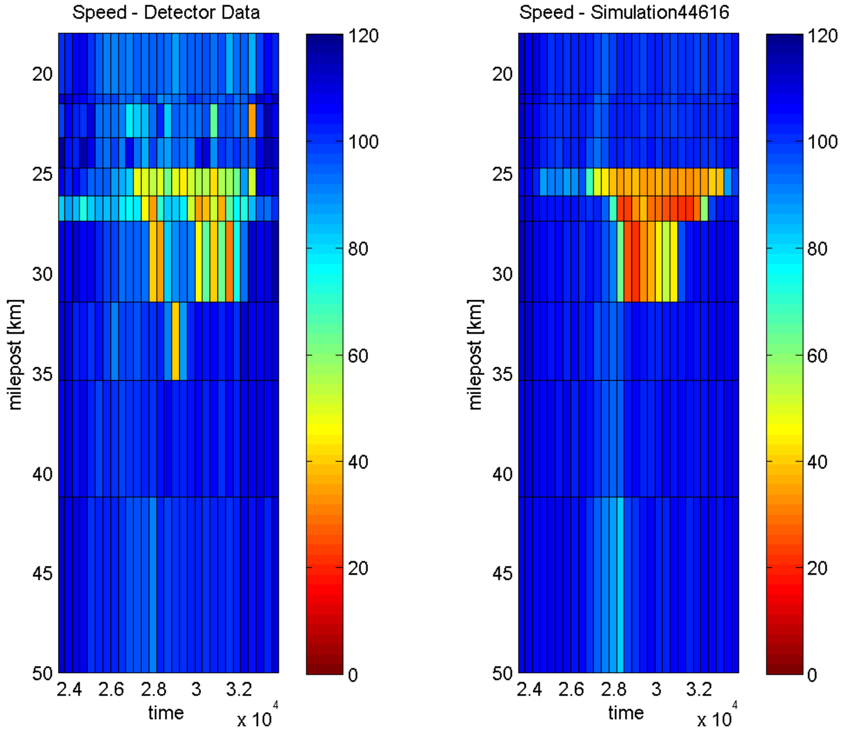


Figure I.1.1.5 Calibration for replication 44616

I.1.2 Alinea

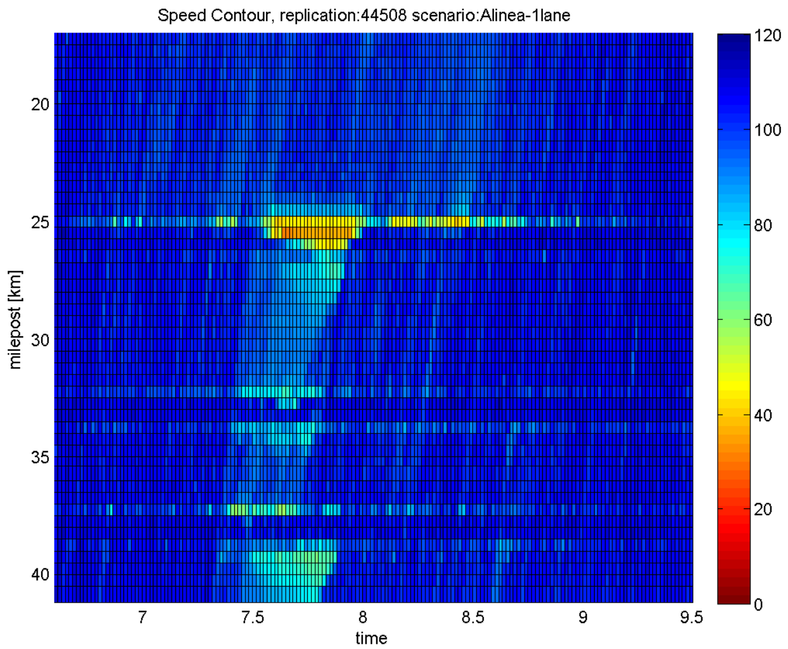
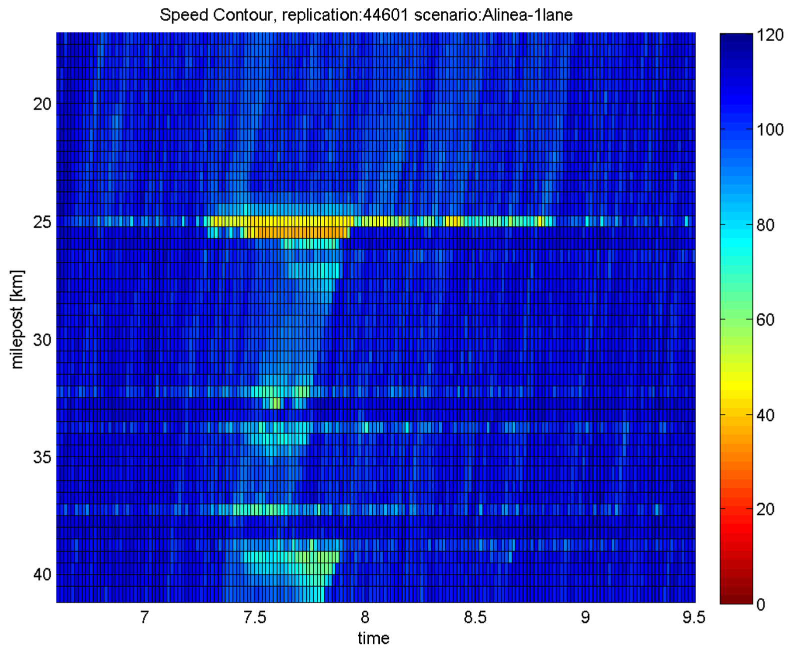


Figure I.1.2.1 Contour plot for replication 44508



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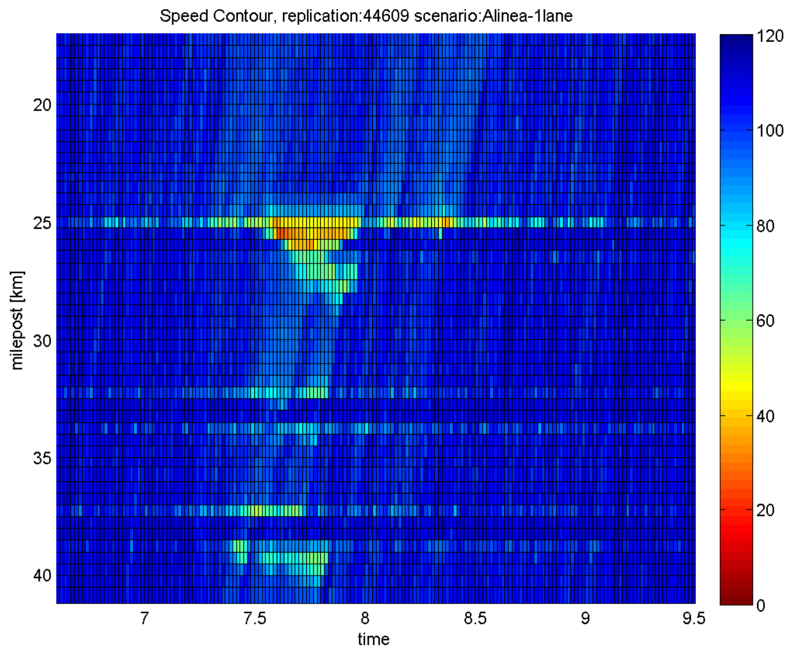


Figure I.1.2.3 Contour plot for replication 44609

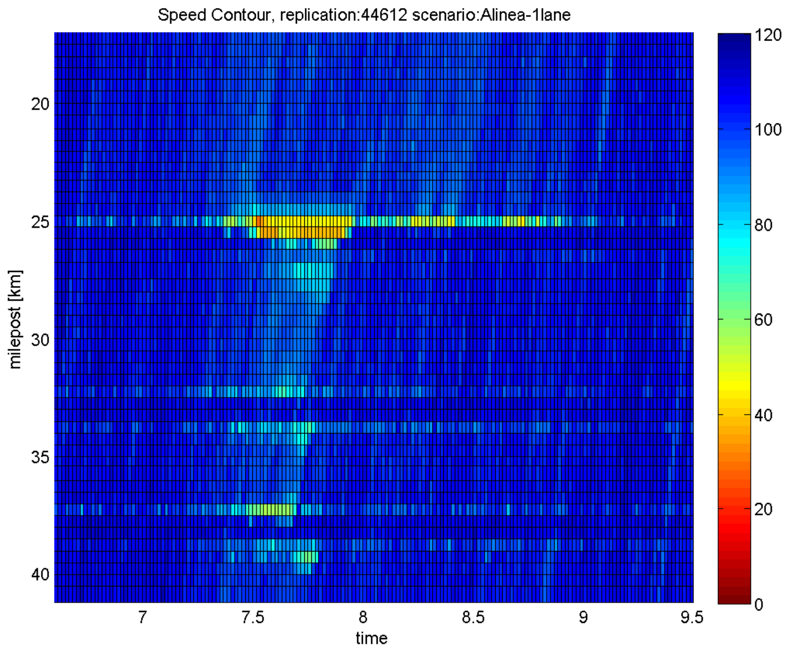


Figure I.1.2.4 Contour plot for replication 44612

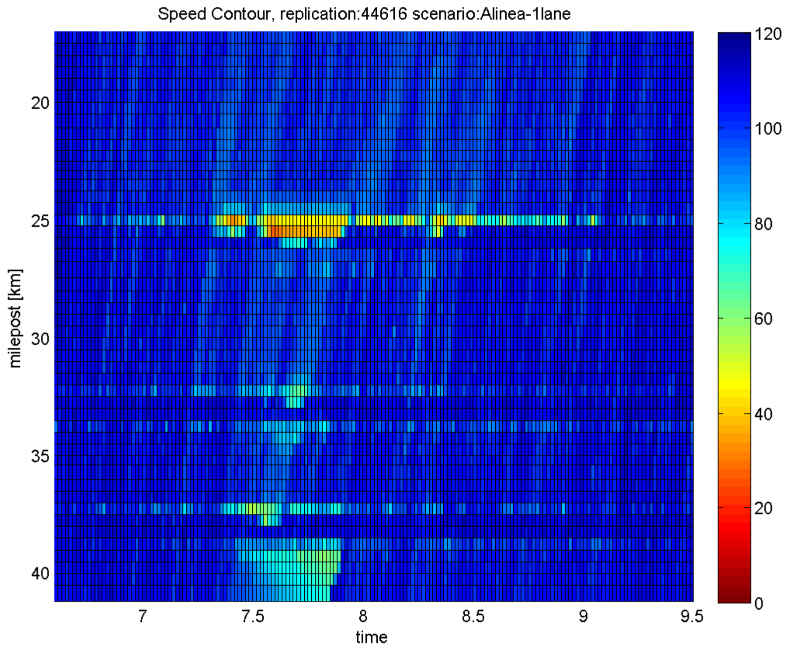


Figure I.1.2.5 Contour plot for replication 44616

I.1.3 Alinea with Queue Constraint

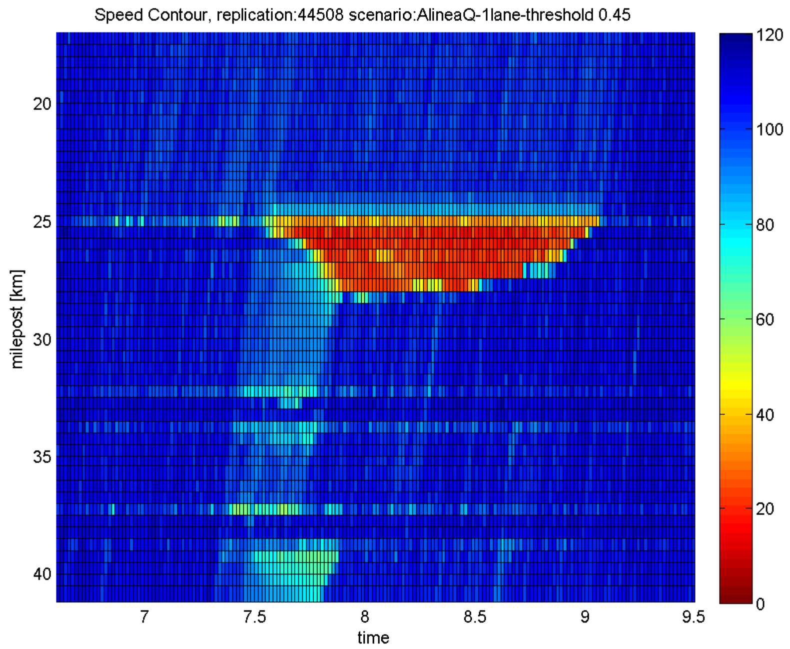


Figure I.1.3.1 Contour plot for replication 44508

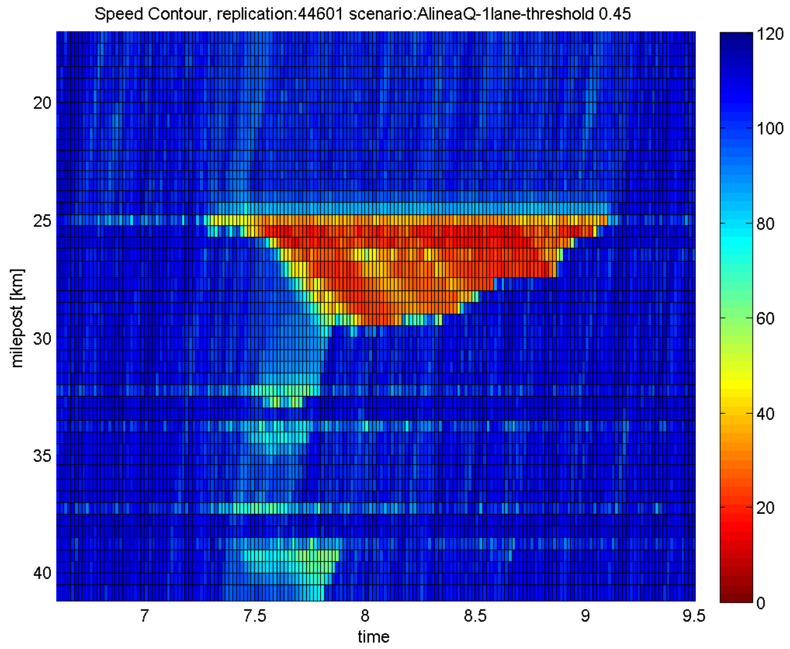


Figure I.1.3.2 Contour plot for replication 44601

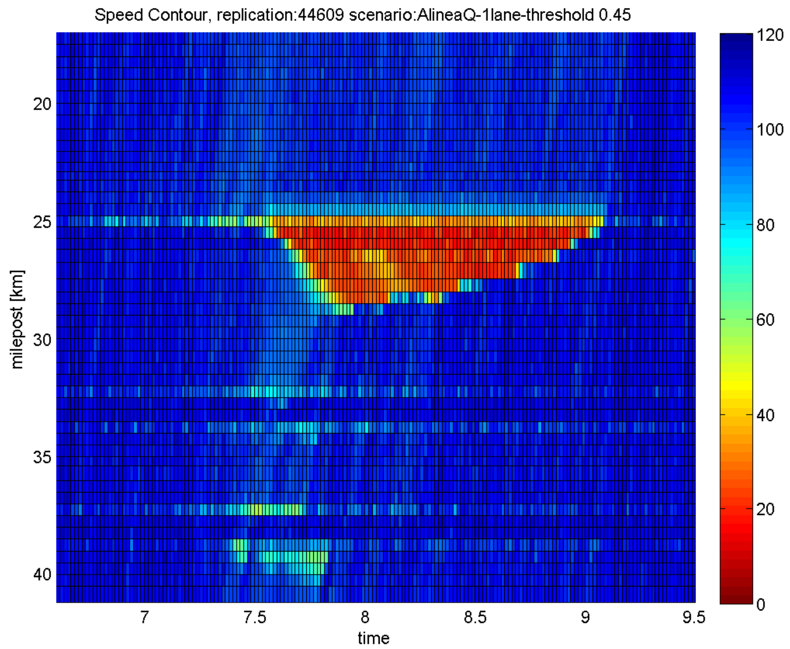


Figure I.1.3.3 Contour plot for replication 44609

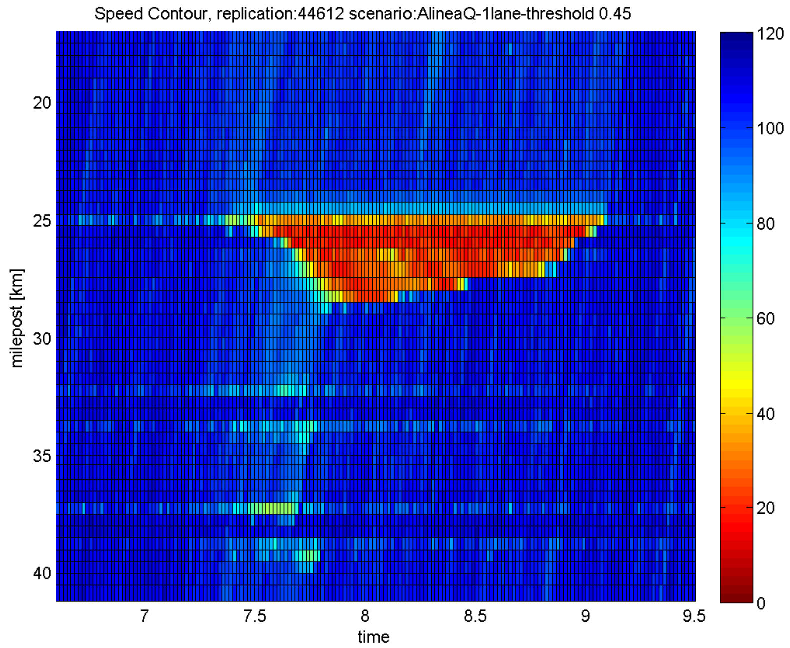


Figure I.1.3.4 Contour plot for replication 44612

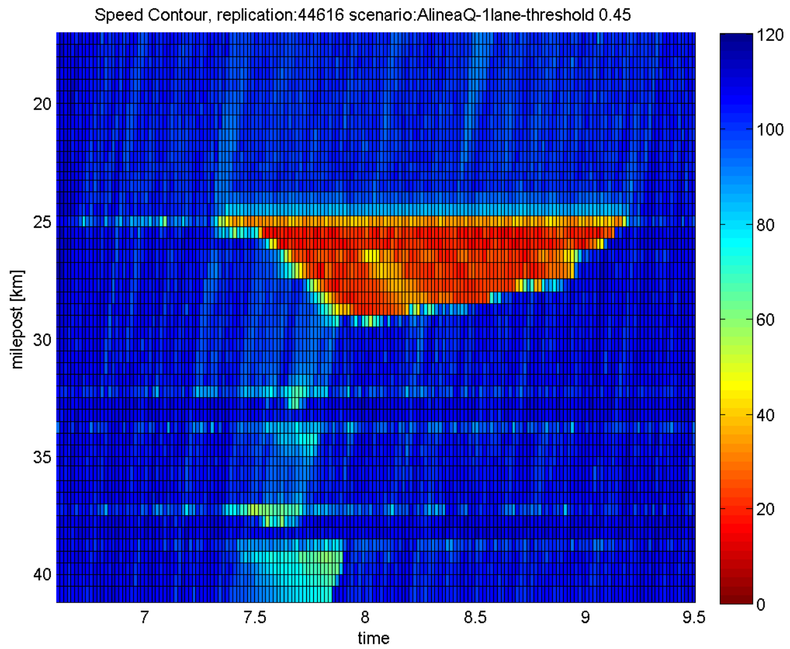


Figure I.1.3.5 Contour plot for replication 44616

I.1.4 Coordinated

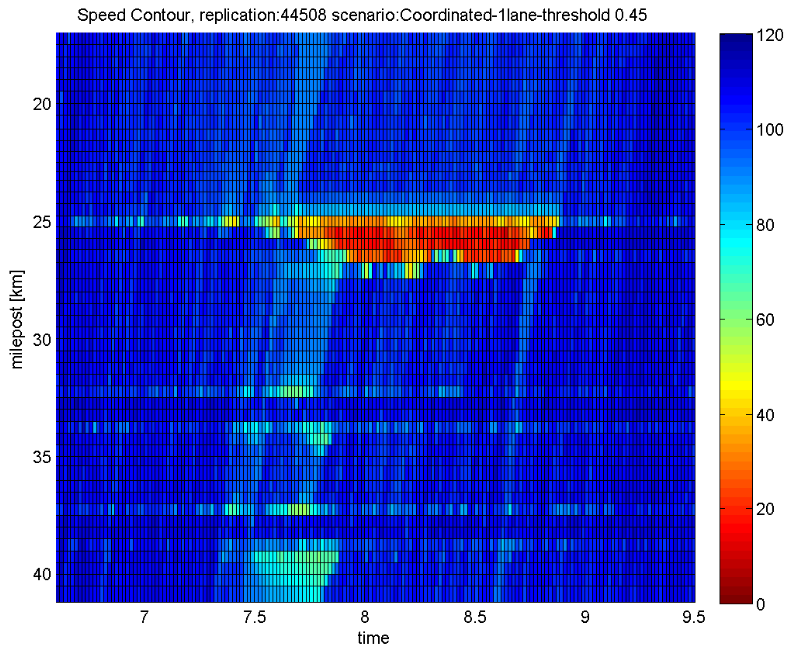


Figure I.1.4.1 Contour plot for replication 44508

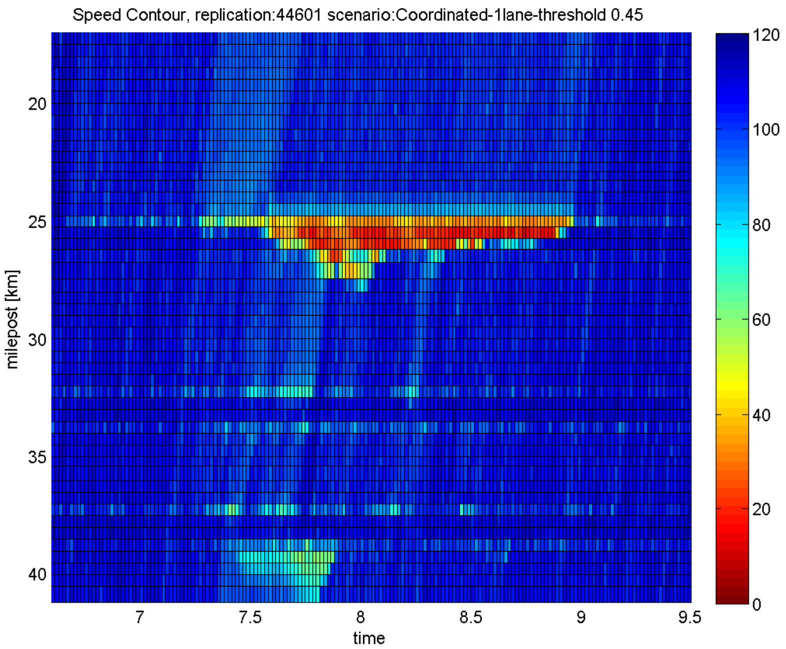


Figure I.1.4.2 Contour plot for replication 44601

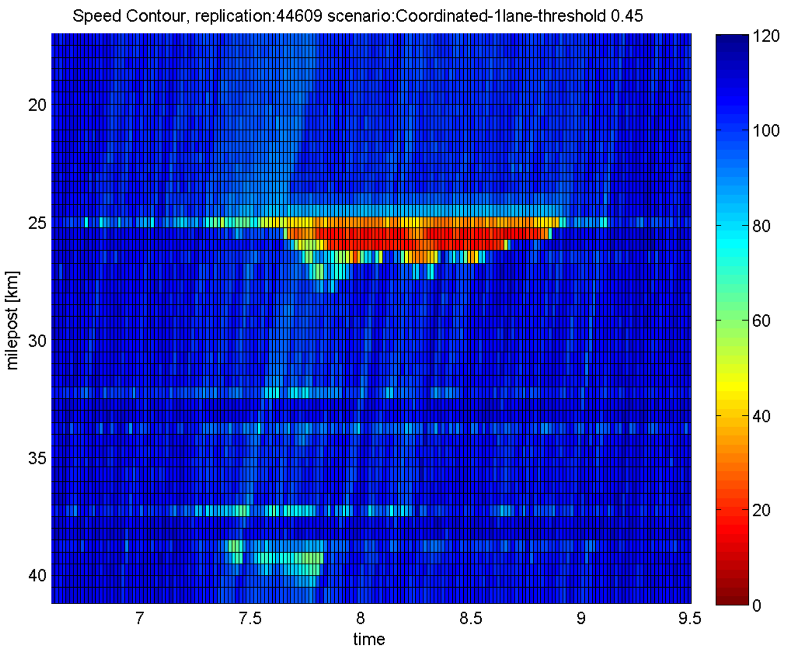


Figure I.1.4.3 Contour plot for replication 44609

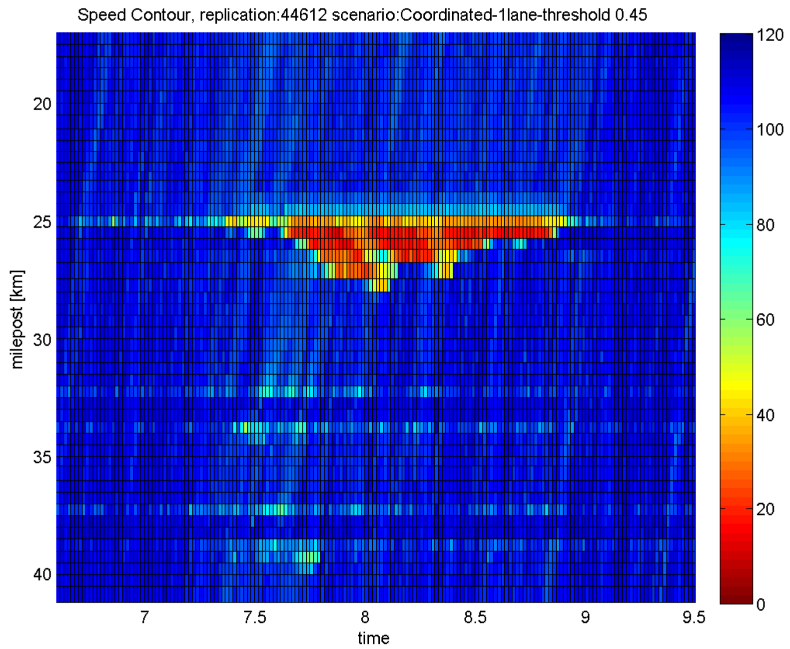


Figure I.1.4.4 Contour plot for replication 44612

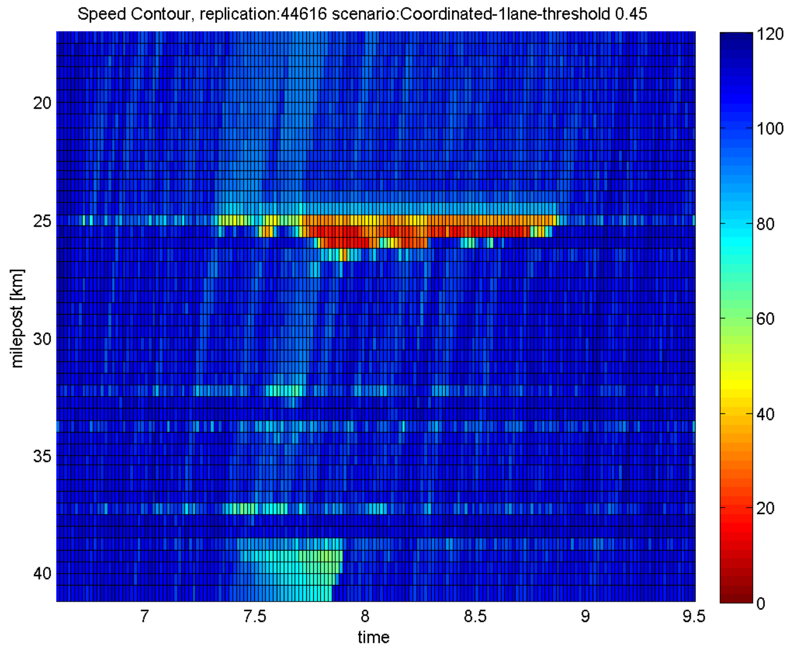


Figure I.1.4.5 Contour plot for replication 44616

I.1.5 Coordinated+VSL

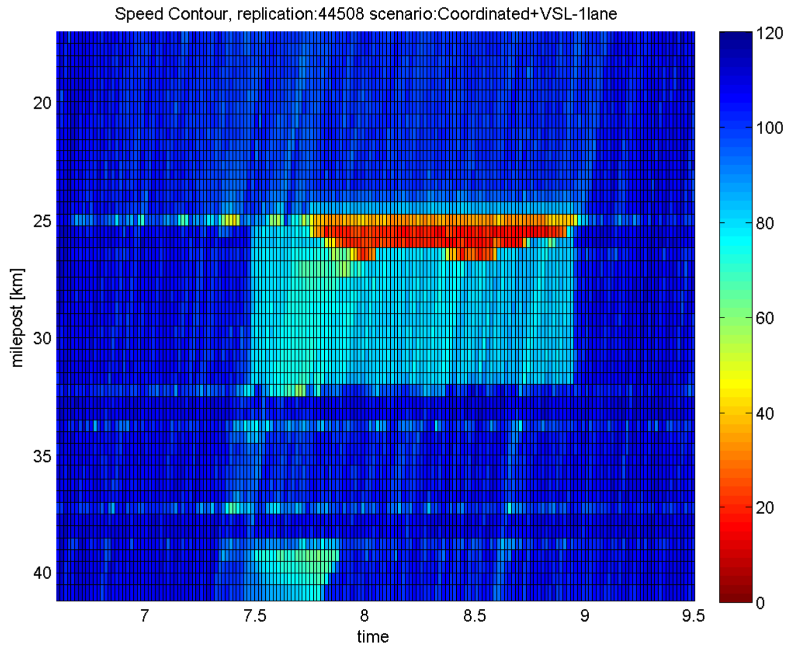


Figure I.1.5.1 Contour plot for replication 44508

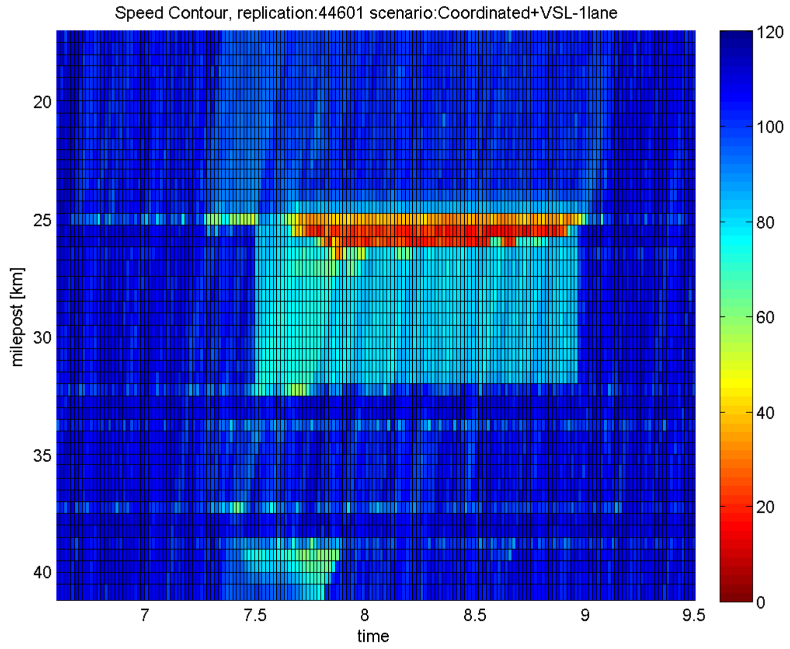


Figure I.1.5.2 Contour plot for replication 44601

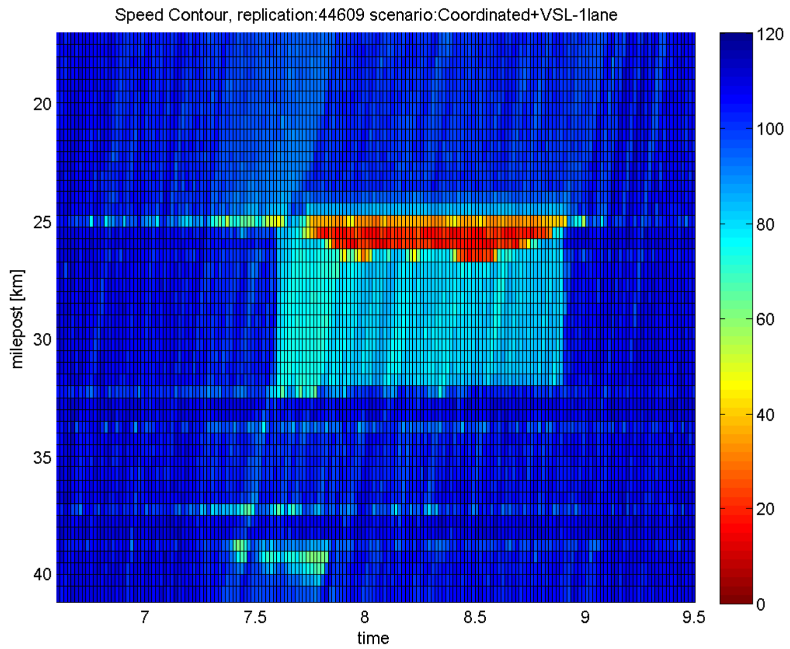


Figure I.1.5.3 Contour plot for replication 44609

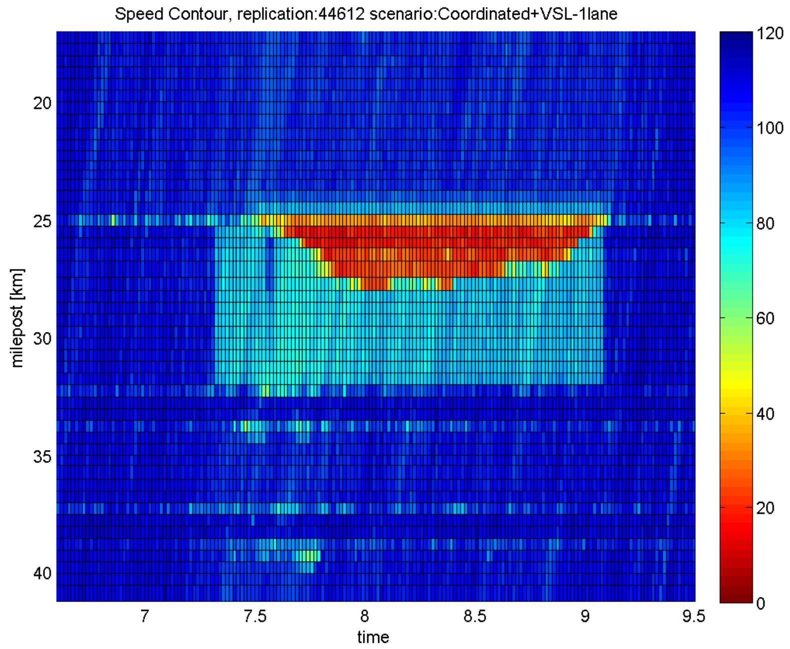


Figure I.1.5.4 Contour plot for replication 44612

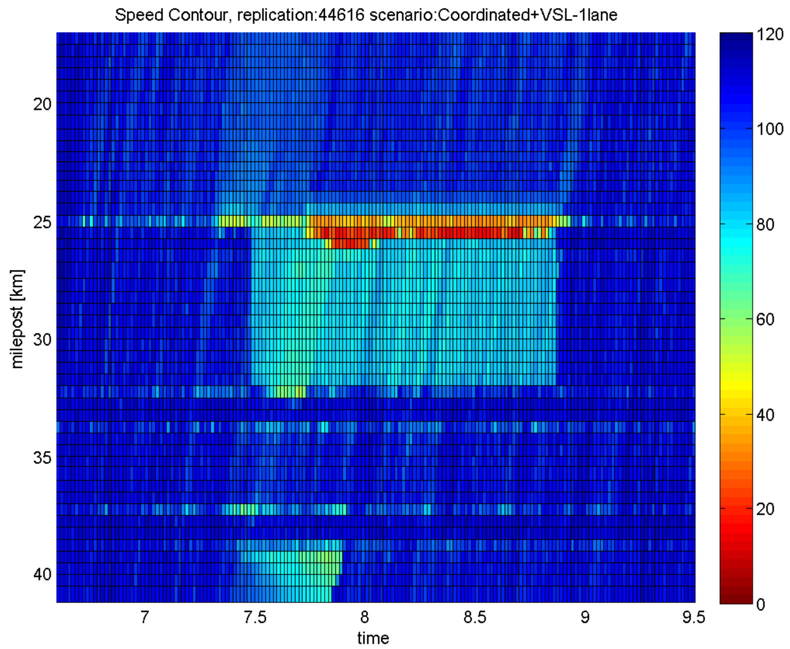
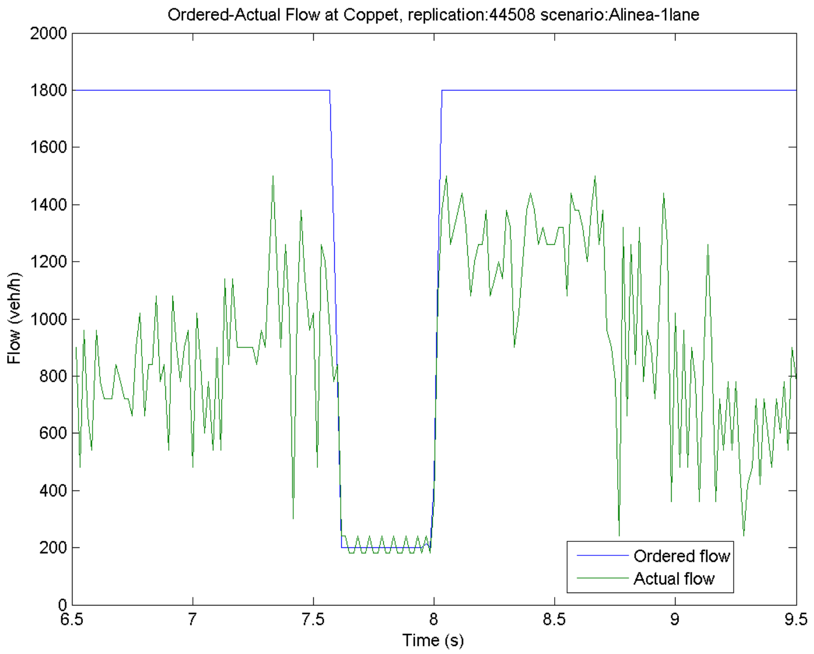


Figure I.1.5.5 Contour plot for replication 44616

I.2 Ordered-Actual Flow

I.2.1 Alinea



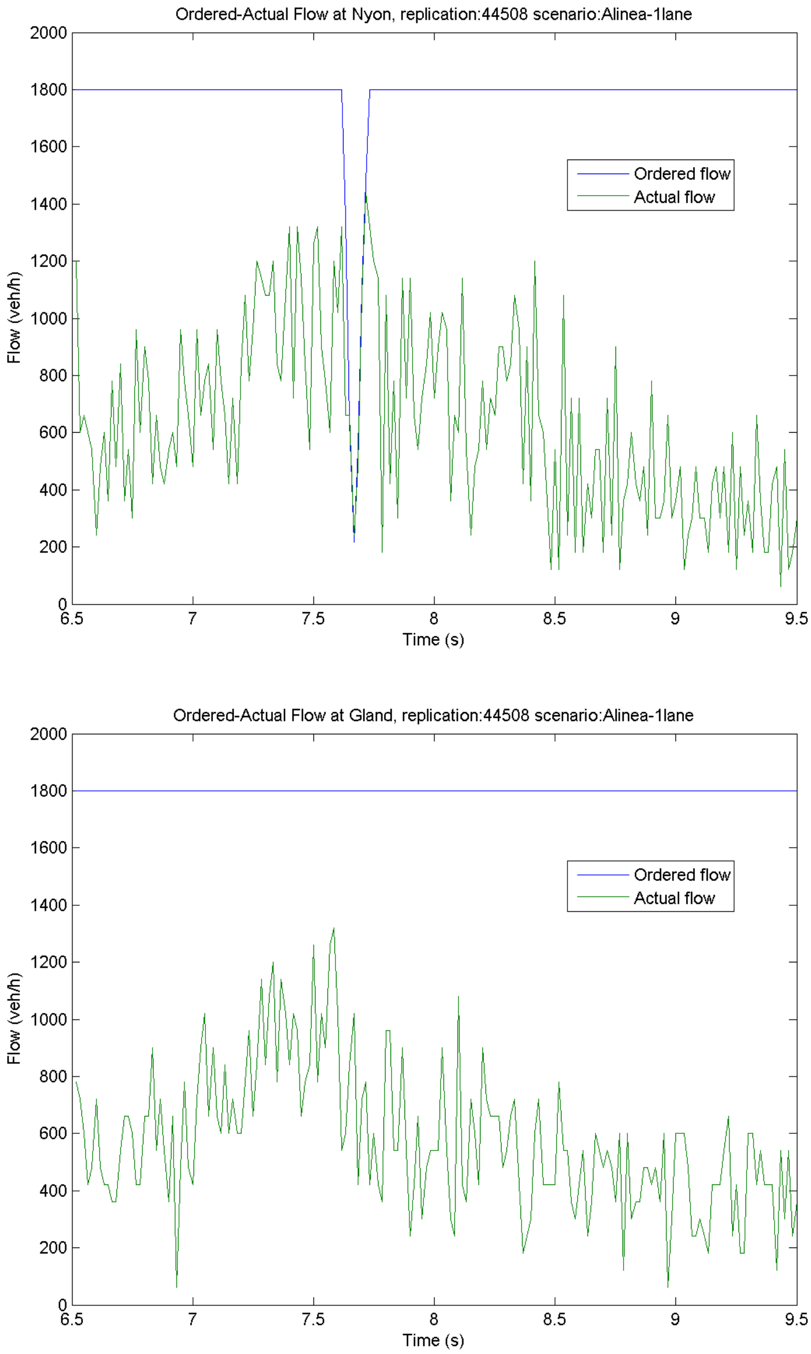
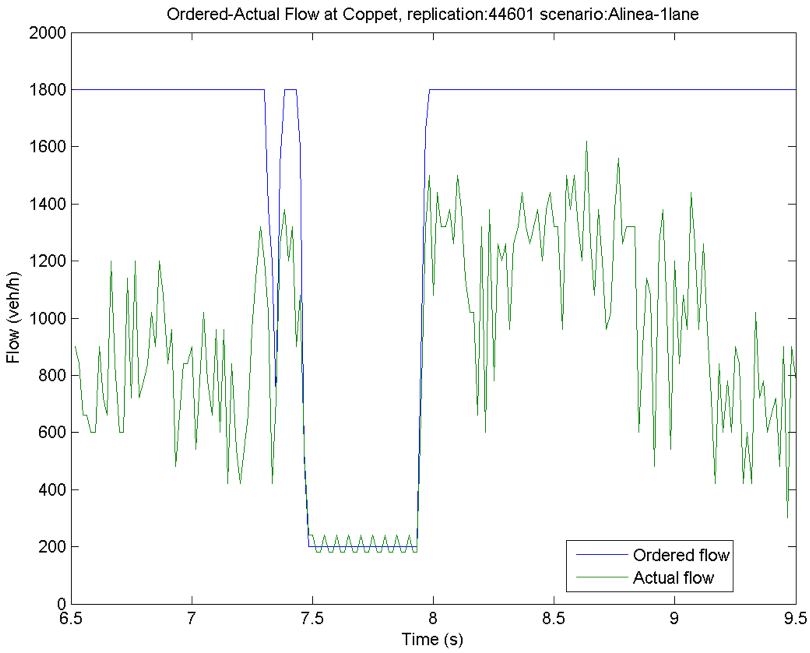
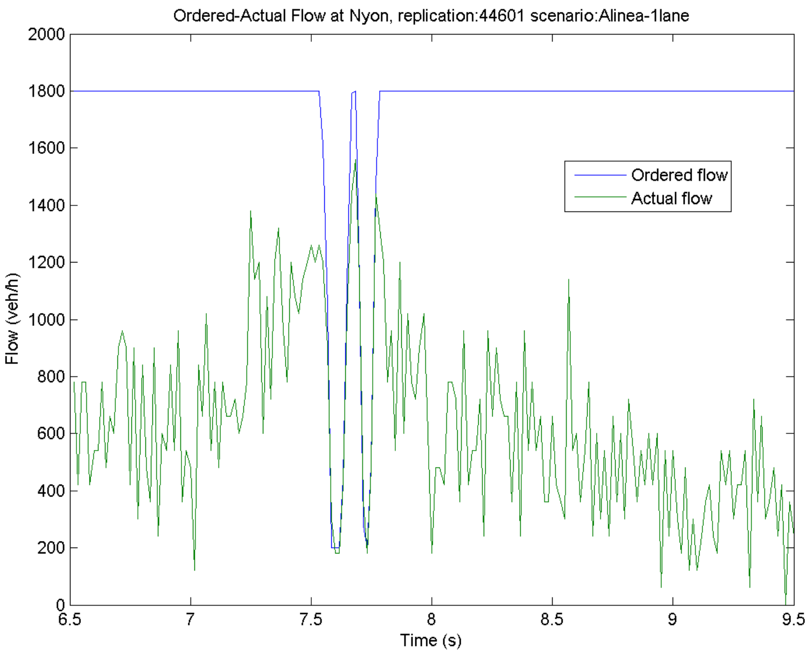


Figure I.2.1.1 Ordered-actual flow for replication 44508


Ordered-Actual Flow at Coppet, replication:44601 scenario:Alinea-1lane
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
2000
1800
1600
1400
1200
1000
800
600
400
200
0
6.5
7
7.5
8
8.5
9
9.5


Ordered-Actual Flow at Nyon, replication:44601 scenario:Alinea-1lane
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
2000
1800
1600
1400
1200
1000
800
600
400
200
0
6.5
7
7.5
8
8.5
9
9.5

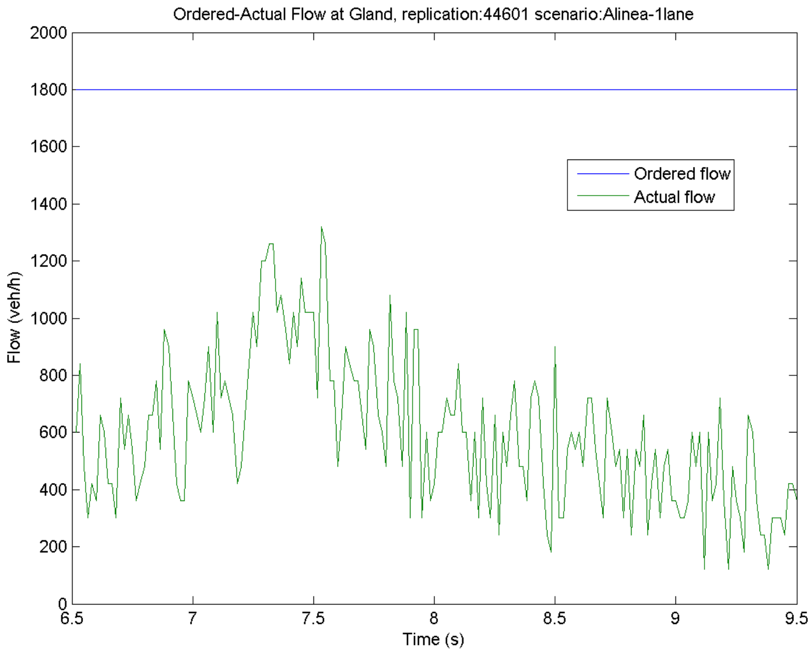
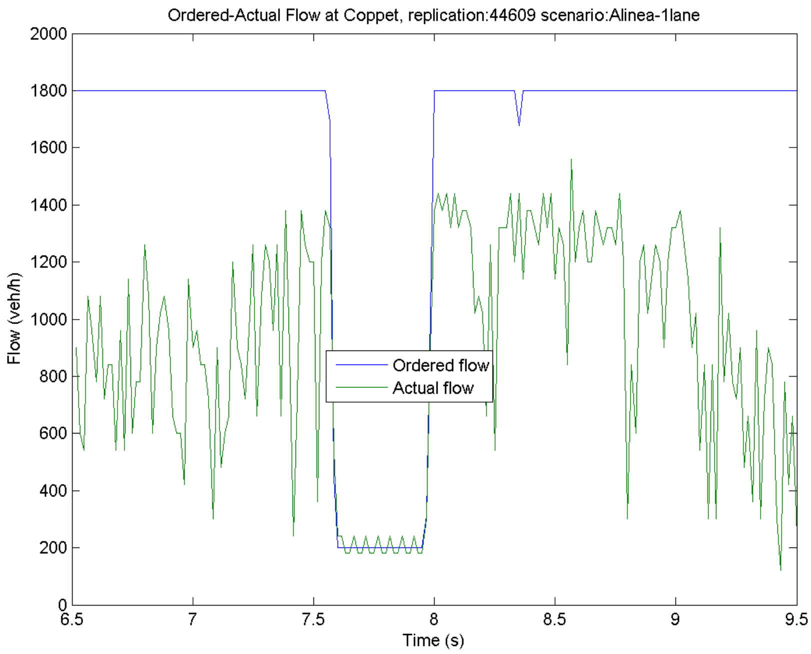
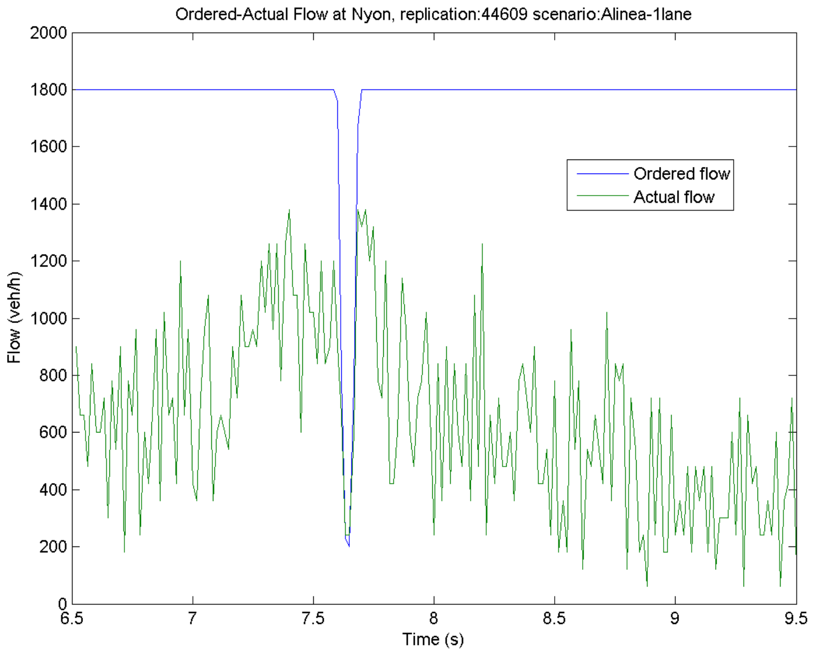


Figure I.2.1.2 Ordered-actual flow for replication 44601





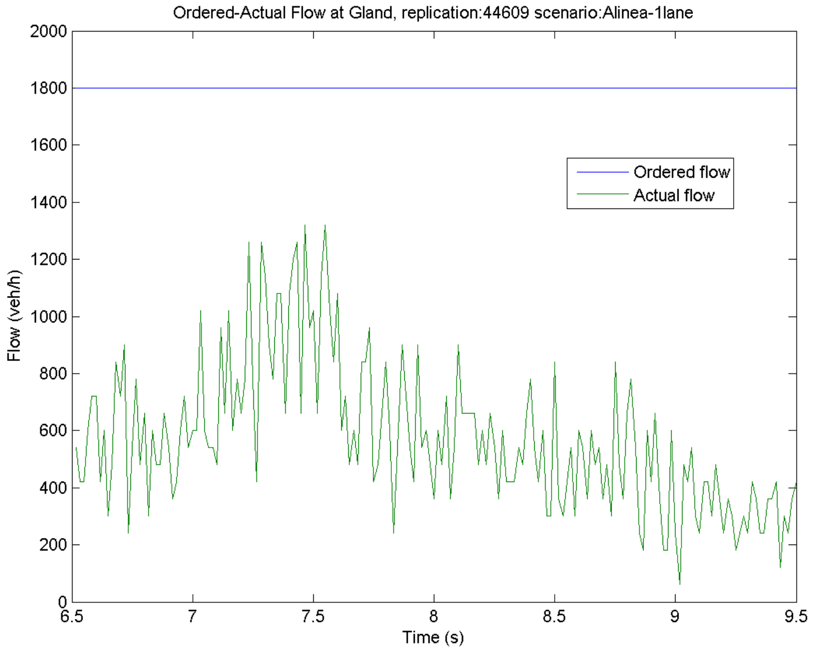
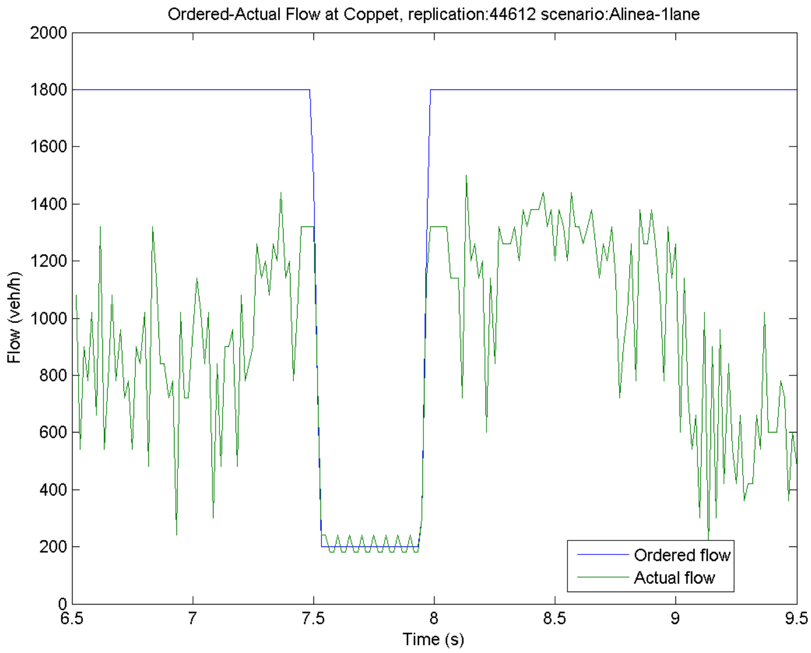
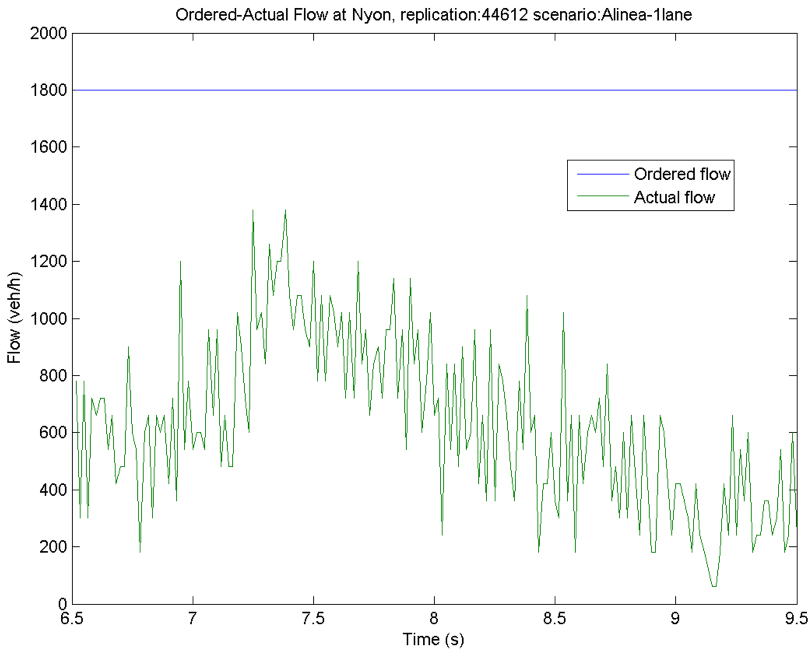


Figure I.2.1.3 Ordered-actual flow for replication 44609


Ordered-Actual Flow at Coppet, replication:44612 scenario:Alinea-1lane
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
2000
1800
1600
1400
1200
1000
800
600
400
200
0
6.5
7
7.5
8
8.5
9
9.5


Ordered-Actual Flow at Nyon, replication:44612 scenario:Alinea-1lane
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
2000
1800
1600
1400
1200
1000
800
600
400
200
0
6.5
7
7.5
8
8.5
9
9.5

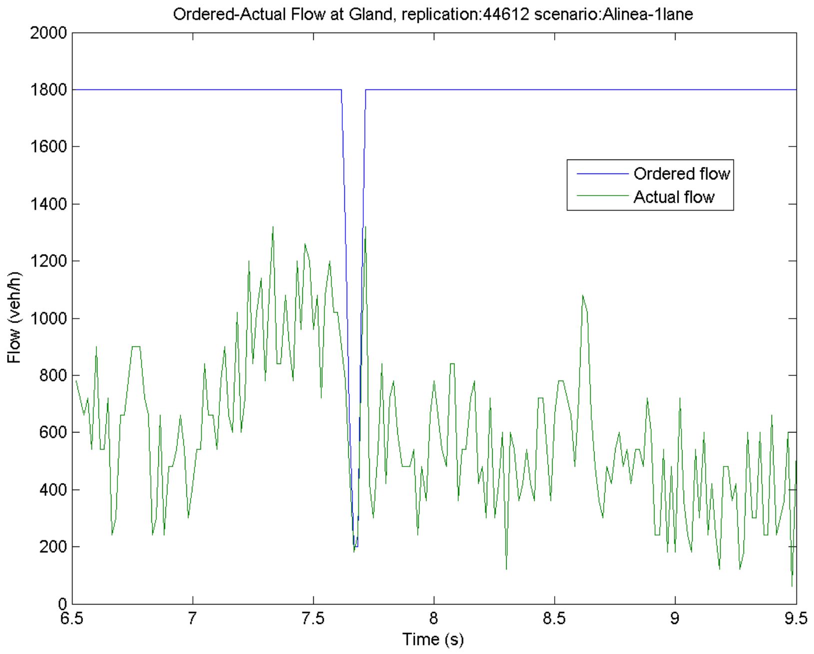
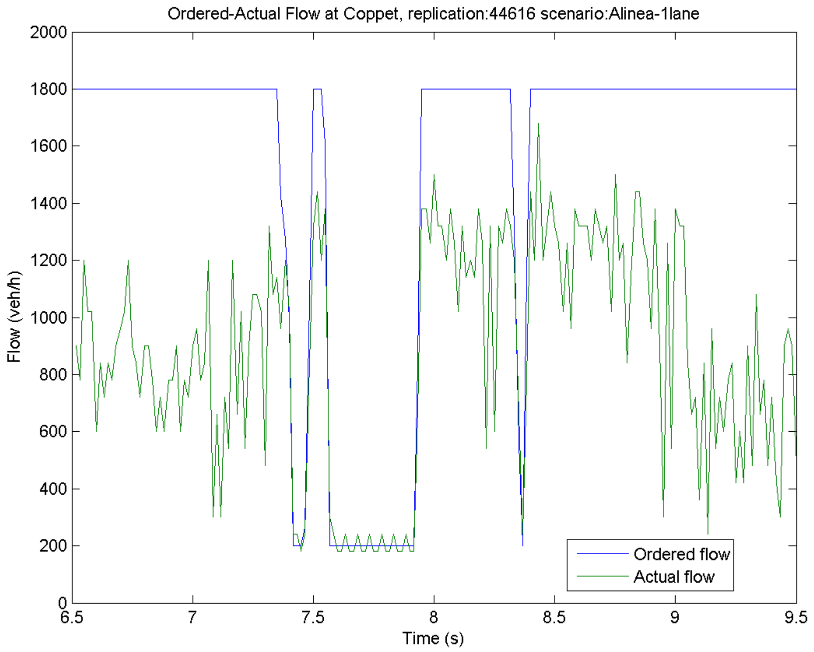


Figure I.2.1.4 Ordered-actual flow for replication 44612



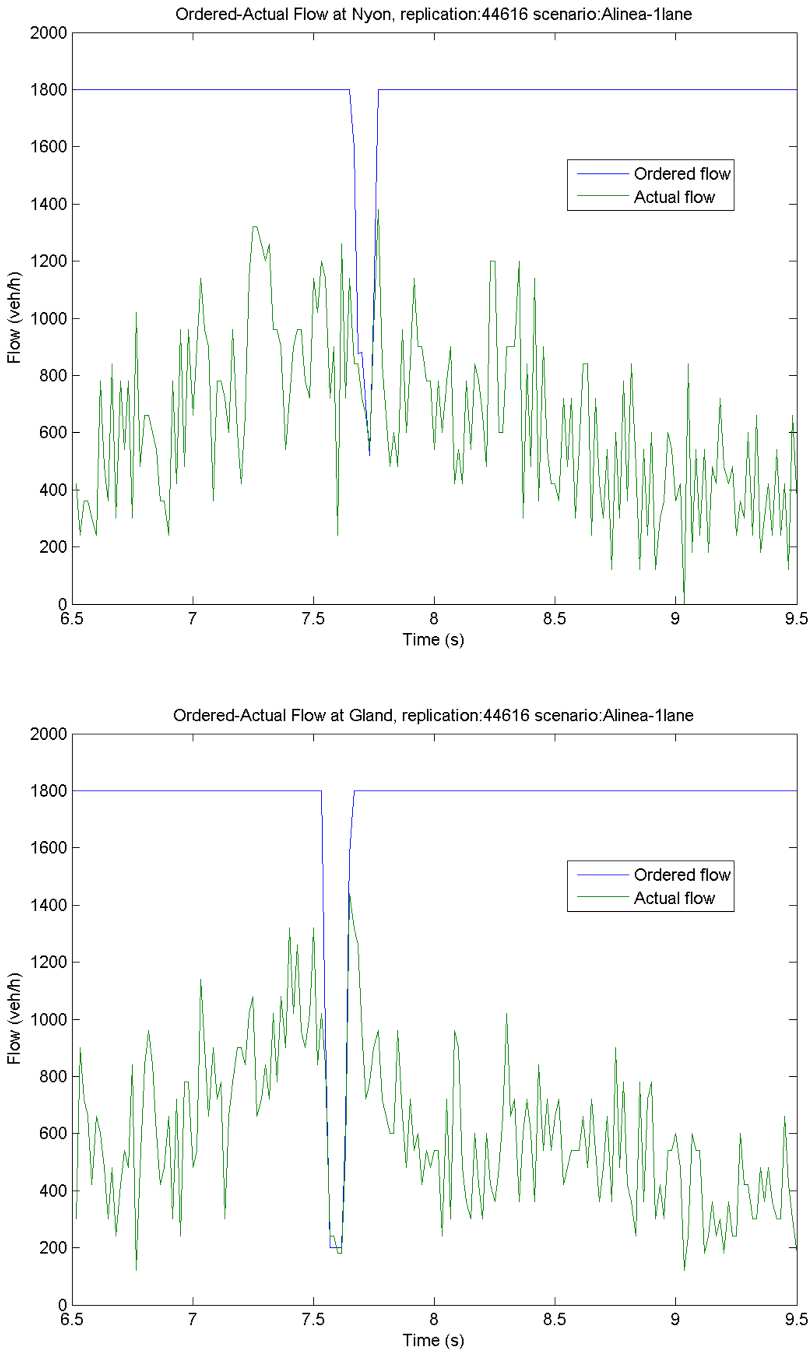
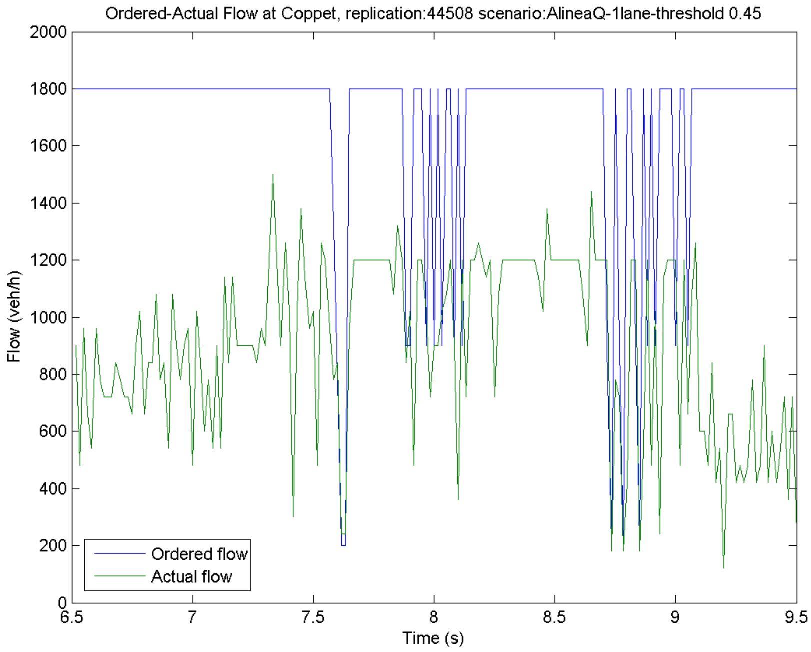
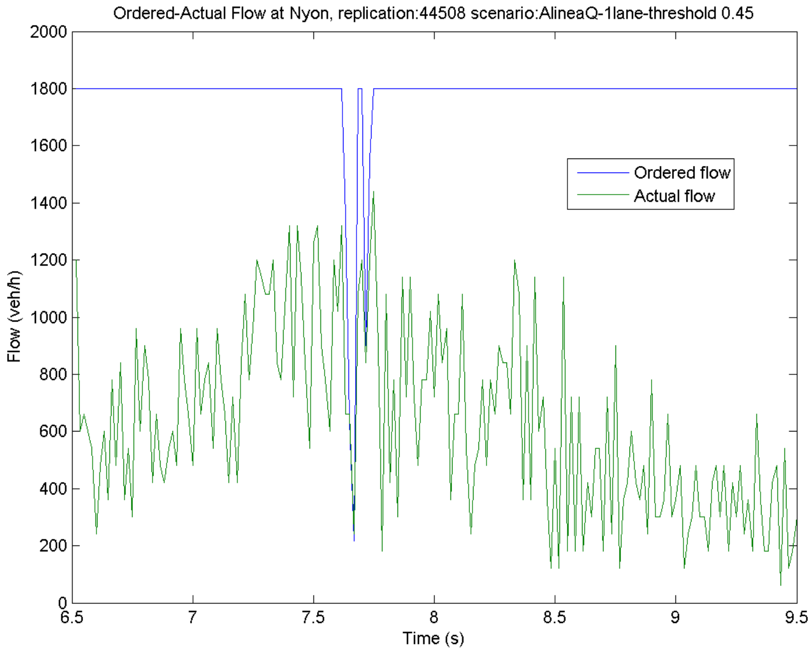


Figure I.2.1.5 Ordered-actual flow for replication 44616

I.2.2 Alinea with Queue Control





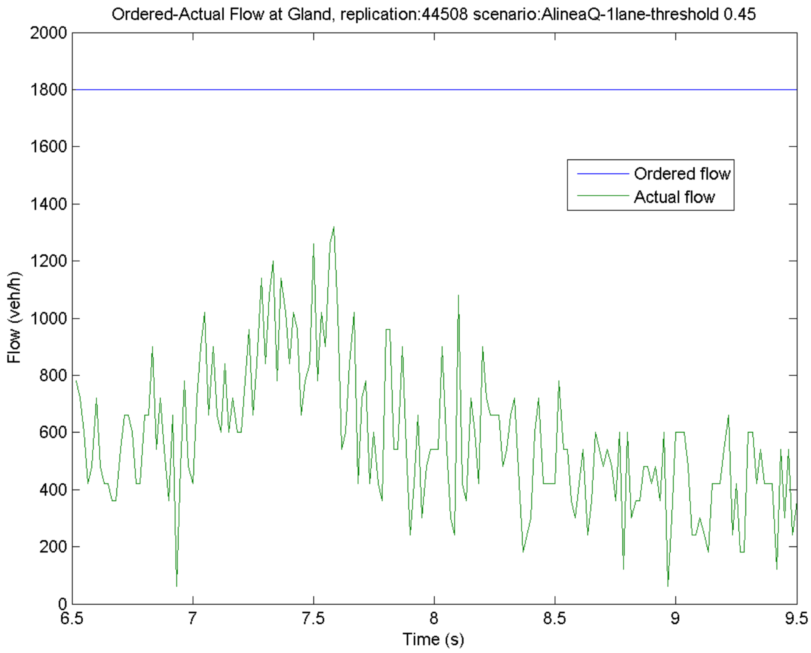
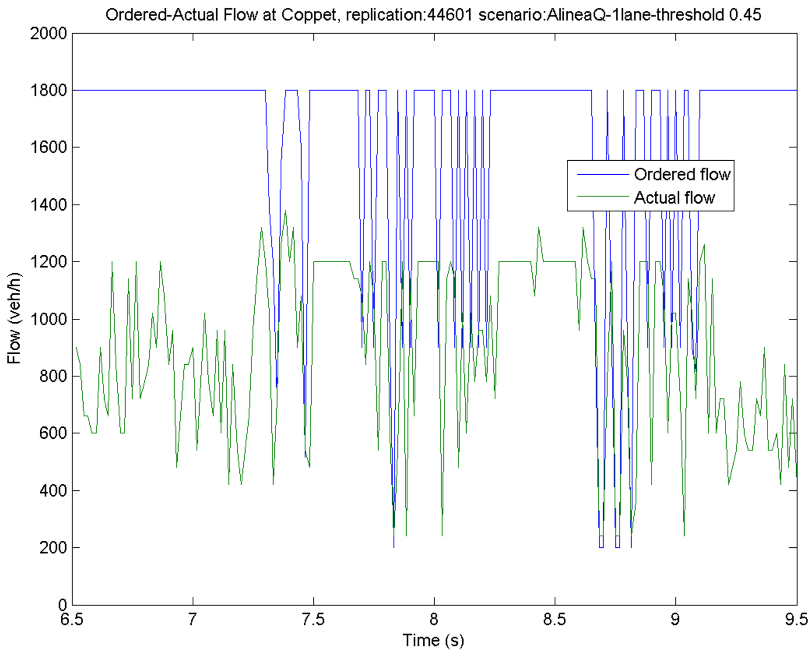
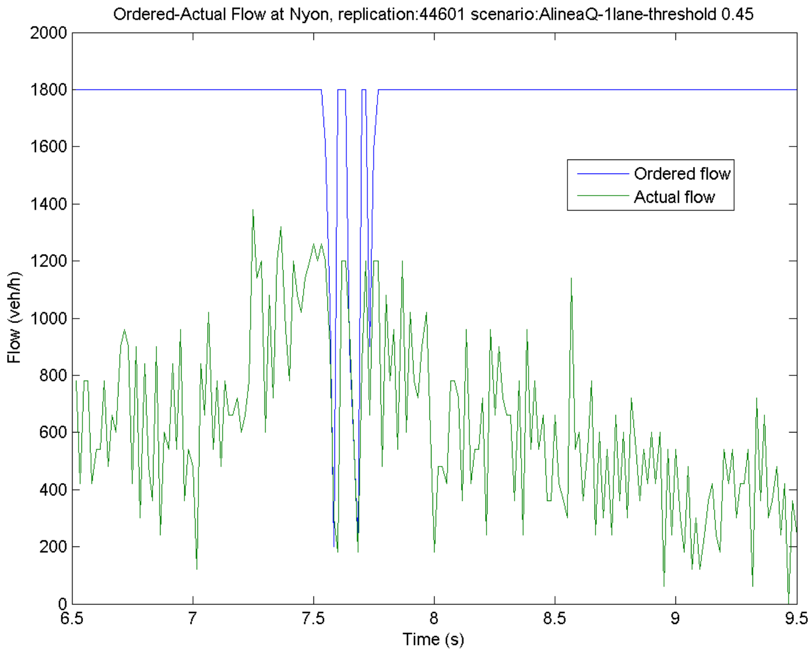


Figure I.2.2.1 Ordered-actual flow for replication 44508





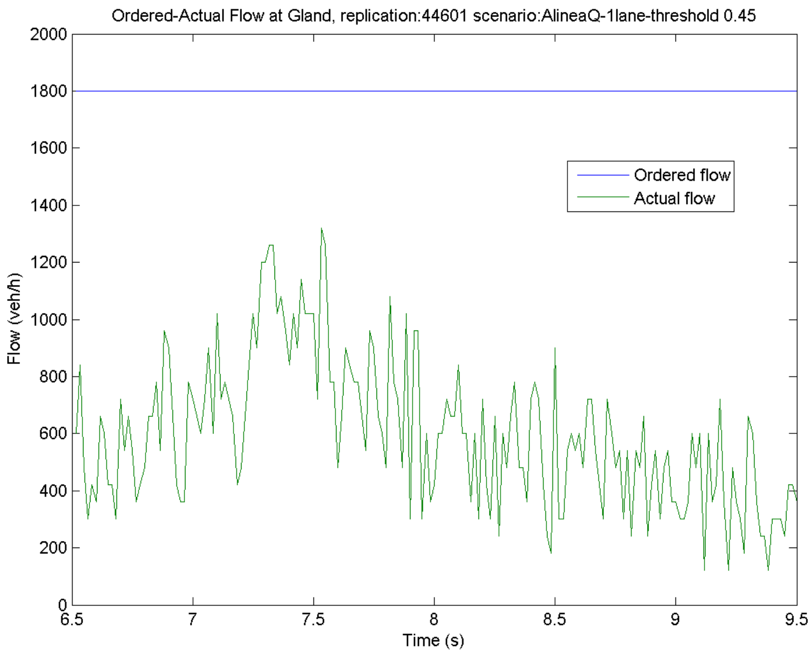
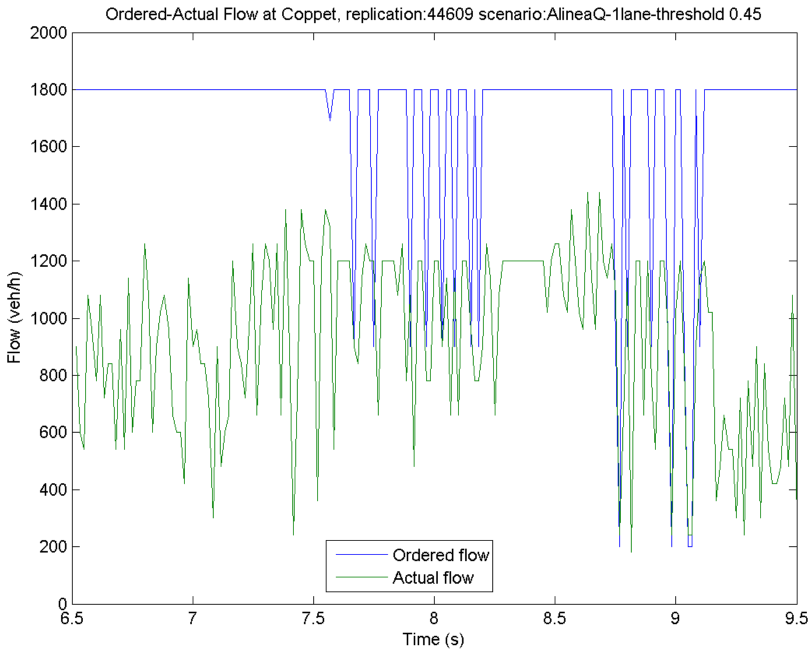
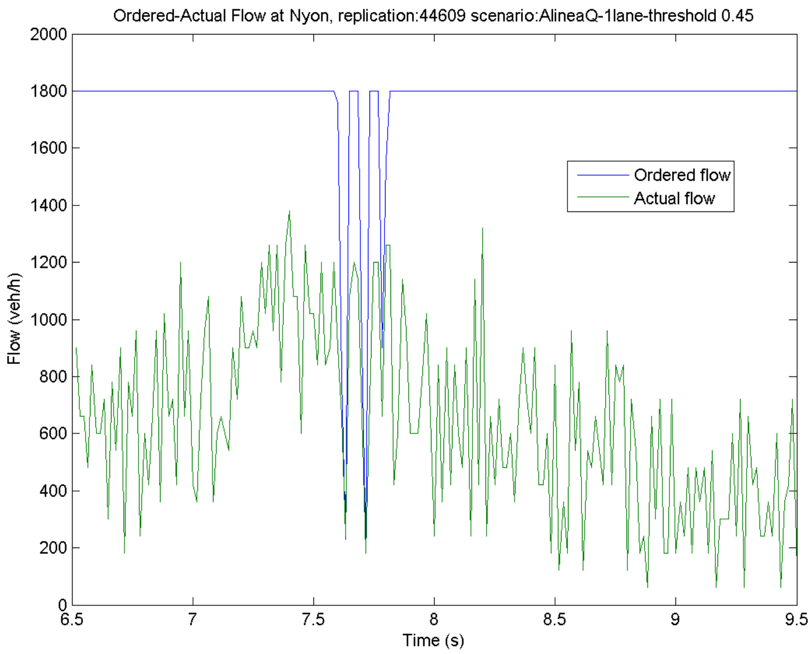


Figure I.2.2.2 Ordered-actual flow for replication 44601


Ordered-Actual Flow at Coppet, replication:44609 scenario:AlineaQ-1lane-threshold 0.45
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
0
200
400
600
800
1000
1200
1400
1600
1800
2000
6.5
7
7.5
8
8.5
9
9.5


Ordered-Actual Flow at Nyon, replication:44609 scenario:AlineaQ-1lane-threshold 0.45
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
0
200
400
600
800
1000
1200
1400
1600
1800
2000
6.5
7
7.5
8
8.5
9
9.5

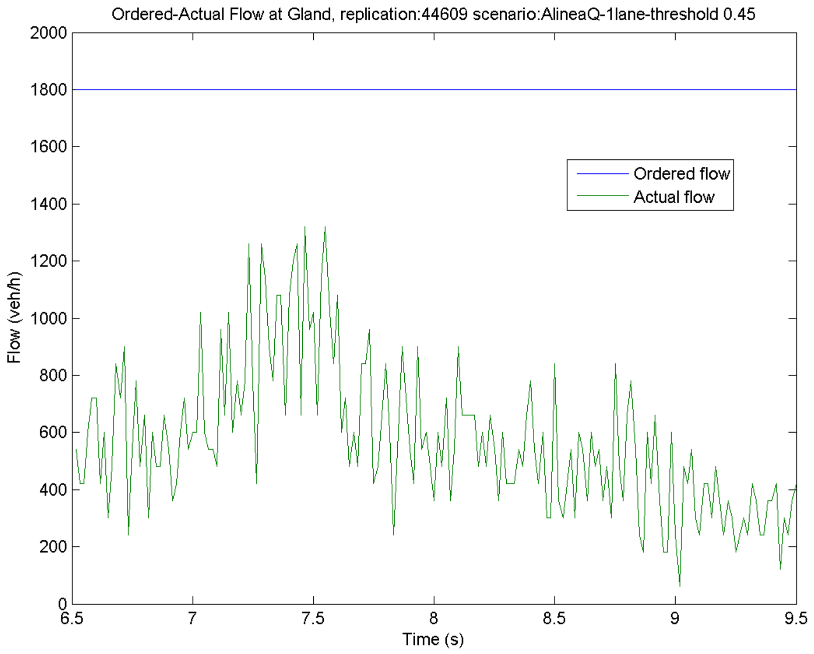
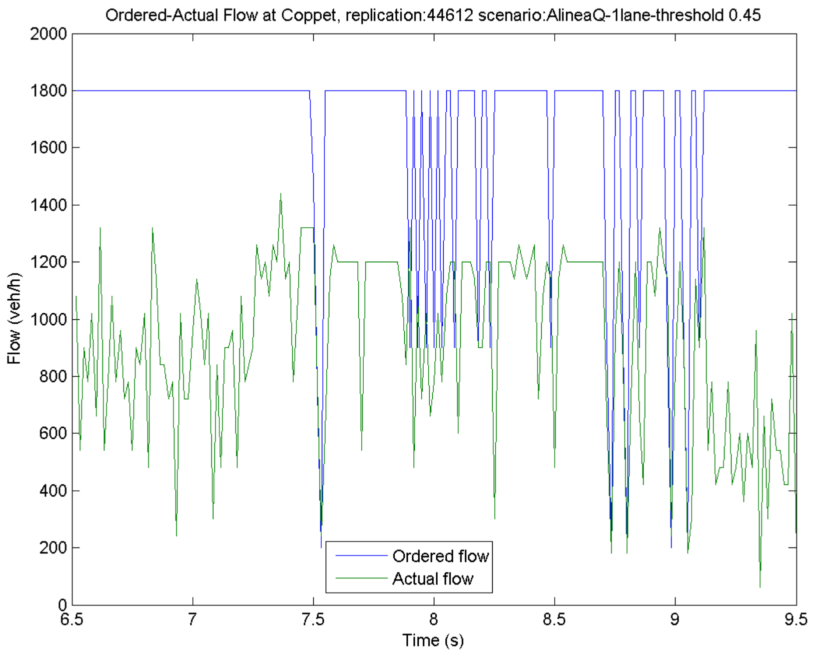


Figure I.2.2.3 Ordered-actual flow for replication 44609



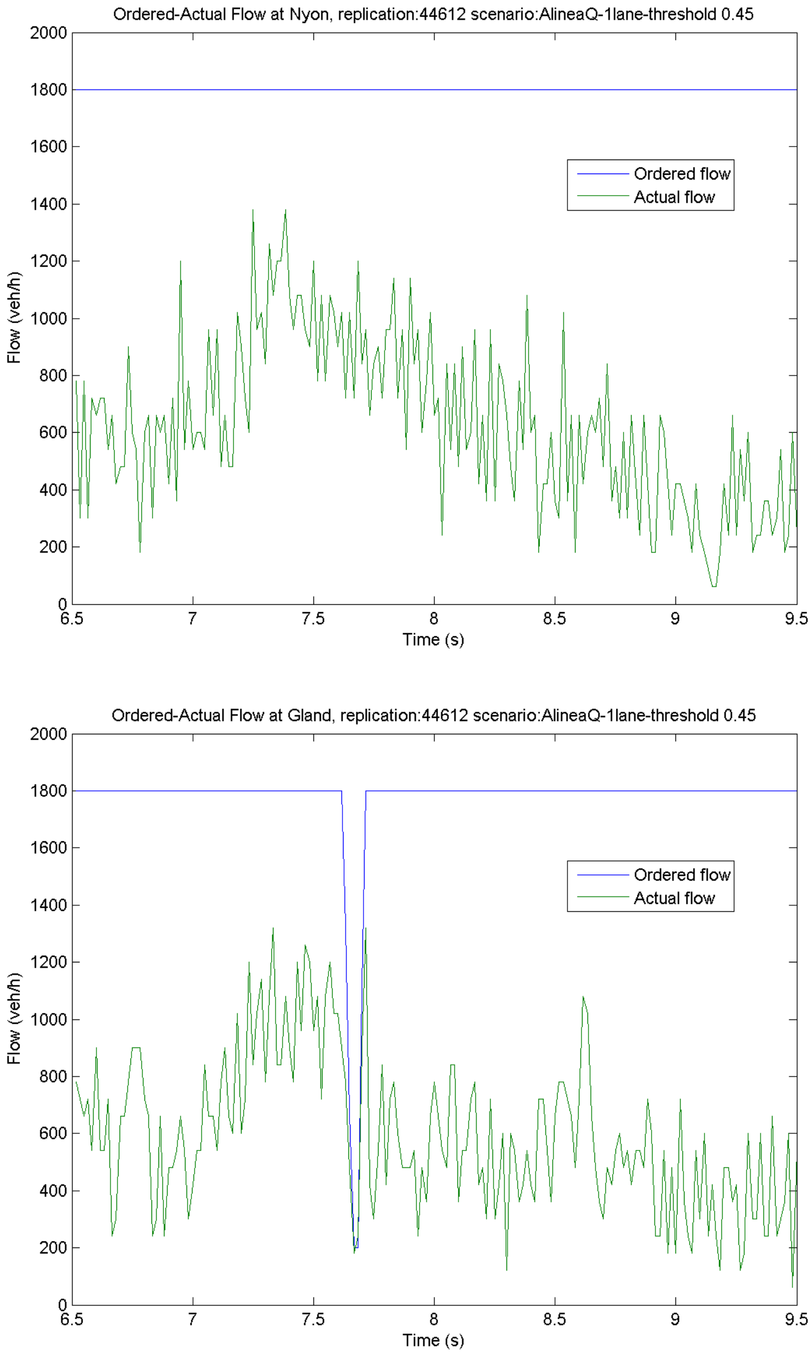
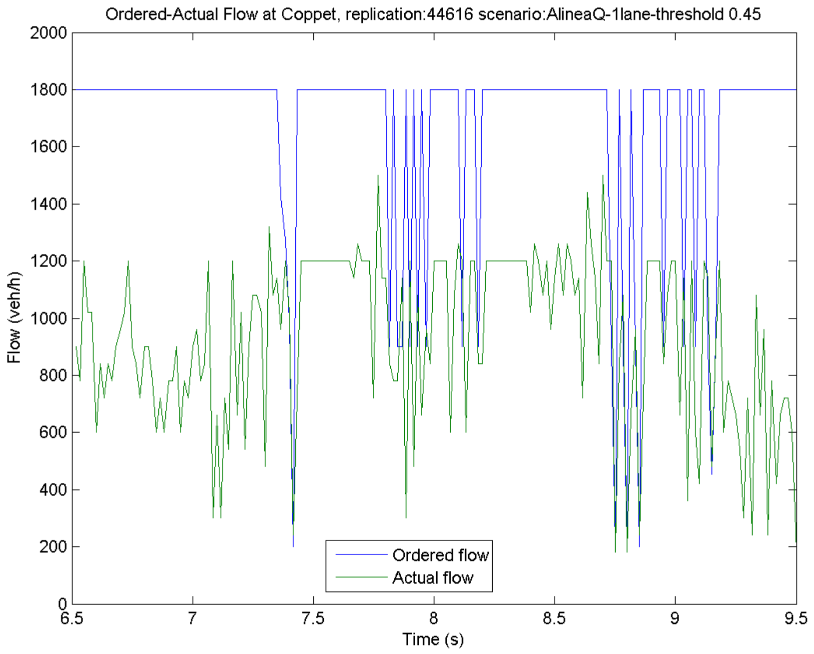
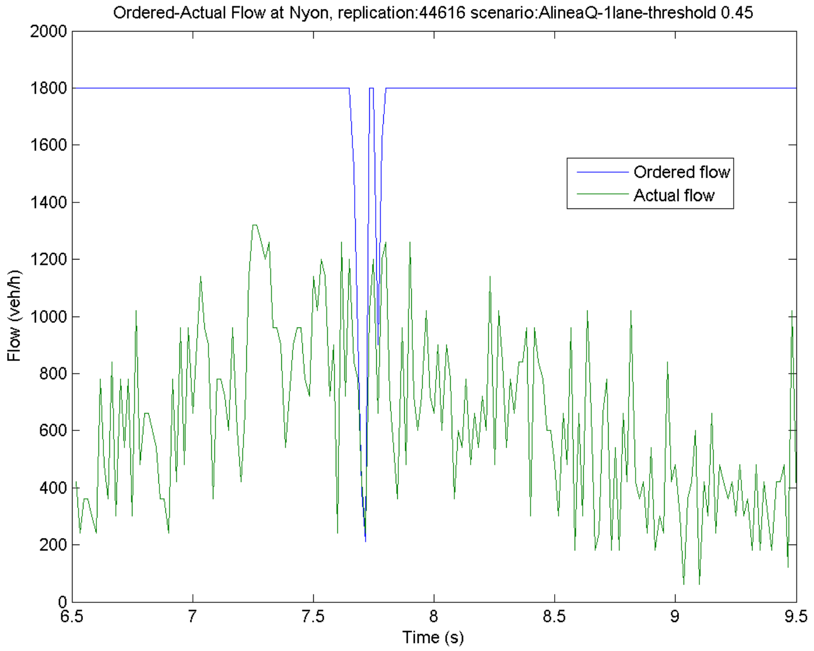


Figure I.2.2.4 Ordered-actual flow for replication 44612


Ordered-Actual Flow at Coppet, replication:44616 scenario:AlineaQ-1lane-threshold 0.45
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
2000
1800
1600
1400
1200
1000
800
600
400
200
0
6.5
7
7.5
8
8.5
9
9.5


Ordered-Actual Flow at Nyon, replication:44616 scenario:AlineaQ-1lane-threshold 0.45
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
2000
1800
1600
1400
1200
1000
800
600
400
200
0
6.5
7
7.5
8
8.5
9
9.5

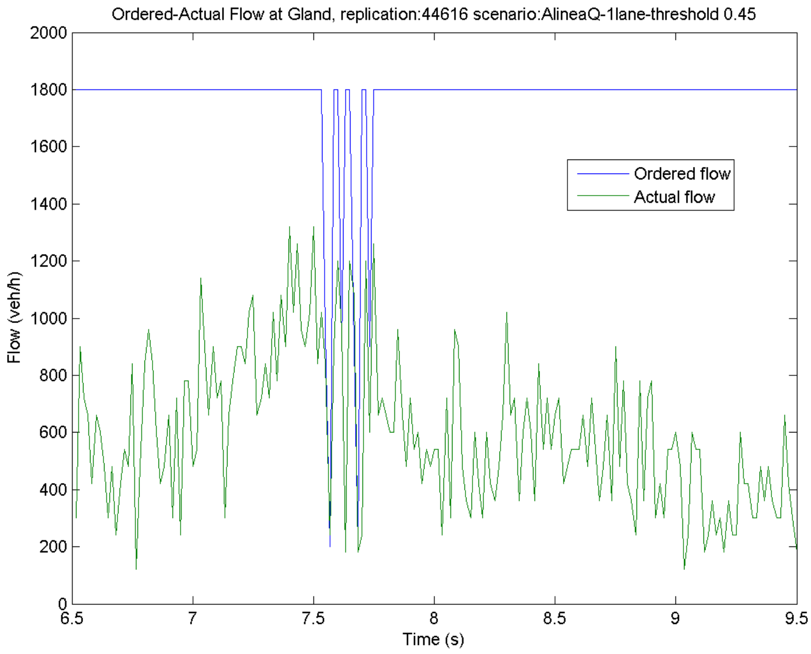
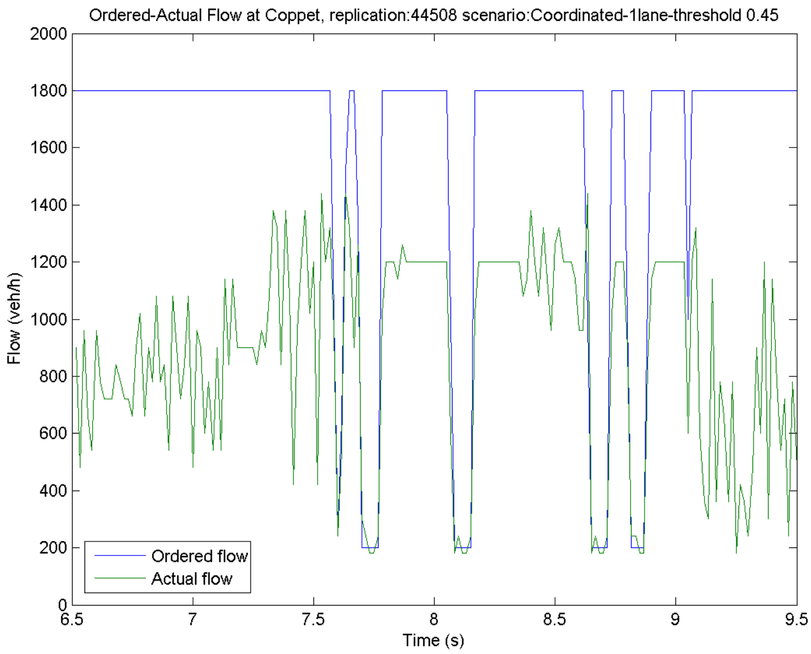


Figure I.2.2.5 Ordered-actual flow for replication 44616

I.2.3 Coordinated



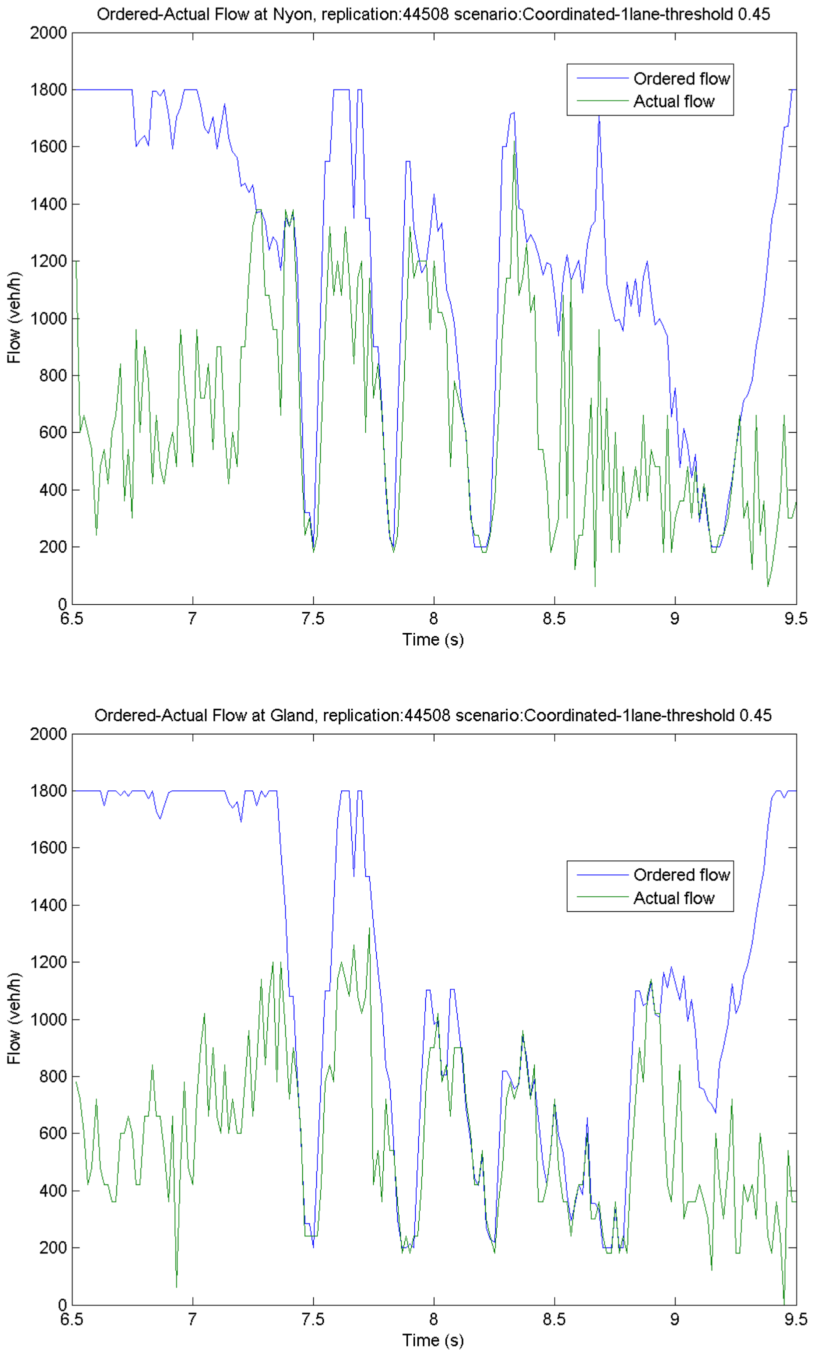
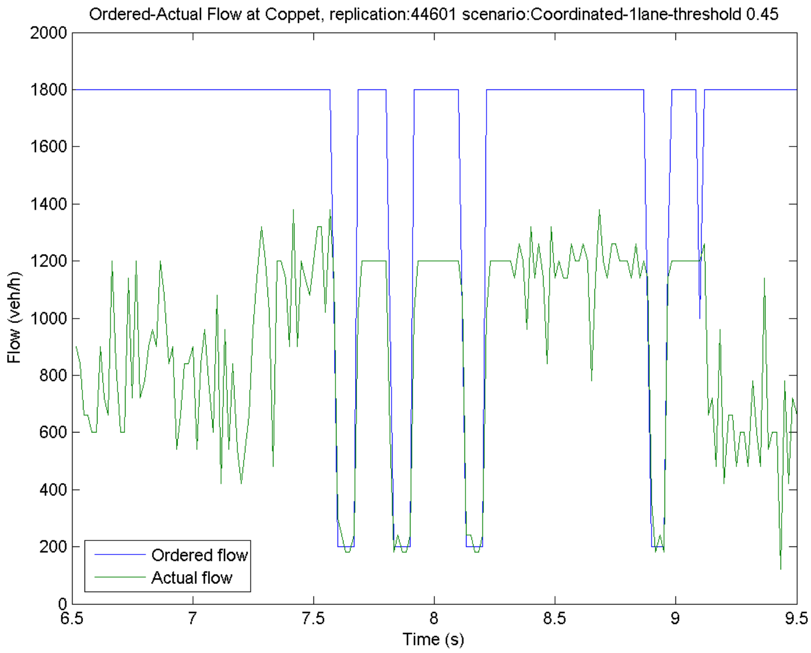
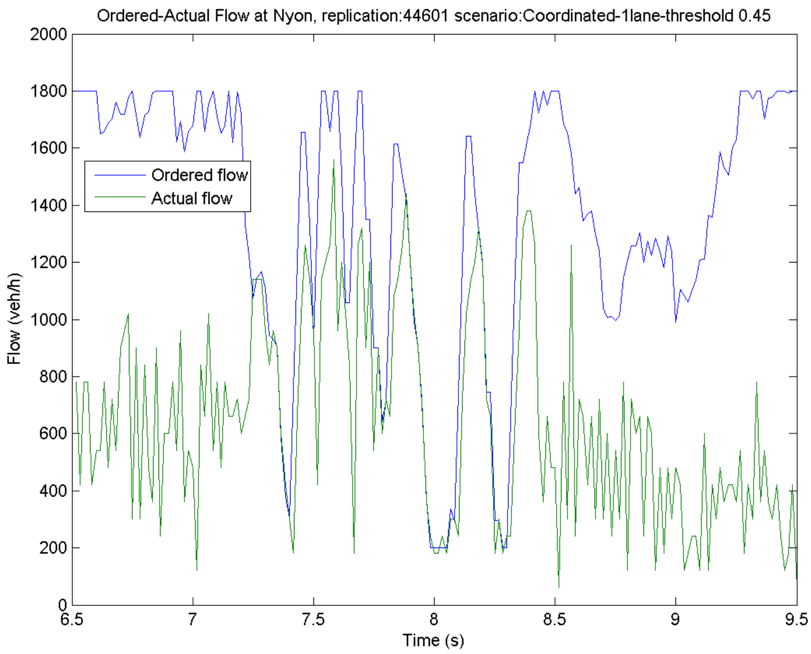


Figure I.2.3.1 Ordered-actual flow for replication 44508


Ordered-Actual Flow at Coppet, replication:44601 scenario:Coordinated-1lane-threshold 0.45
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
2000
1800
1600
1400
1200
1000
800
600
400
200
0
6.5
7
7.5
8
8.5
9
9.5


Ordered-Actual Flow at Nyon, replication:44601 scenario:Coordinated-1lane-threshold 0.45
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
2000
1800
1600
1400
1200
1000
800
600
400
200
0
6.5
7
7.5
8
8.5
9
9.5

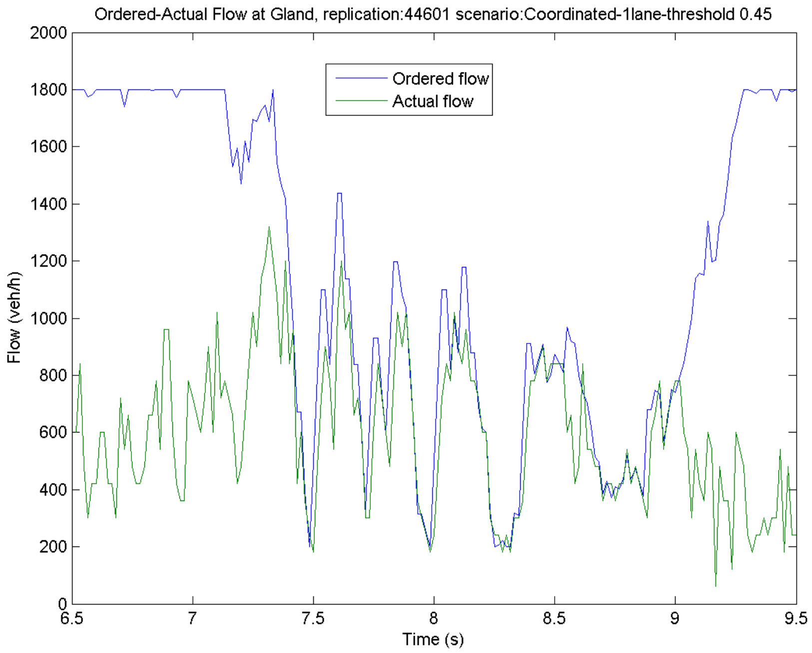
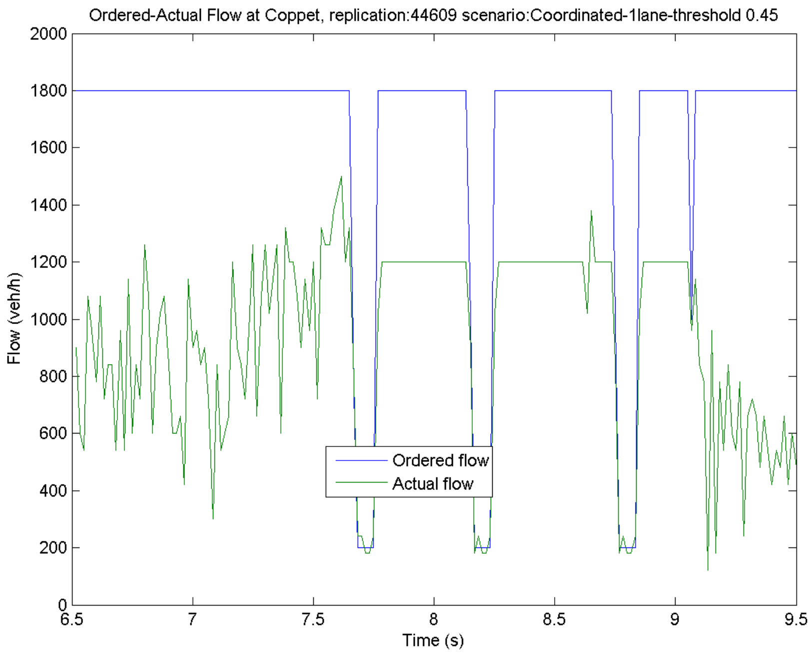
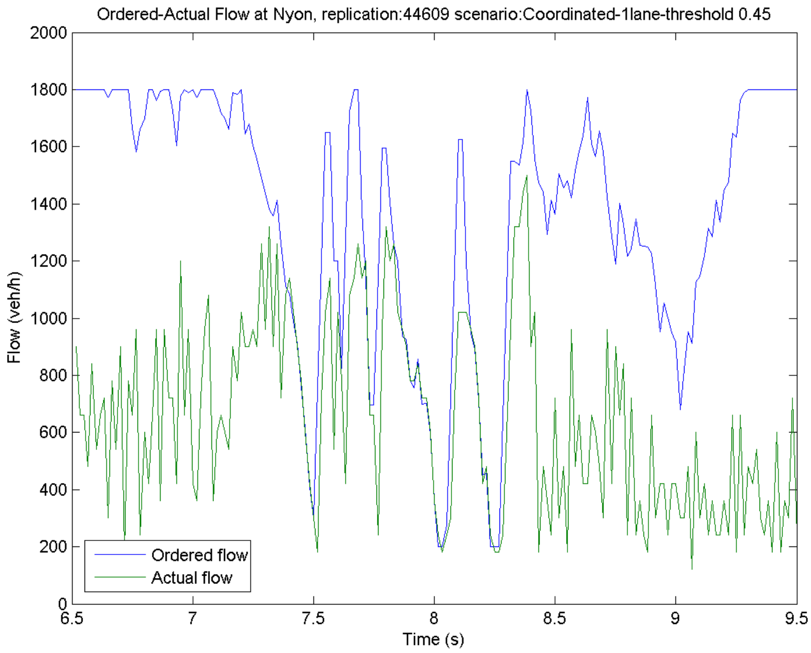


Figure I.2.3.2 Ordered-actual flow for replication 44601





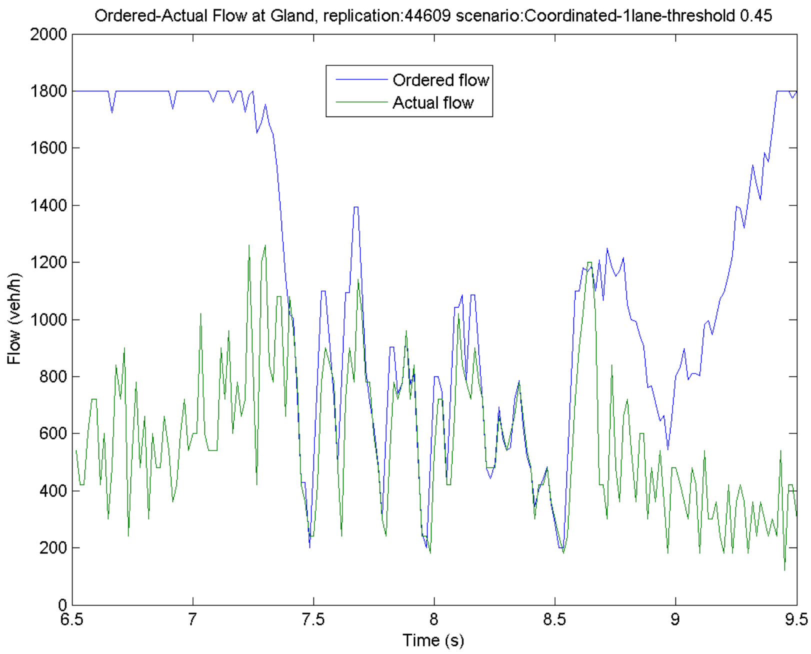
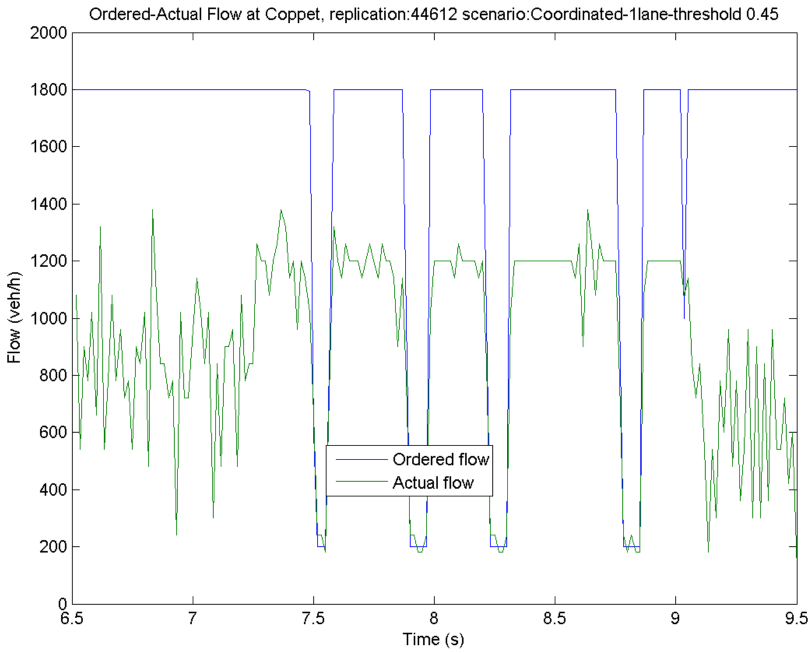
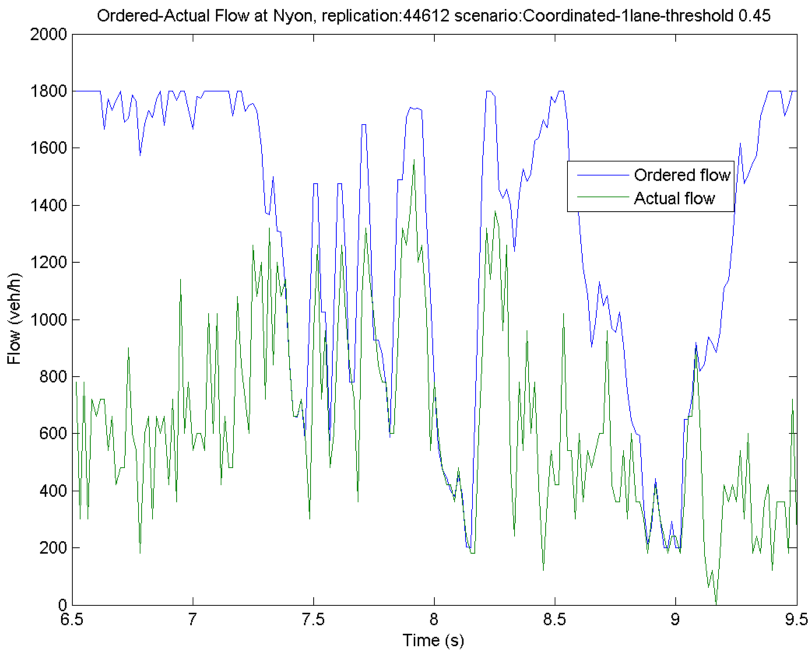


Figure I.2.3.3 Ordered-actual flow for replication 44609


Ordered-Actual Flow at Coppet, replication:44612 scenario:Coordinated-1lane-threshold 0.45
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
0
200
400
600
800
1000
1200
1400
1600
1800
2000
6.5
7
7.5
8
8.5
9
9.5


Ordered-Actual Flow at Nyon, replication:44612 scenario:Coordinated-1lane-threshold 0.45
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
0
200
400
600
800
1000
1200
1400
1600
1800
2000
6.5
7
7.5
8
8.5
9
9.5

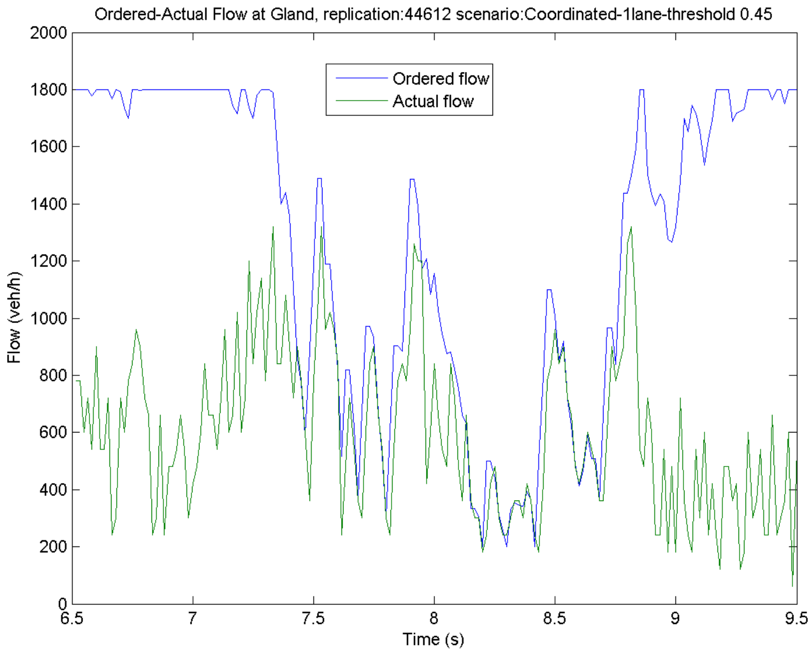
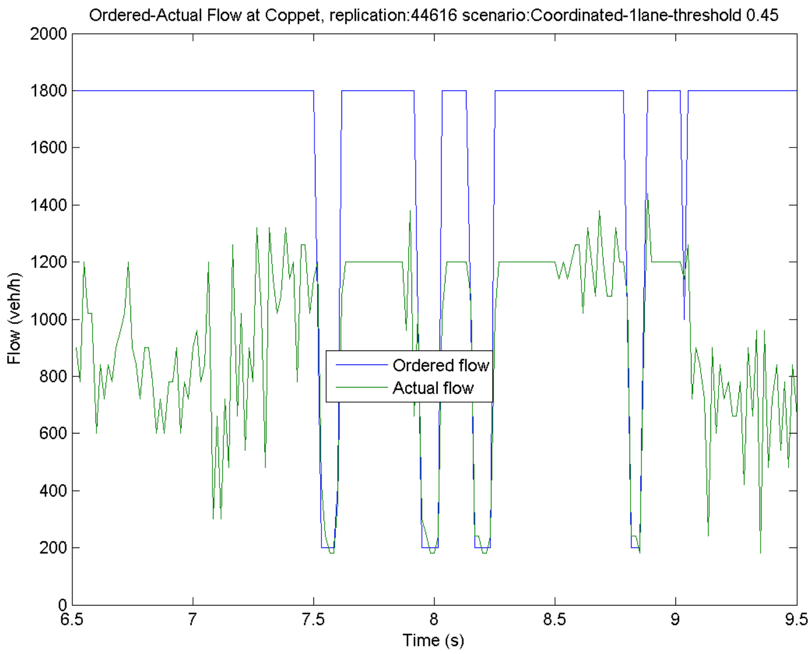


Figure I.2.3.4 Ordered-actual flow for replication 44612



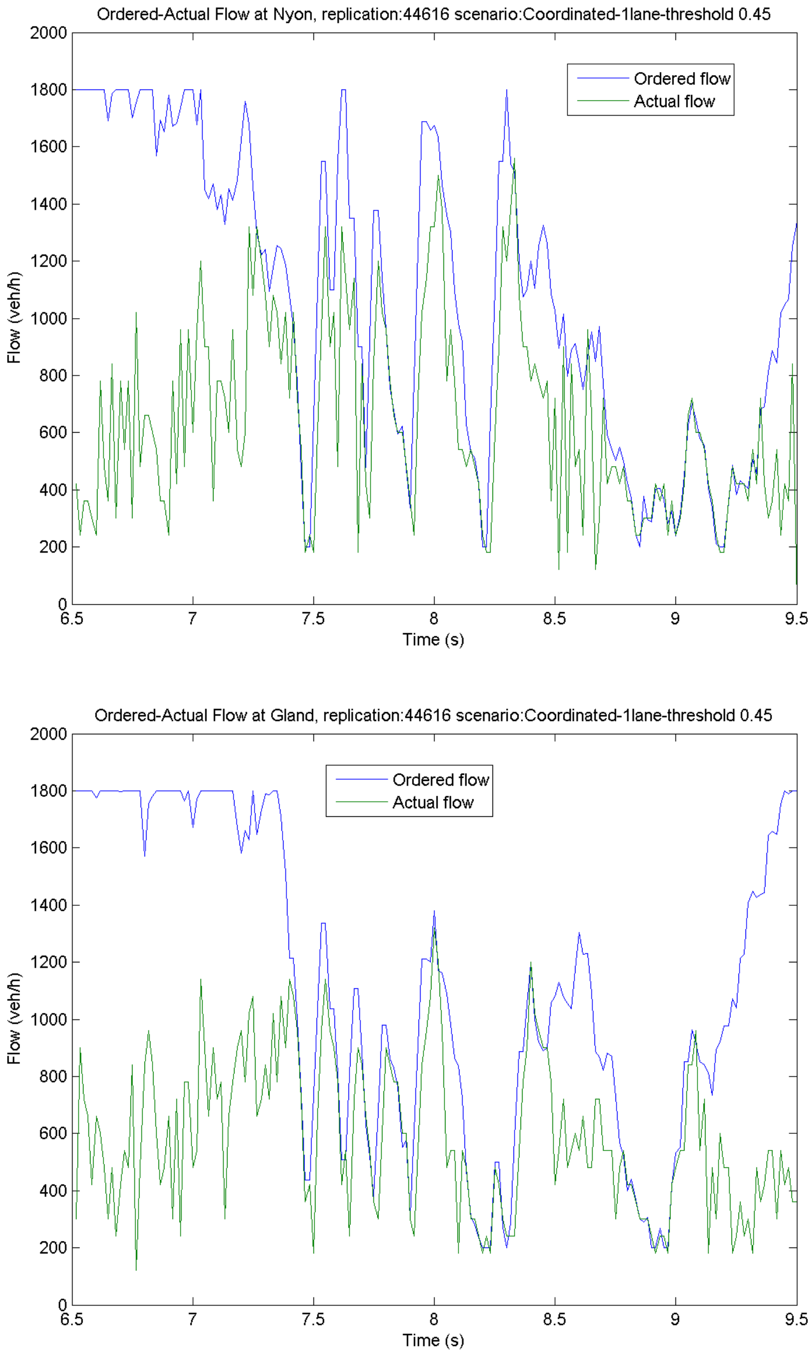
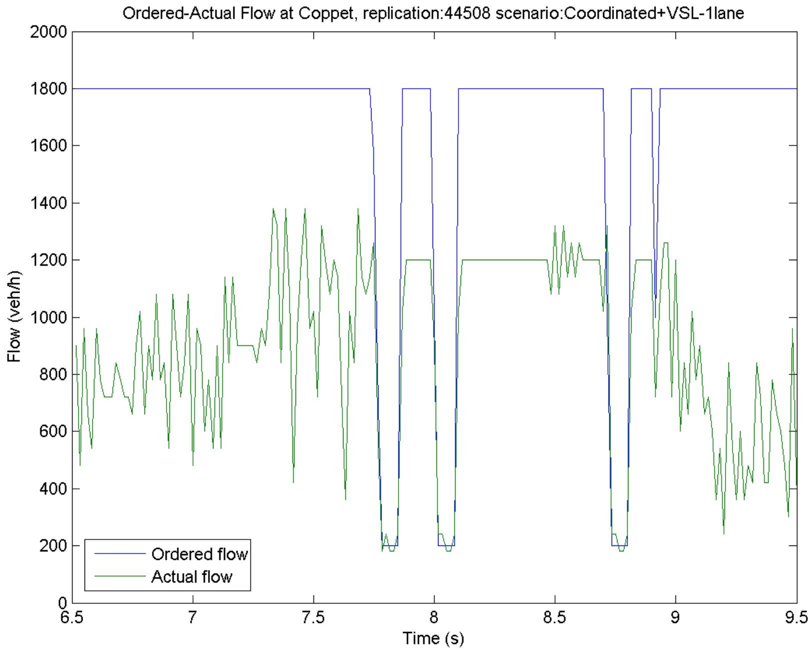
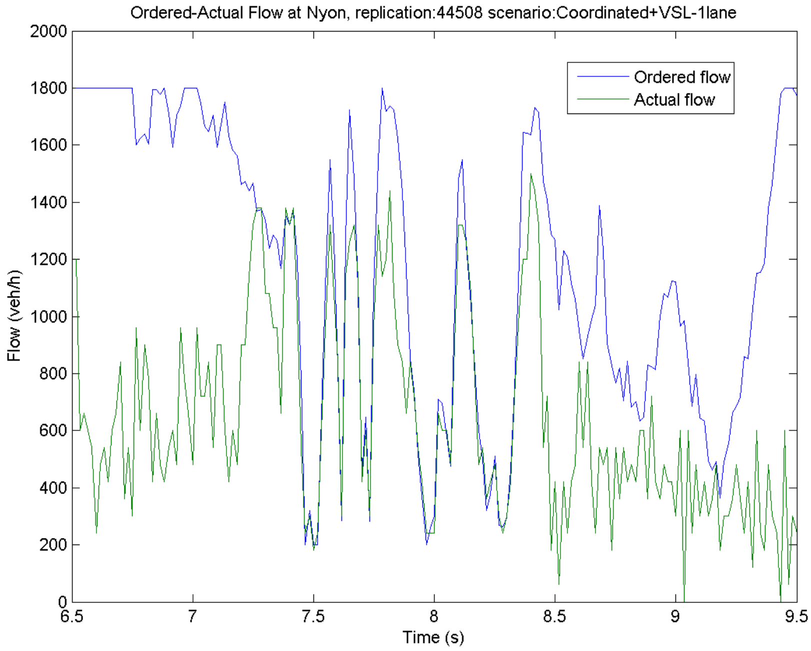


Figure I.2.3.5 Ordered-actual flow for replication 44616

I.2.4 Coordinated+VSL





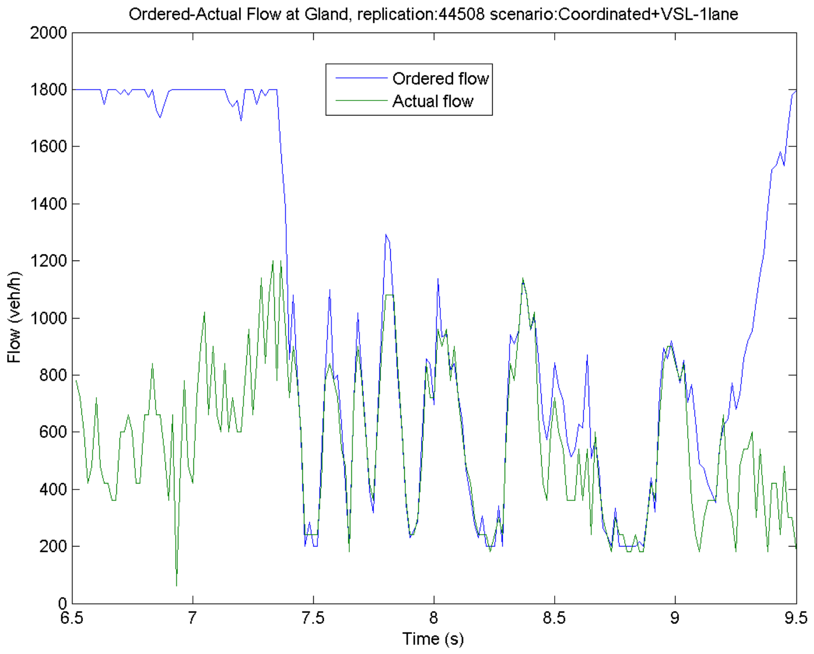
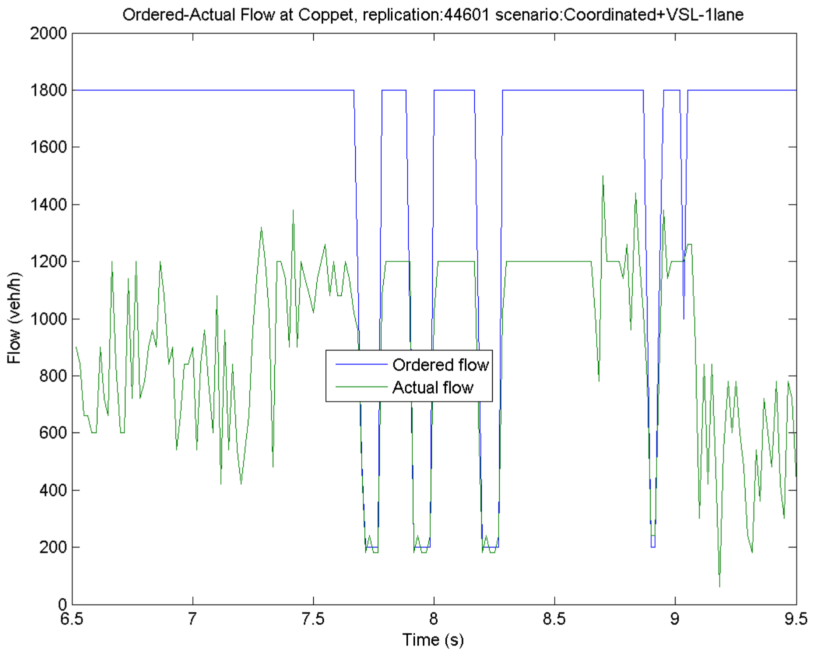
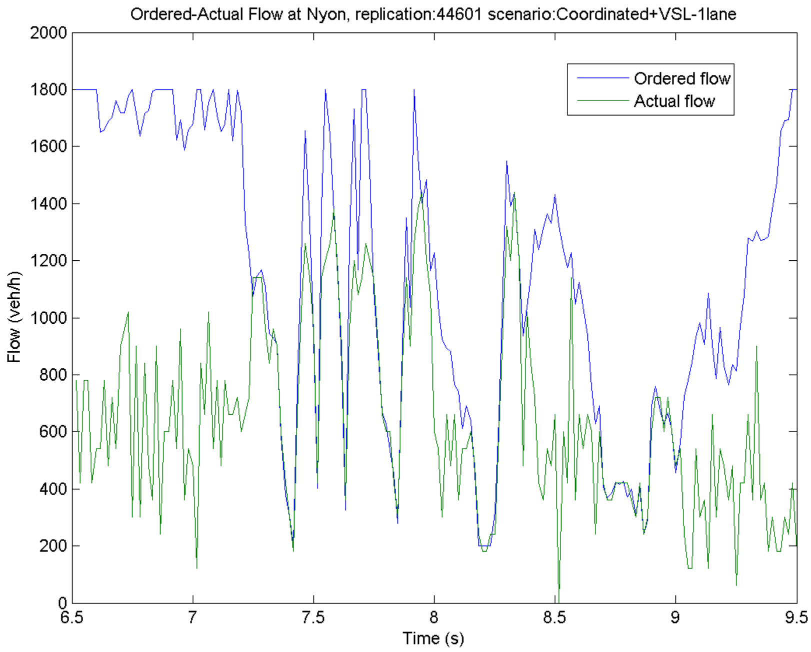


Figure I.2.4.1 Ordered-actual flow for replication 44508





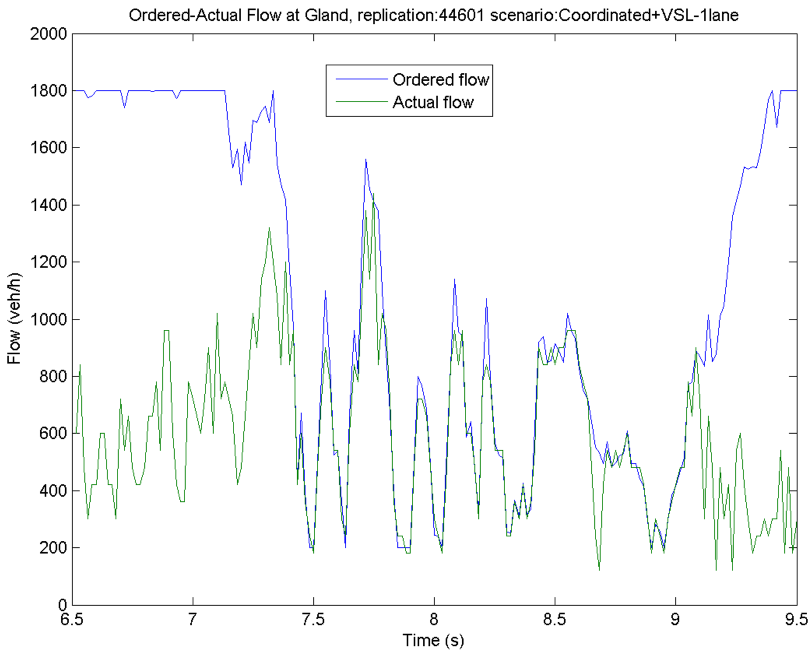
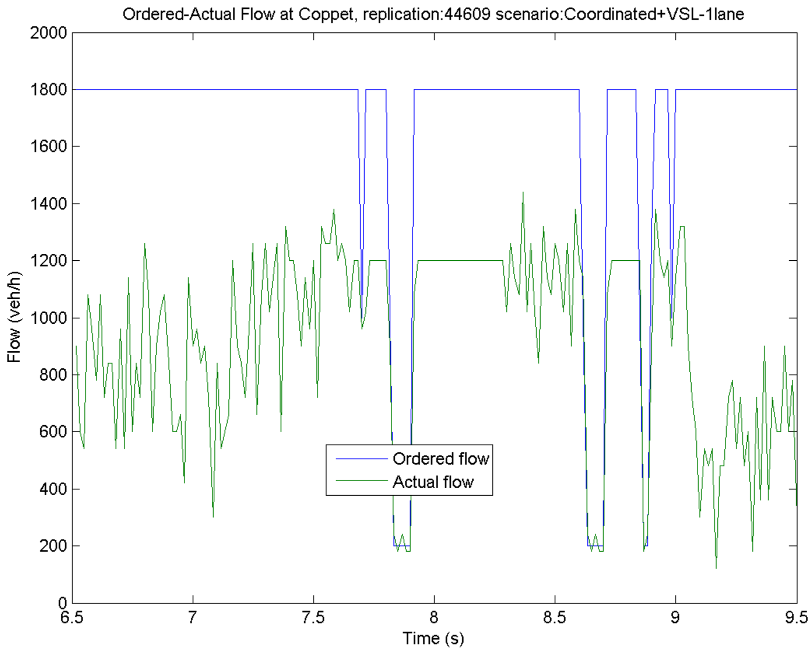
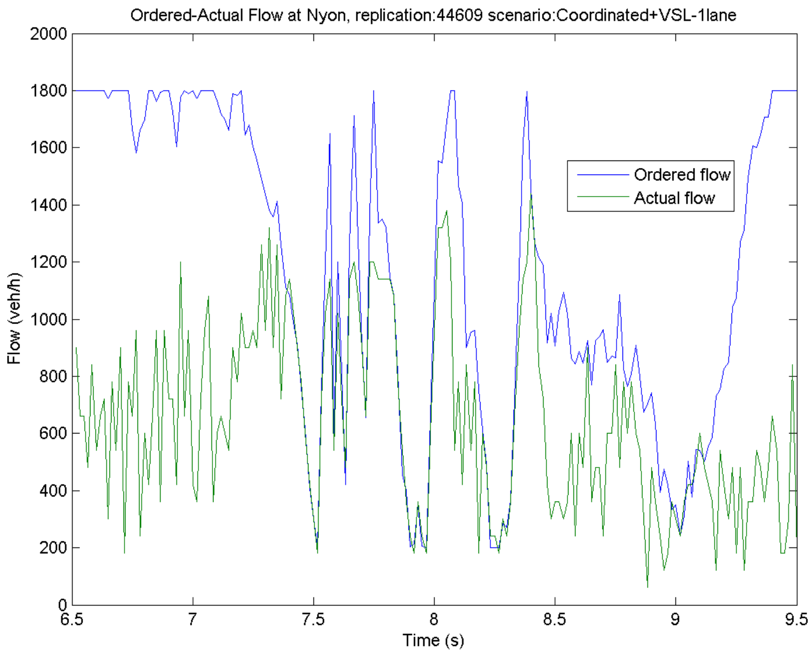


Figure I.2.4.2 Ordered-actual flow for replication 44601


Ordered-Actual Flow at Coppet, replication:44609 scenario:Coordinated+VSL-1lane
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
0
200
400
600
800
1000
1200
1400
1600
1800
2000
6.5
7
7.5
8
8.5
9
9.5


Ordered-Actual Flow at Nyon, replication:44609 scenario:Coordinated+VSL-1lane
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
0
200
400
600
800
1000
1200
1400
1600
1800
2000
6.5
7
7.5
8
8.5
9
9.5

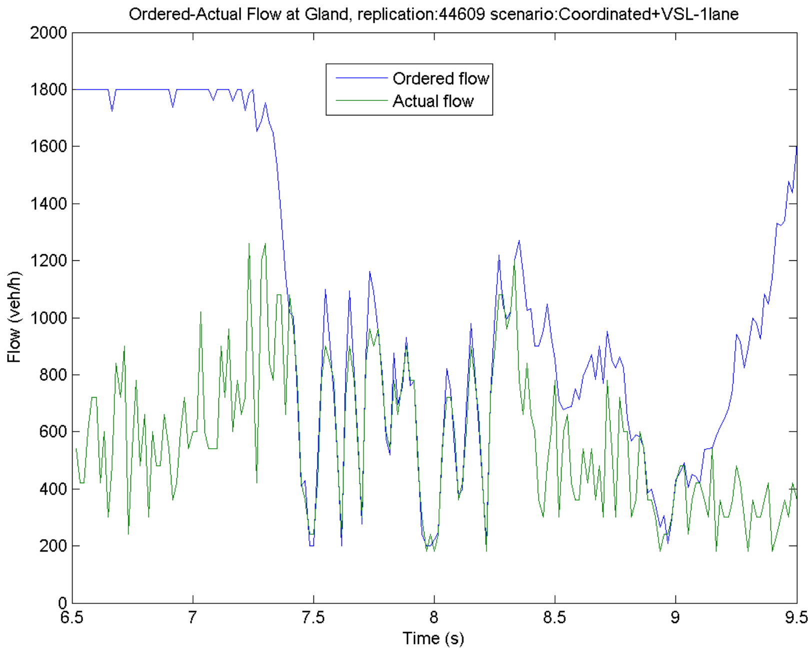
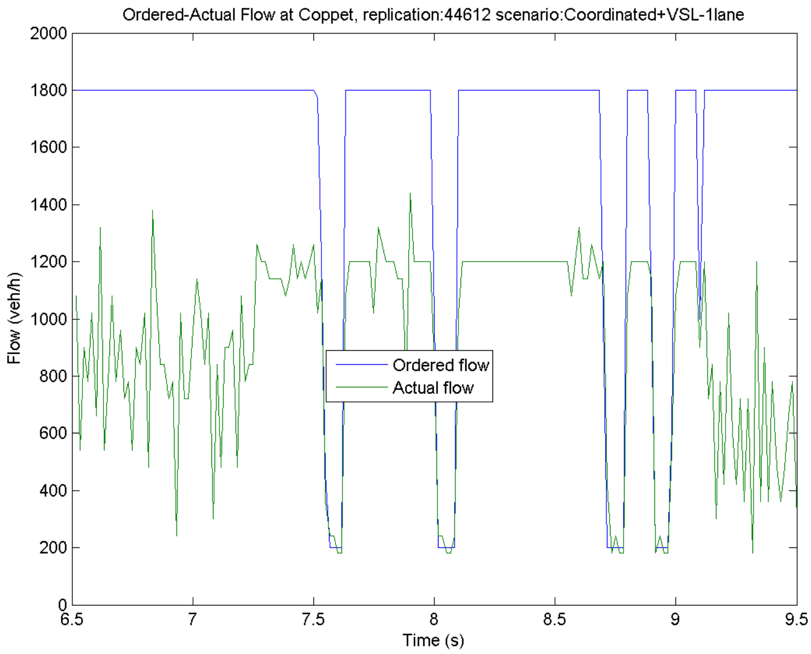


Figure I.2.4.3 Ordered-actual flow for replication 44609



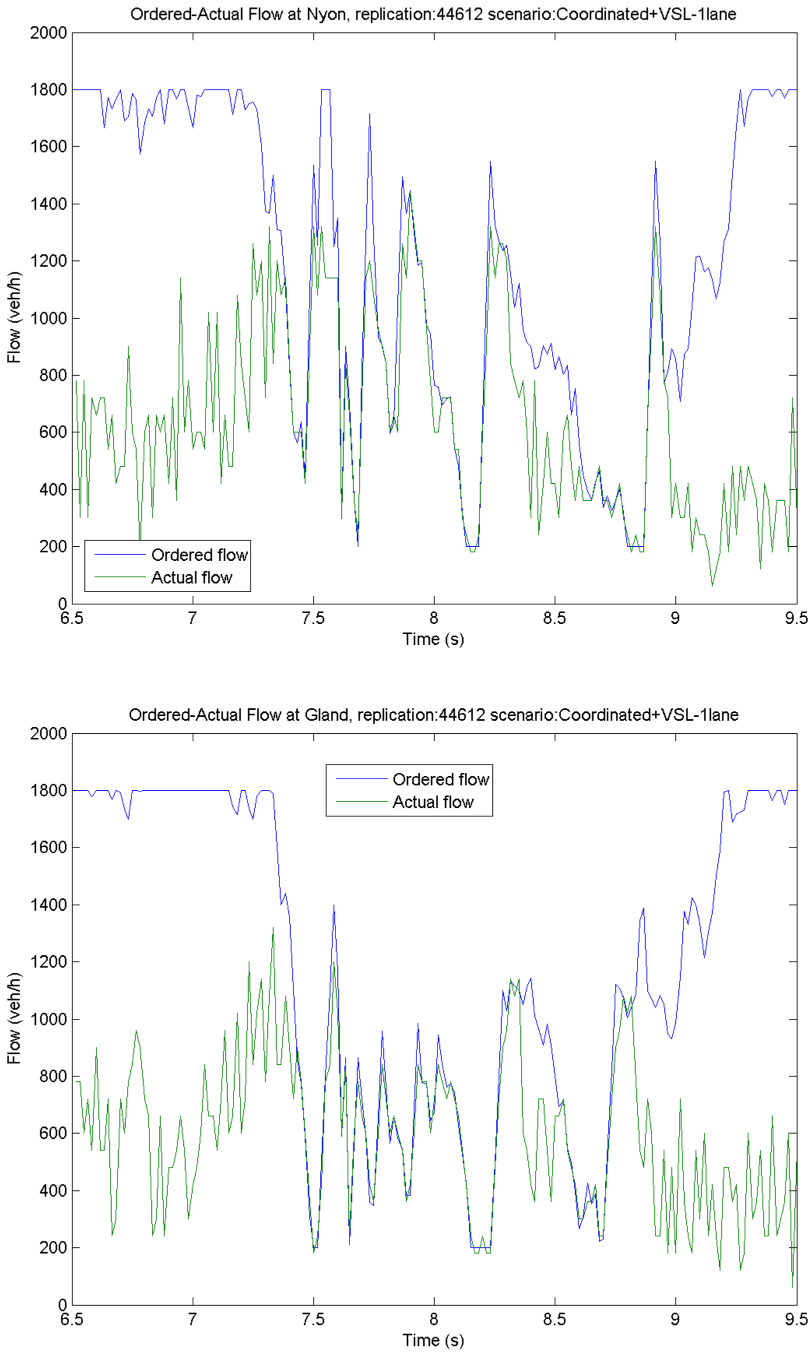
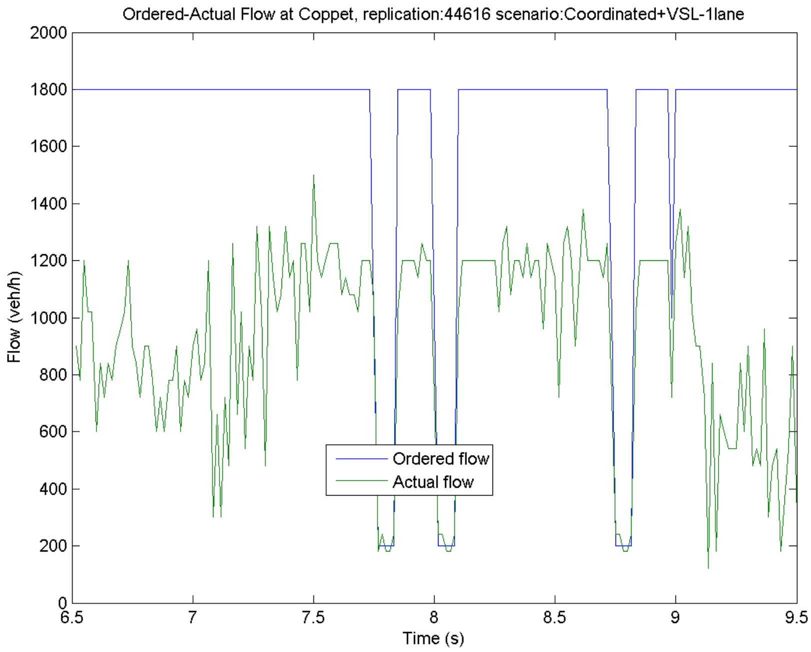
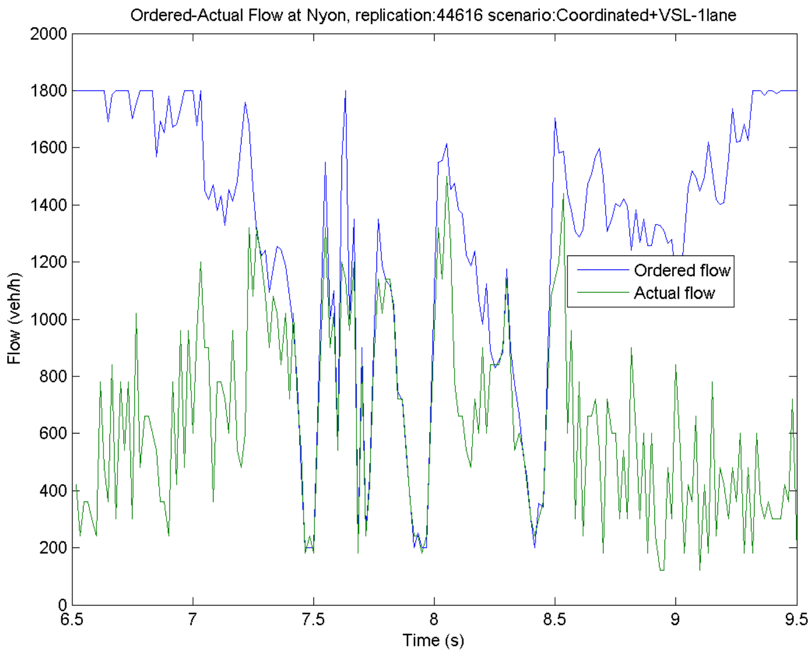


Figure I.2.4.4 Ordered-actual flow for replication 44612


Ordered-Actual Flow at Coppet, replication:44616 scenario:Coordinated+VSL-1lane
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
0
200
400
600
800
1000
1200
1400
1600
1800
2000
6.5
7
7.5
8
8.5
9
9.5


Ordered-Actual Flow at Nyon, replication:44616 scenario:Coordinated+VSL-1lane
Flow (veh/h)
Time (s)
Ordered flow
Actual flow
0
200
400
600
800
1000
1200
1400
1600
1800
2000
6.5
7
7.5
8
8.5
9
9.5

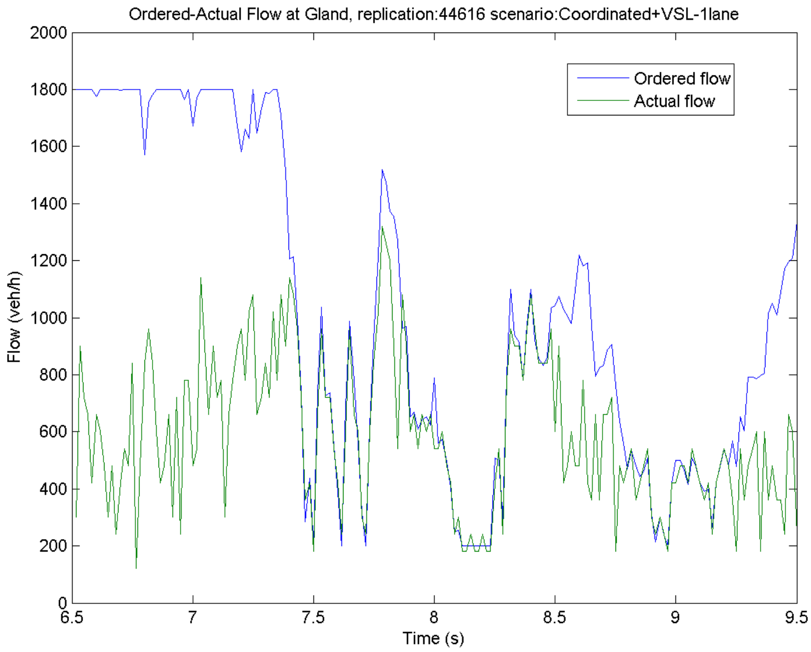
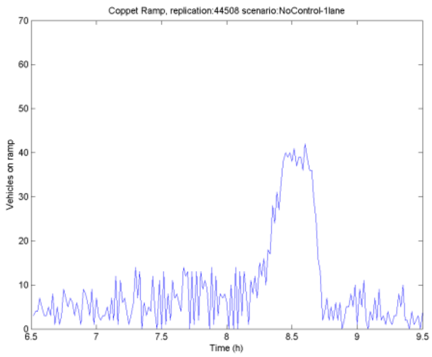


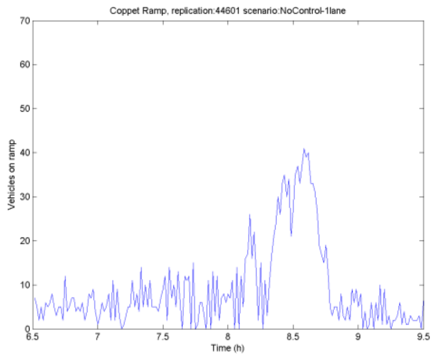
Figure I.2.4.5 Ordered-actual flow for replication 44616

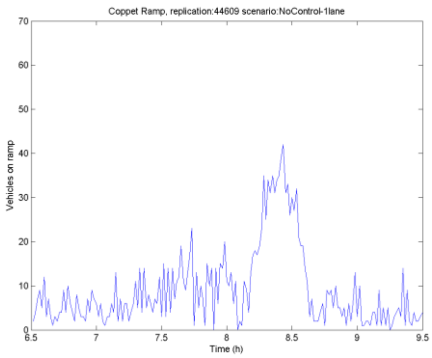
I.3 Ramp Queue Sizes

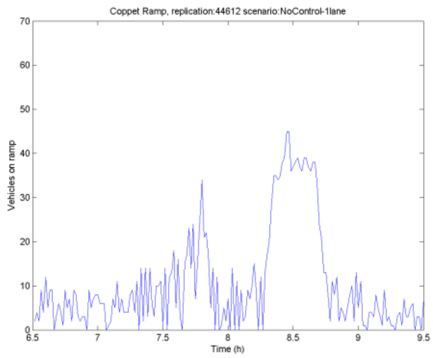
I.3.1 No Control

I.3.1.1 Coppet









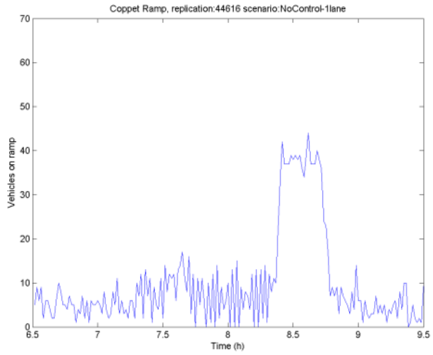


Figure I.3.1.1 Coppet Ramp queue size

I.3.1.2 Nyon

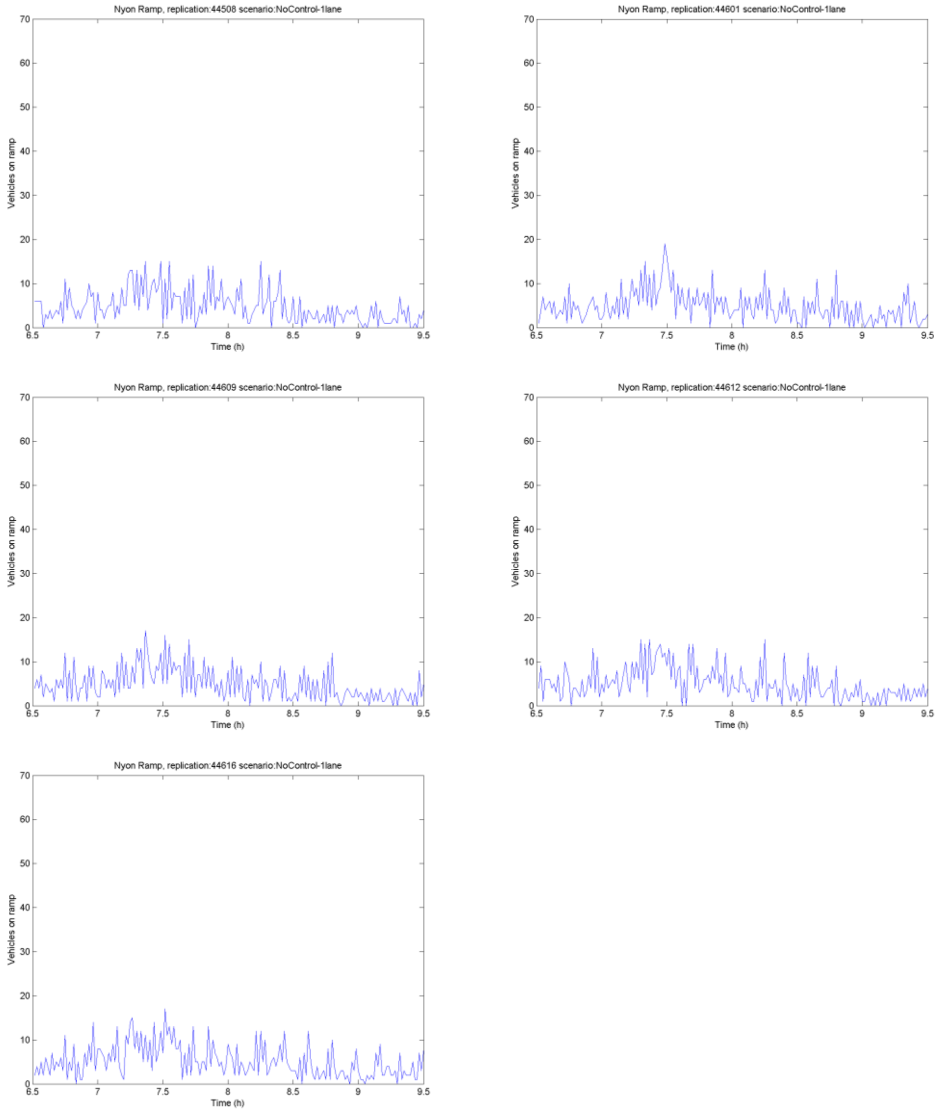


Figure I.3.1.2 Nyon Ramp queue size

I.3.1.3 Gland

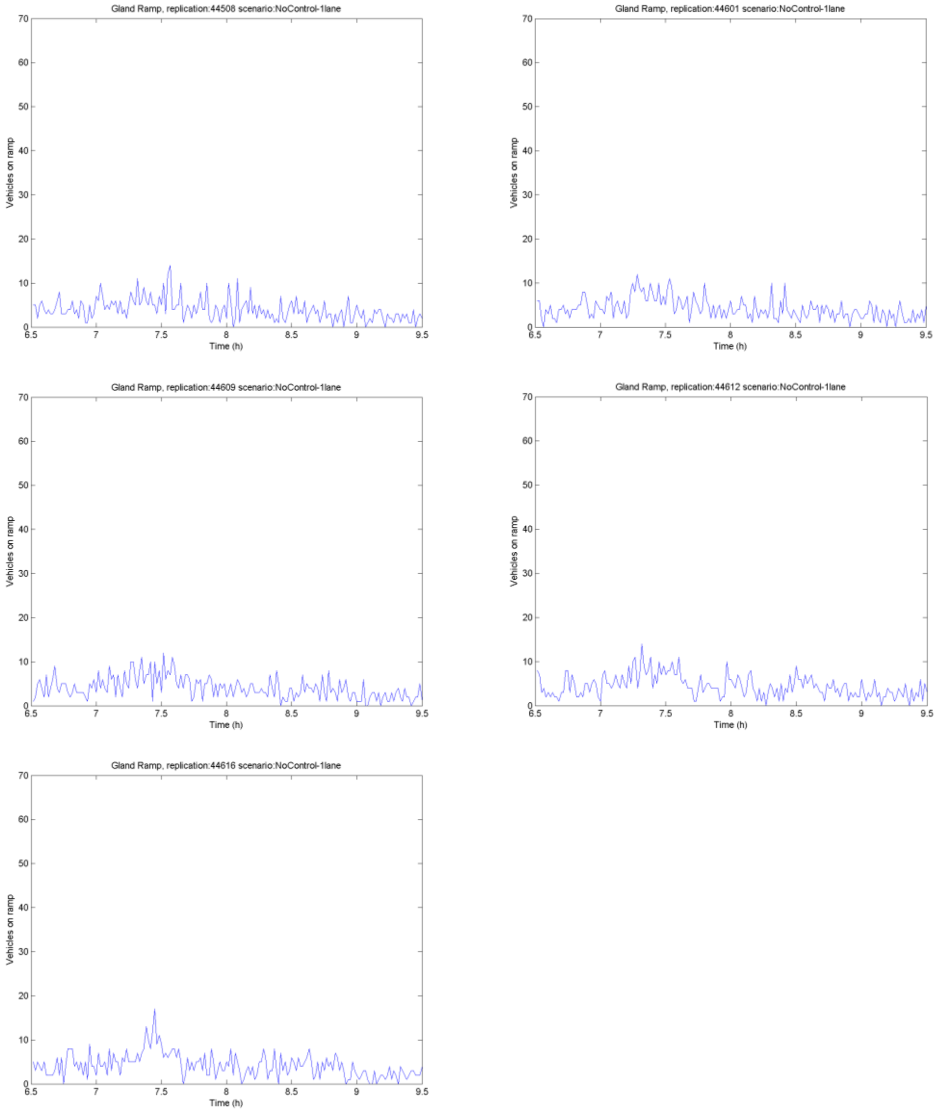
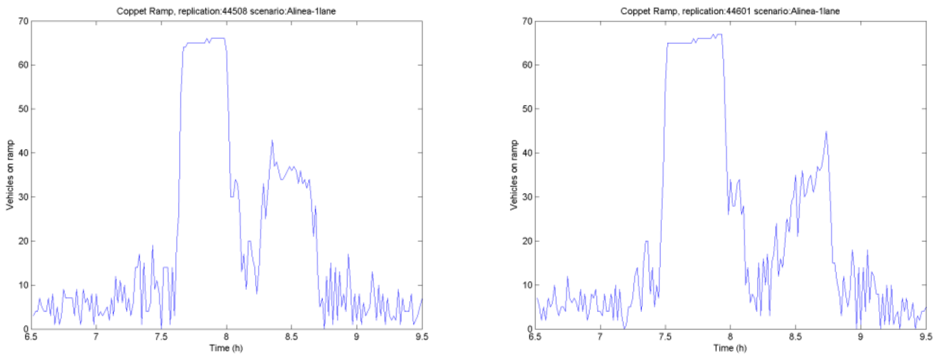


Figure I.3.1.3 Gland Ramp queue size

I.3.2 Alinea

I.3.2.1 Coppet



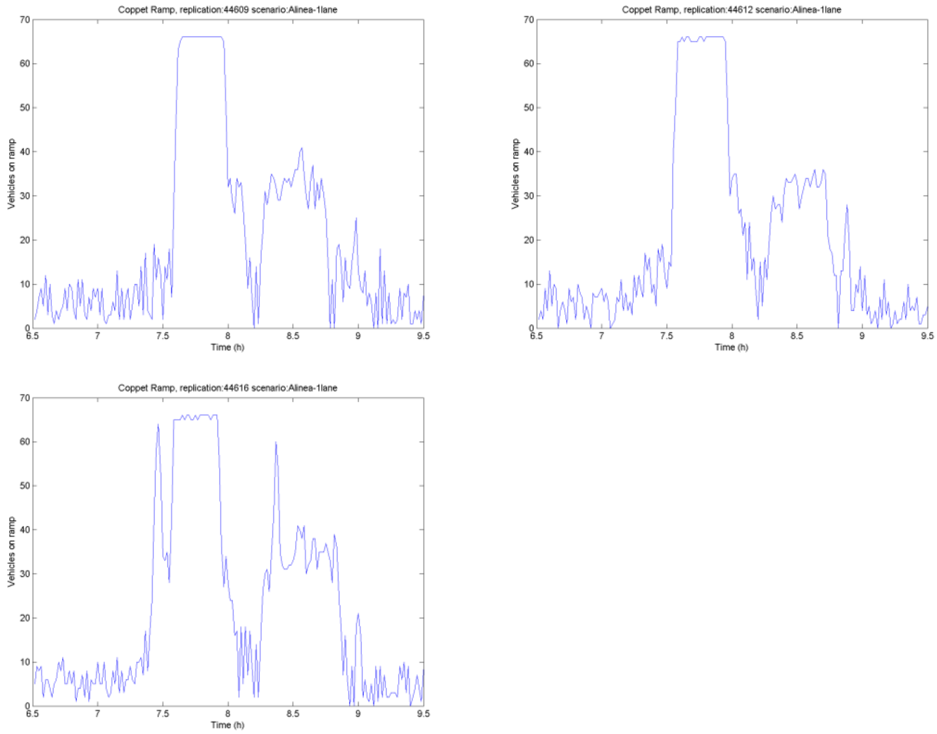
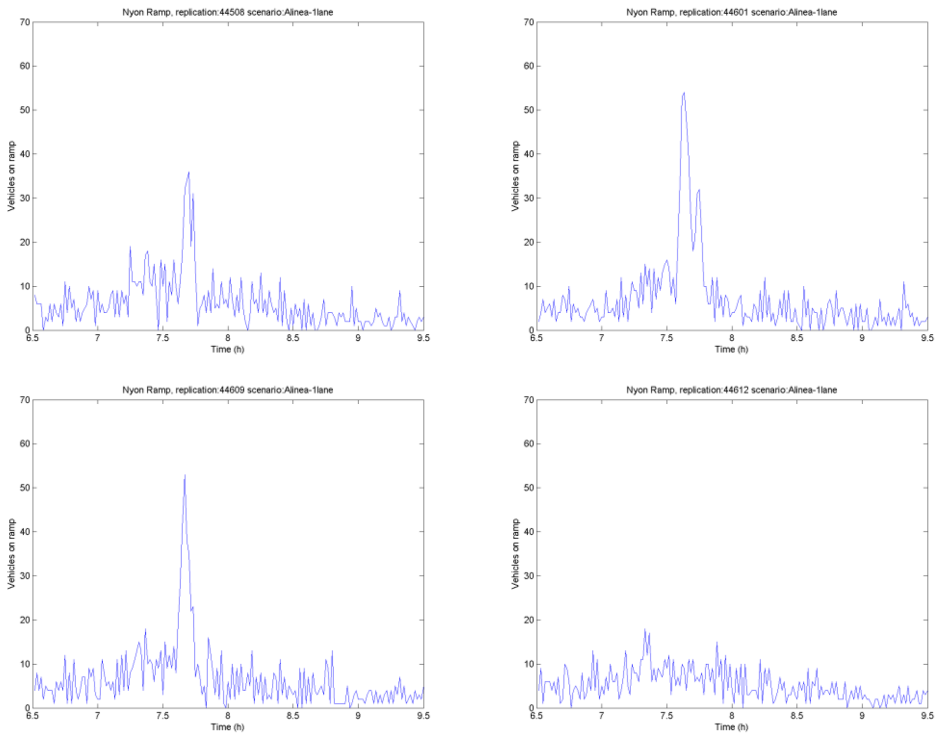


Figure I.3.2.1 Coppet Ramp queue size

I.3.2.3 Nyon



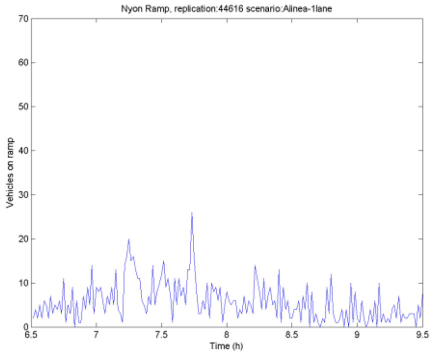


Figure I.3.2.2 Nyon Ramp queue size

I.3.2.3 Gland

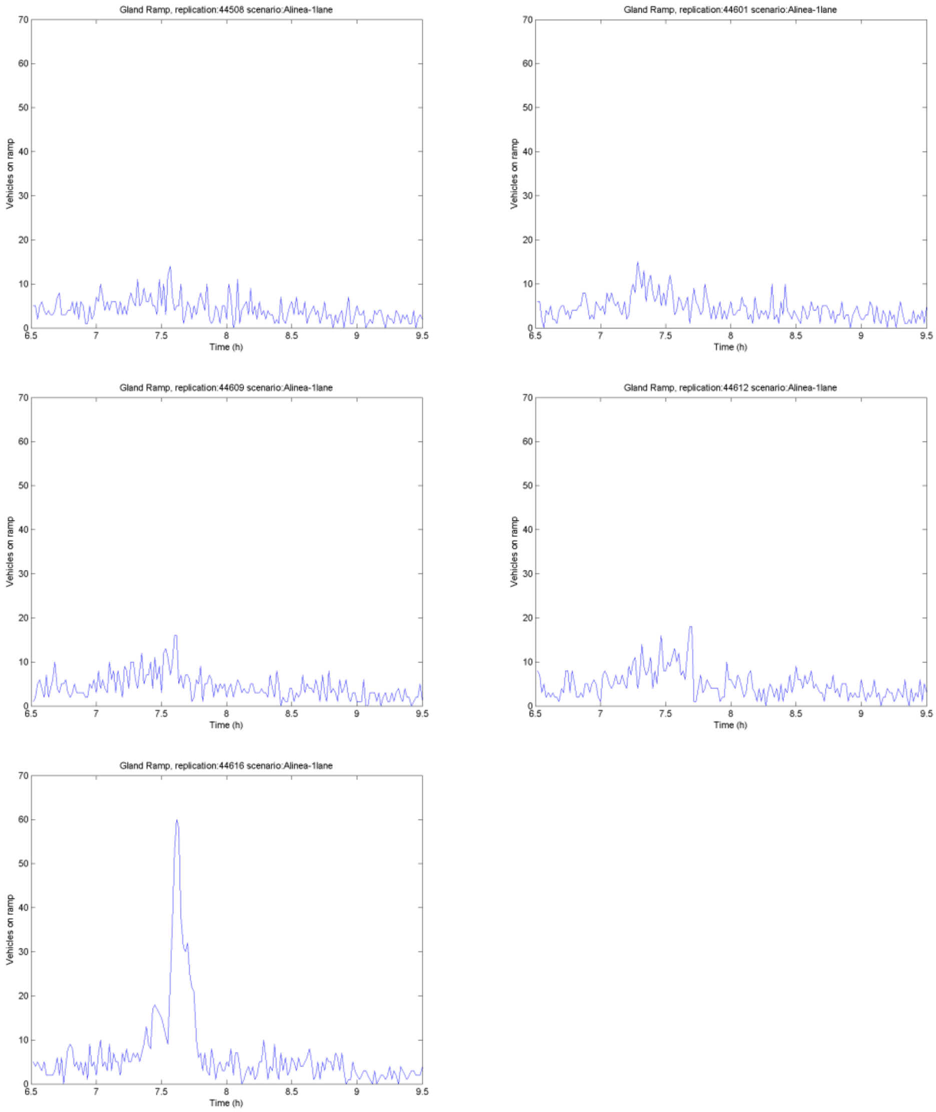


Figure I.3.2.3 Gland Ramp queue size

I.3.3 Alinea with Queue Constraint

I.3.3.1 Coppet

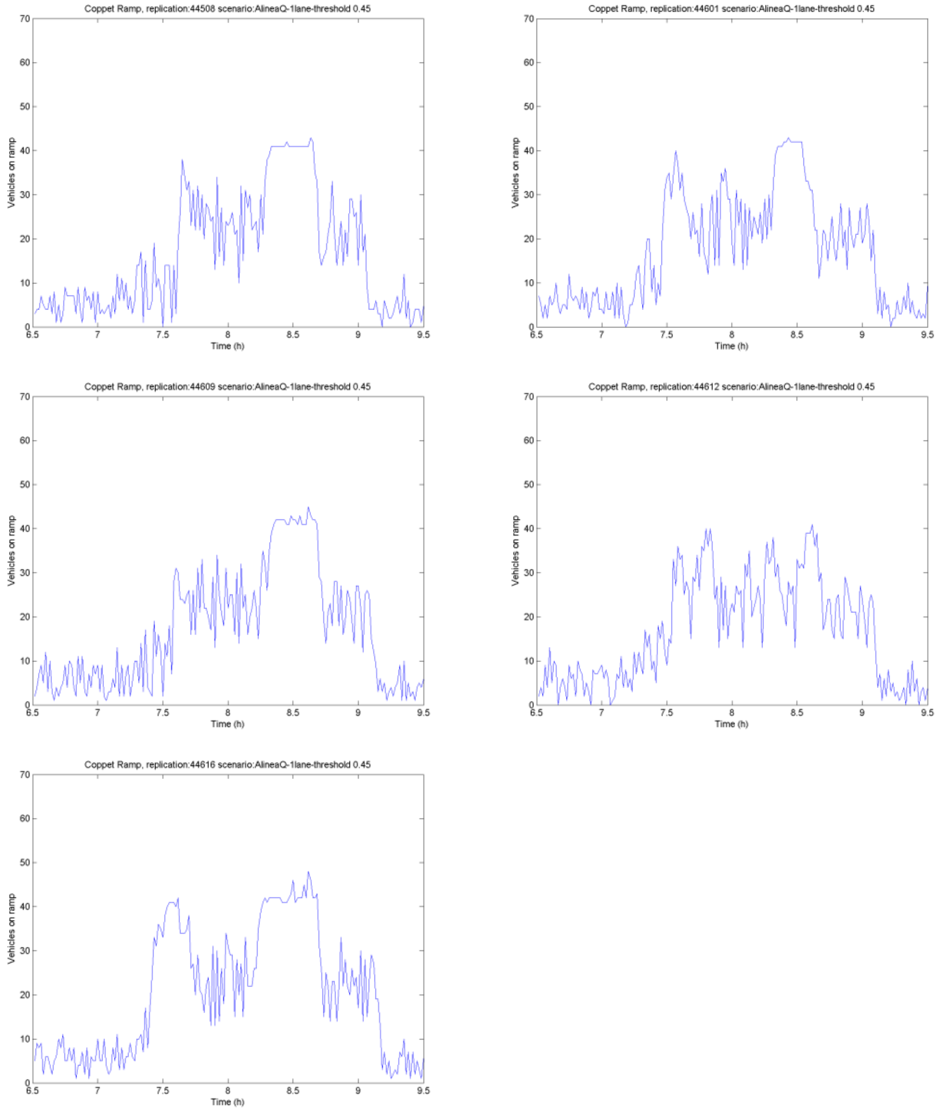
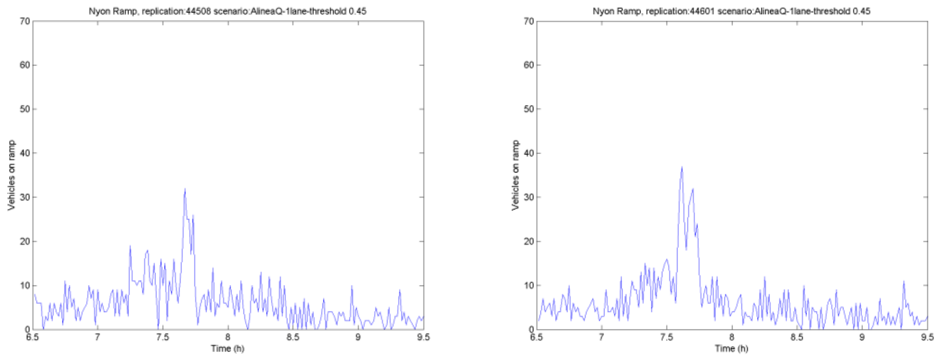


Figure I.3.3.1 Coppet Ramp queue size

I.3.3.2 Nyon



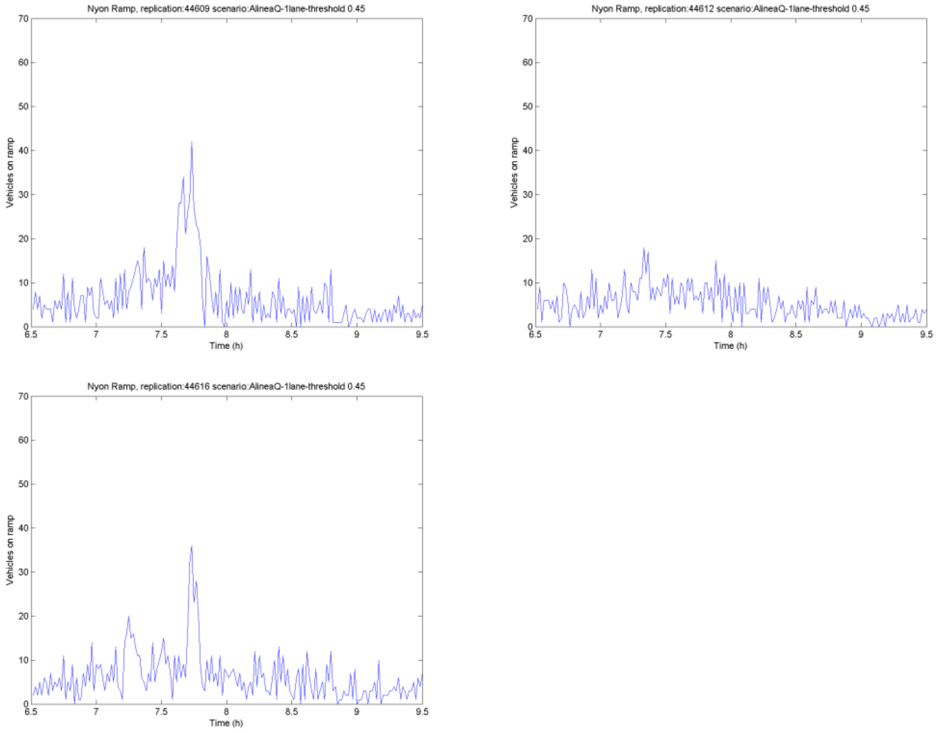
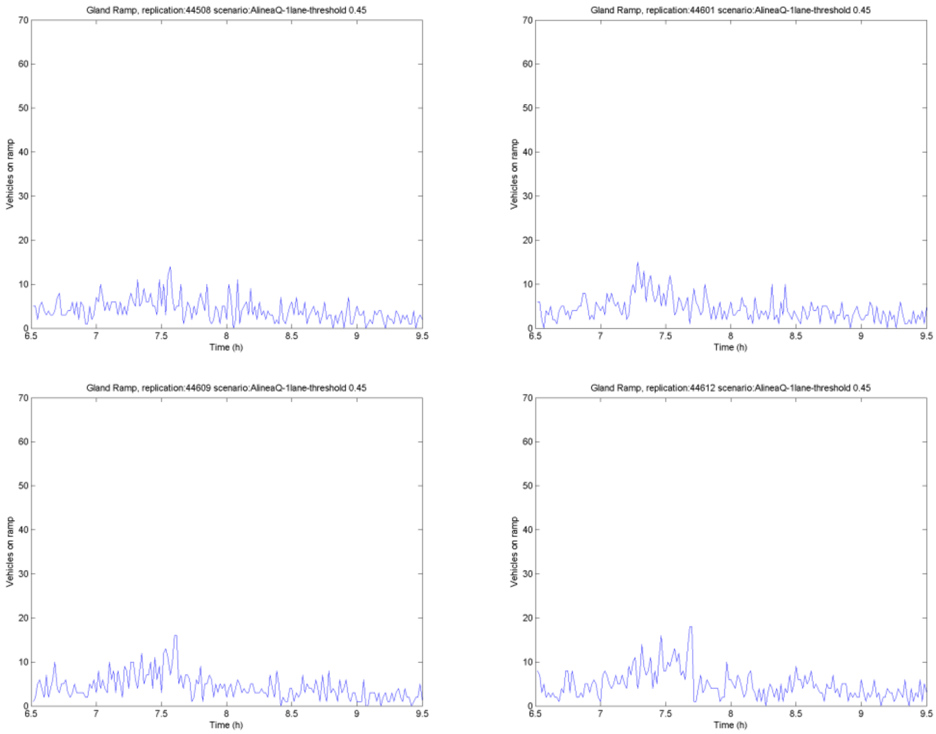


Figure I.3.3.2 Nyon Ramp queue size

I.3.3.3 Gland



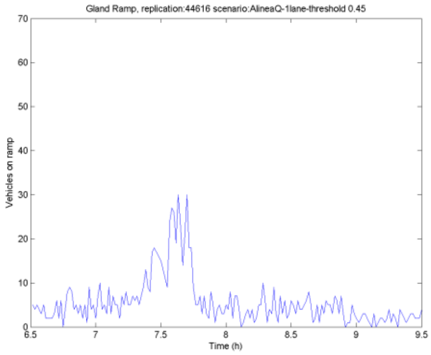


Figure I.3.3.3 Gland Ramp queue size

I.3.4 Coordinated

I.3.4.1 Coppet

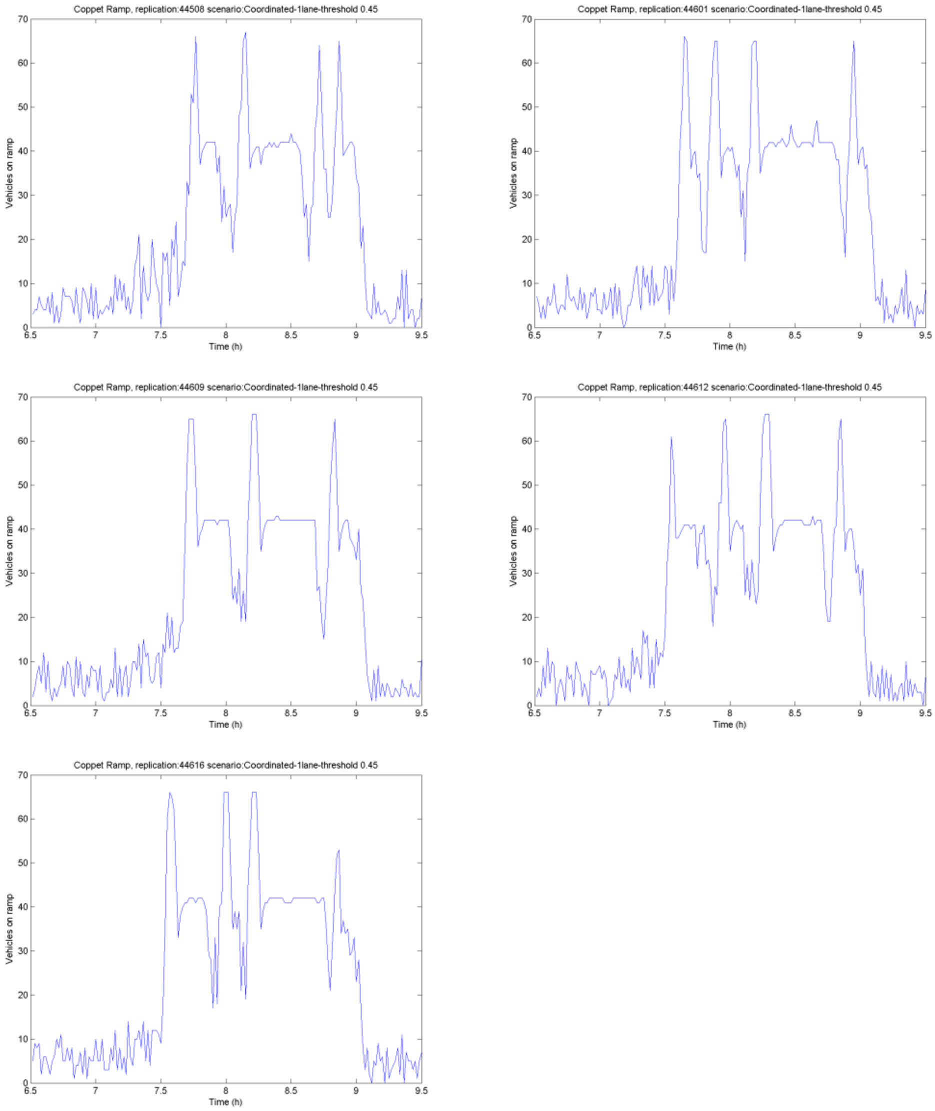


Figure I.3.4.1 Coppet Ramp queue size

I.3.4.2 Nyon

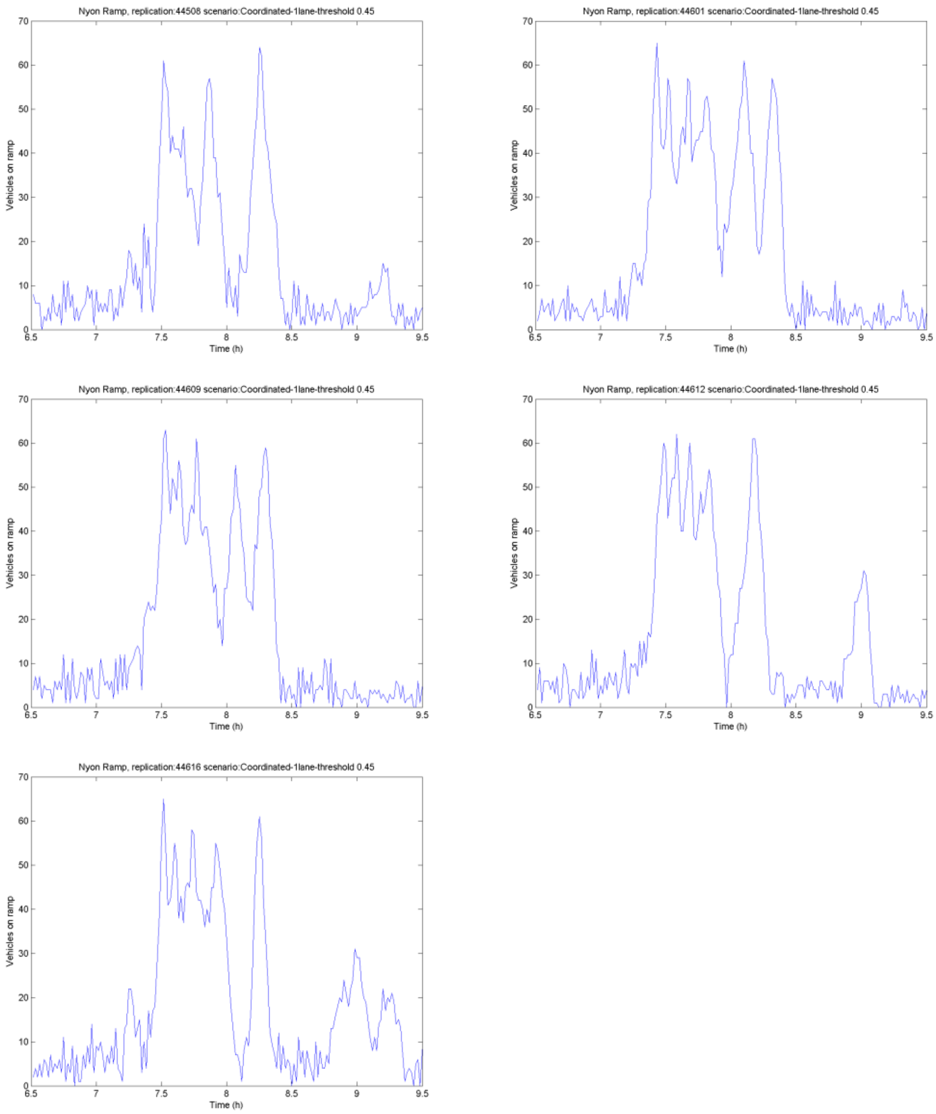
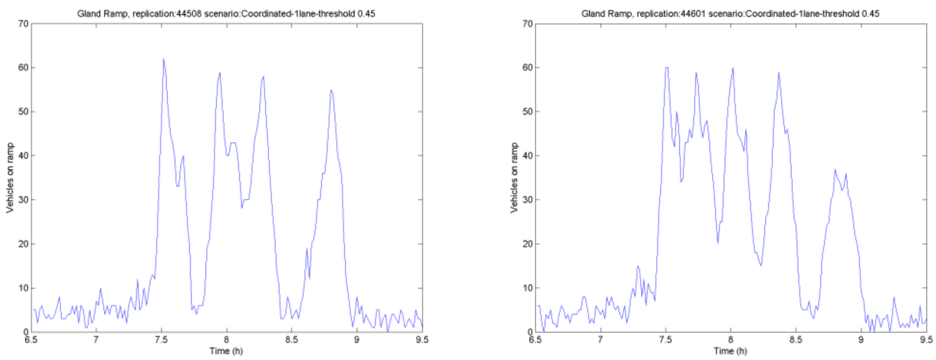


Figure I.3.4.2 Nyon Ramp queue size

I.3.4.3 Gland



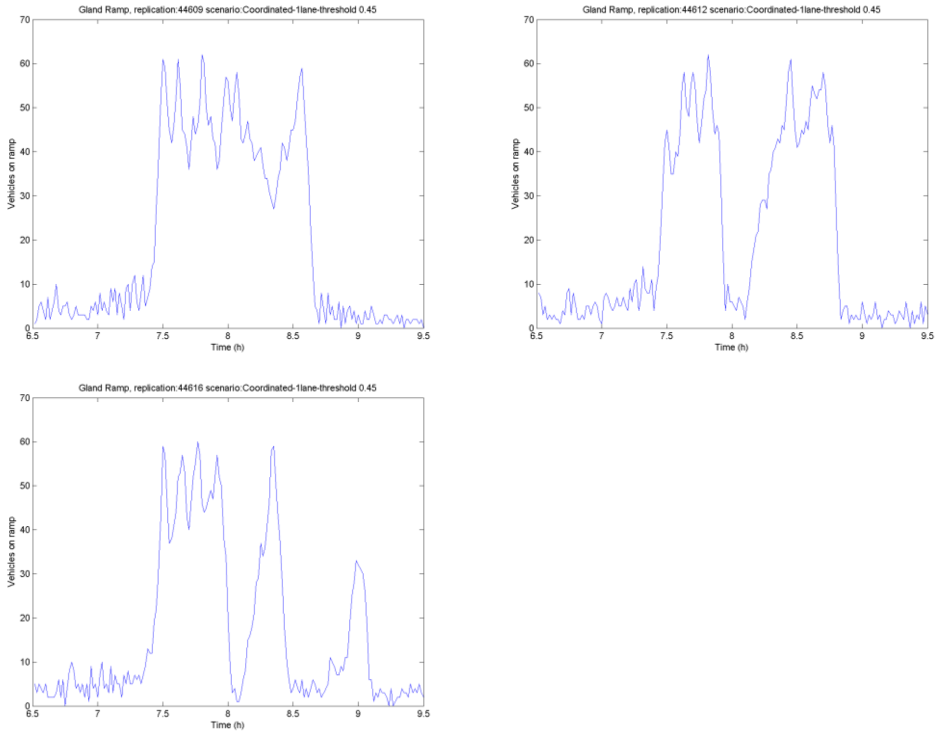
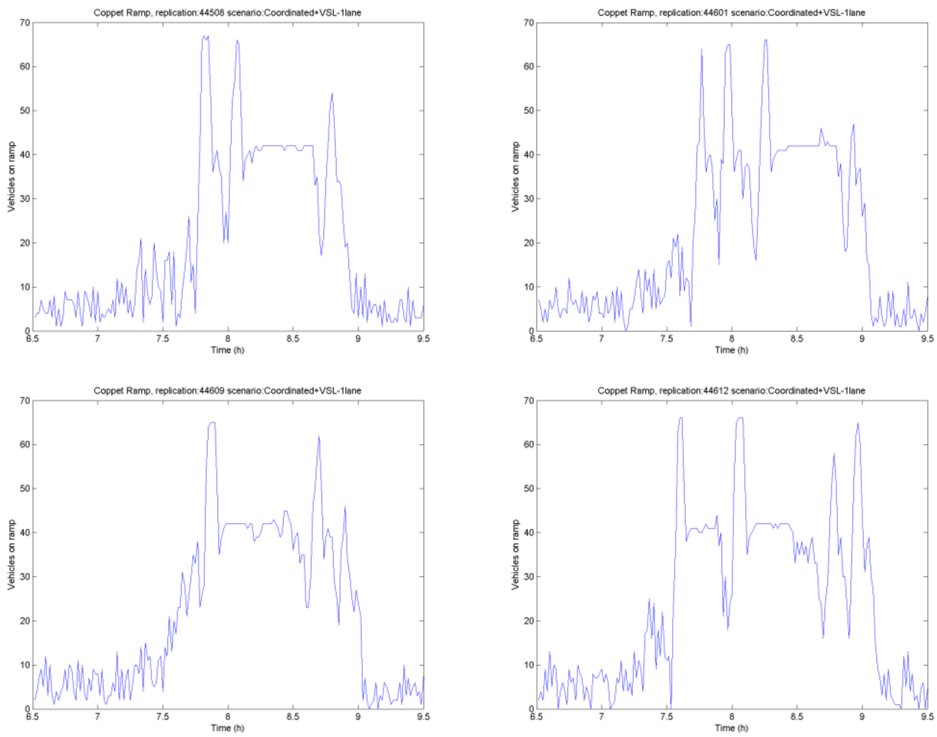


Figure I.3.4.3 Gland Ramp queue size

I.3.5 Coordinated+VSL

I.3.5.1 Coppet



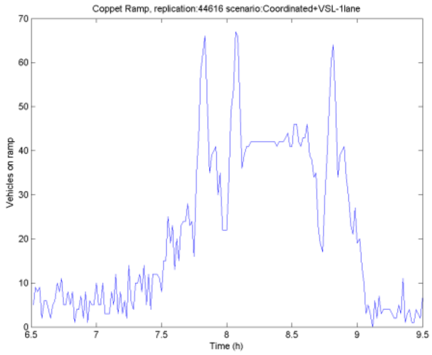


Figure I.3.5.1 Coppet Ramp queue size

I.3.5.2 Nyon

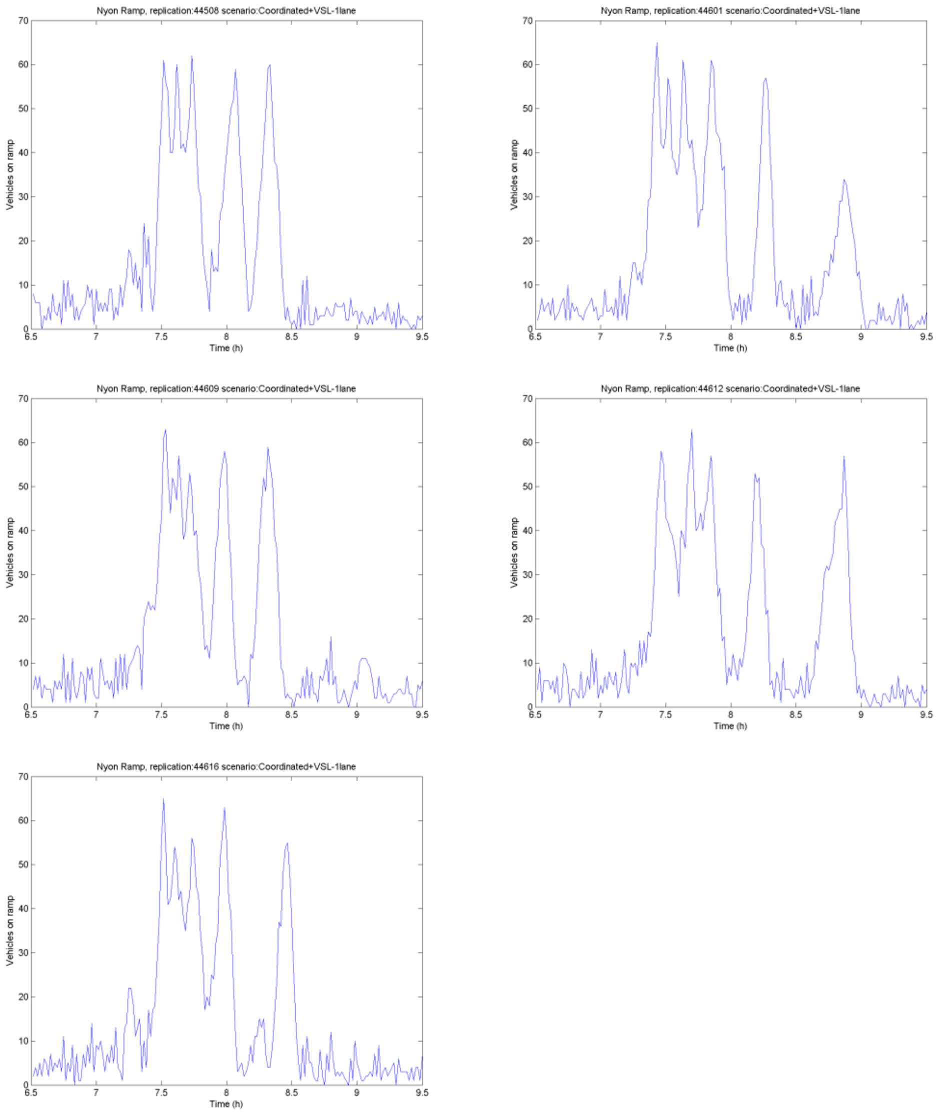


Figure I.3.5.2 Nyon Ramp queue size

I.3.5.3 Gland

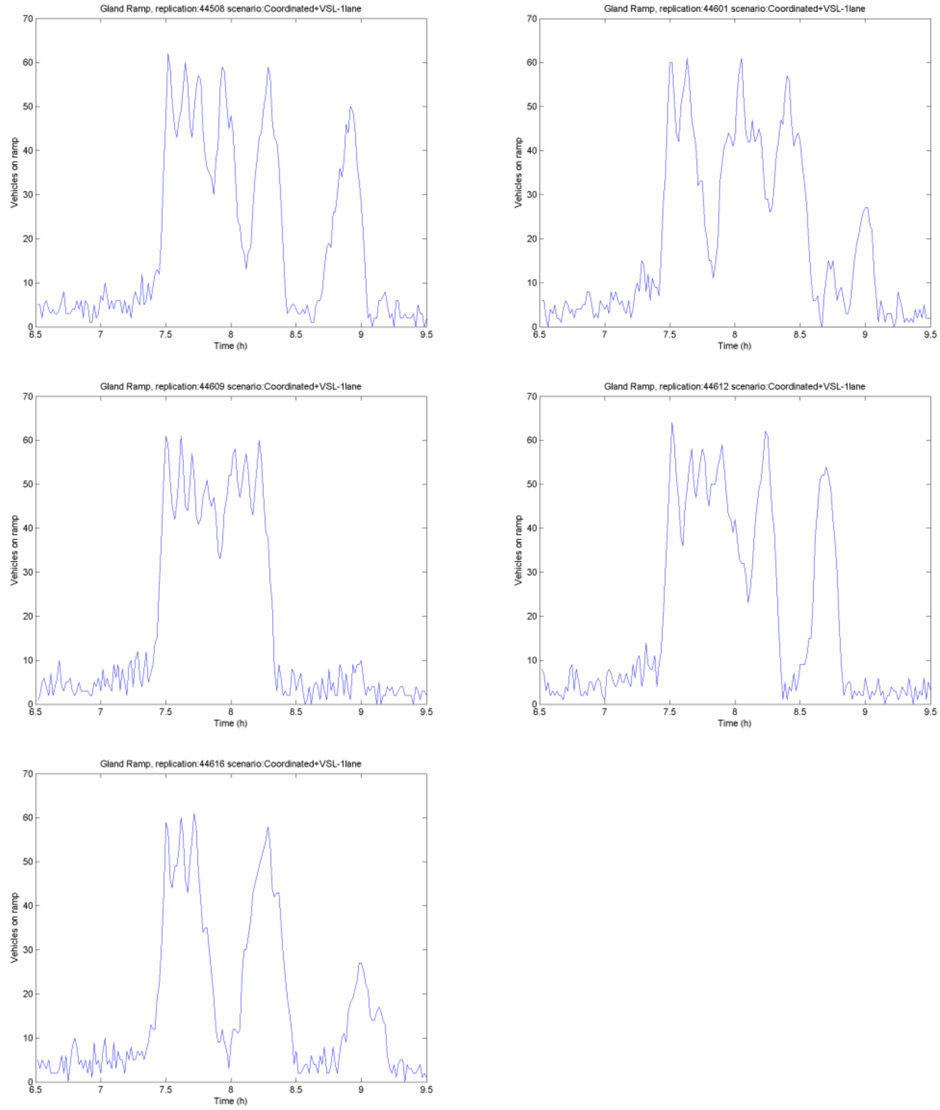


Figure I.3.5.3 Gland Ramp queue size

I.4 +10% Demand Scenario

I.4.1 No Control

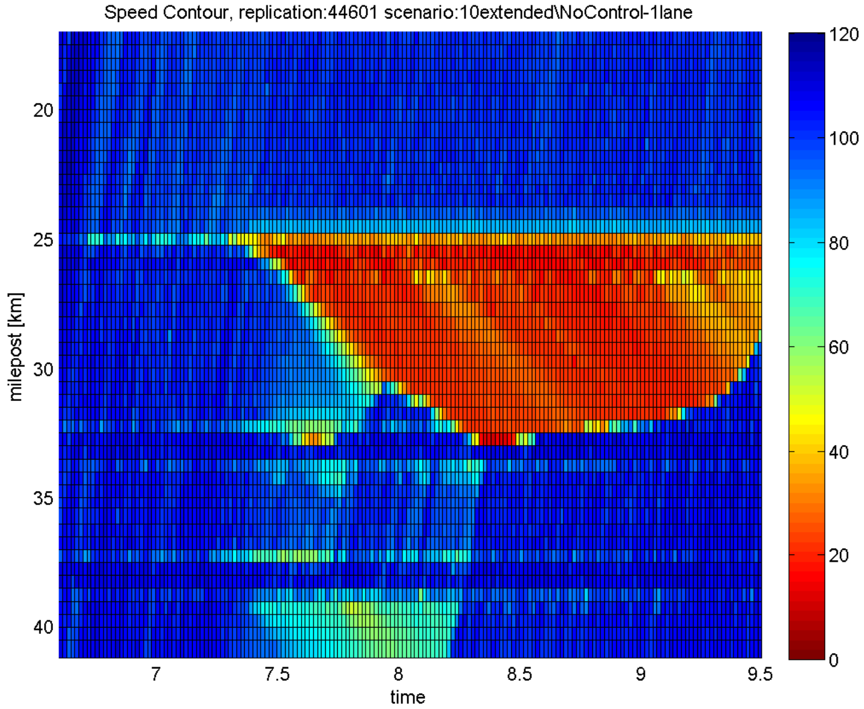


Figure I.4.1 No Control speed contour

I.4.2 Alinea

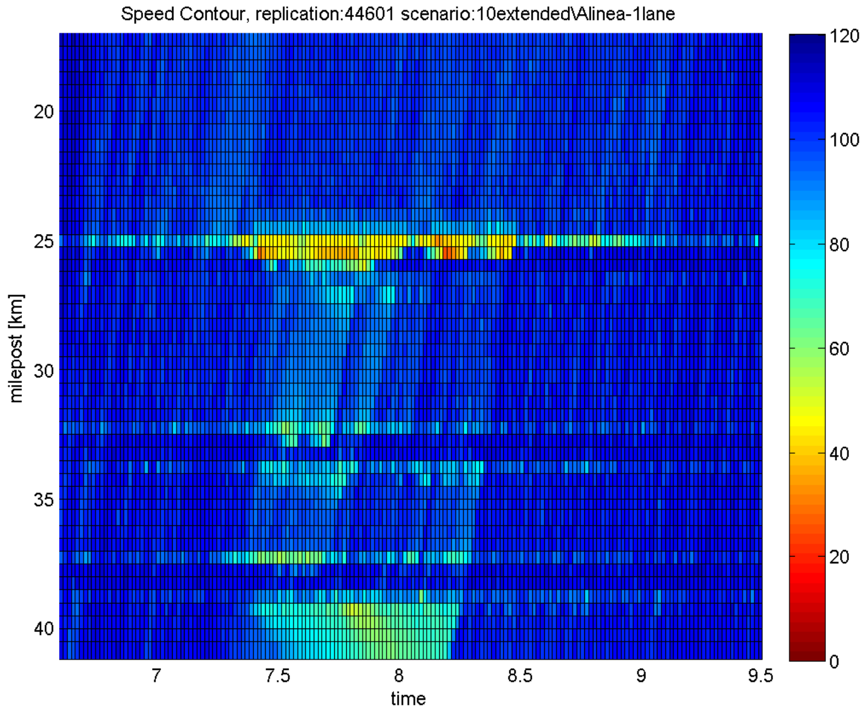


Figure I.4.2 Alinea speed contour

I.4.3 Alinea w/Queue Constraint

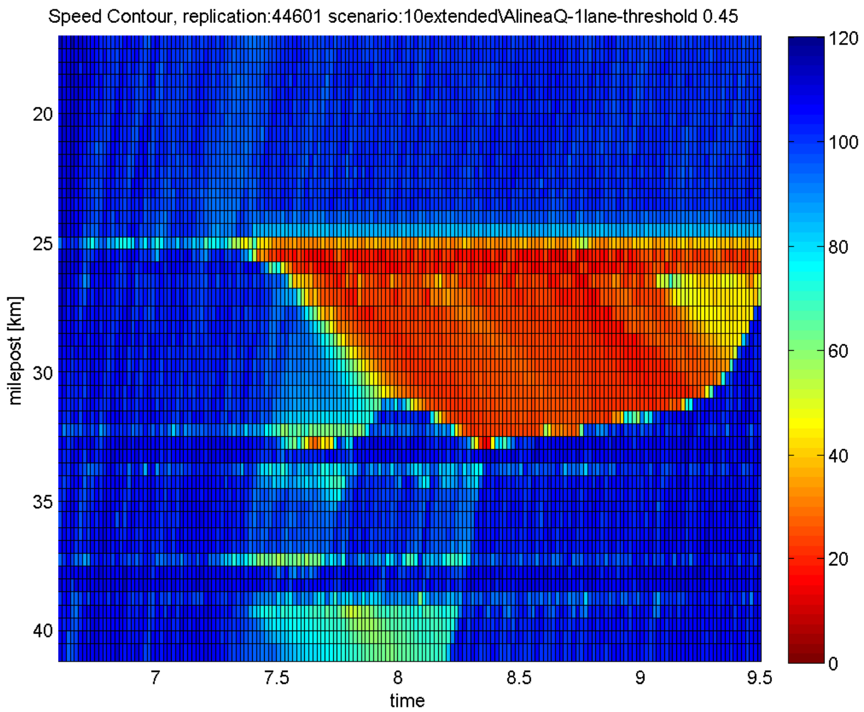


Figure I.4.3 Alinea w/Queue speed contour

I.4.4 Coordinated

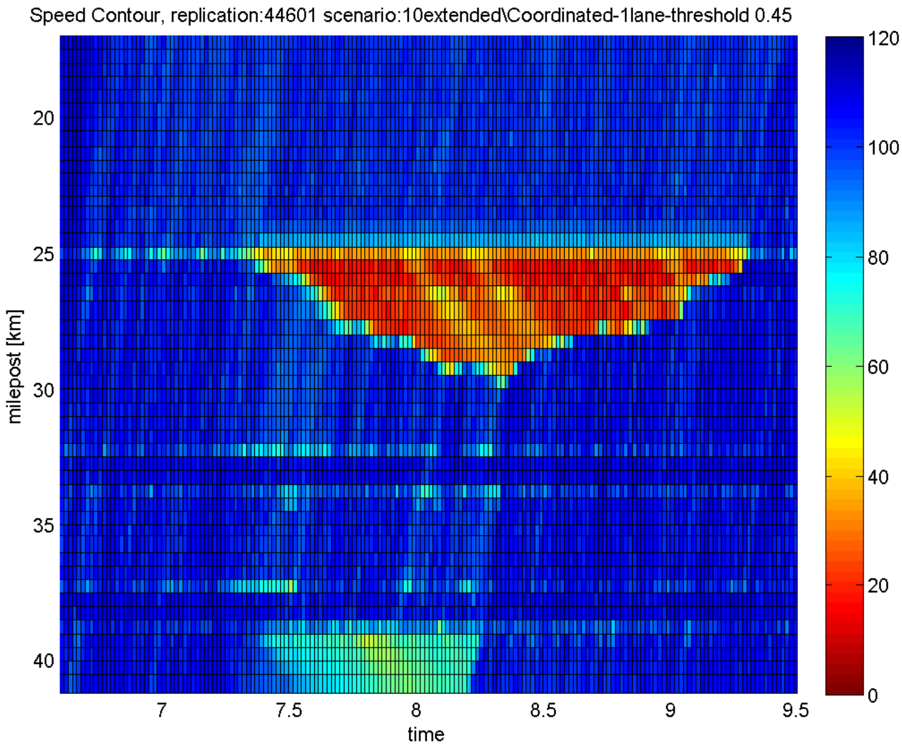


Figure I.4.4 Coordinated speed contour

I.4.5 Coordinated + VSL

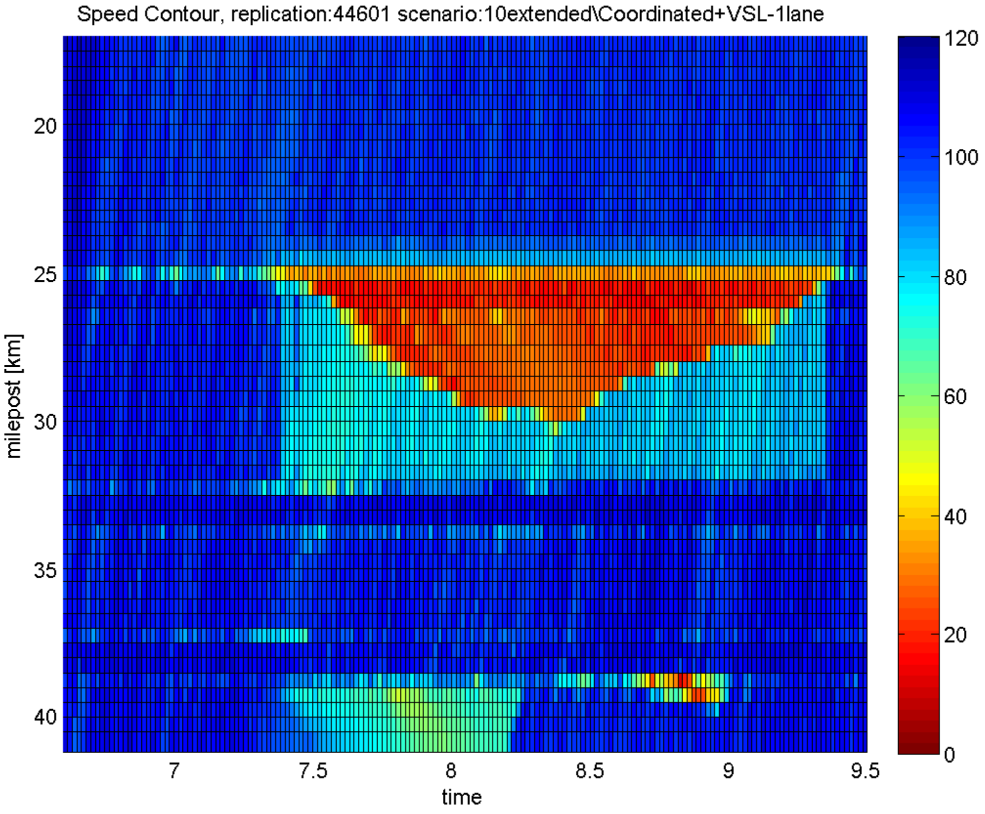


Figure I.4.5 Coordinated + VSL speed contour

Clôture du projet

Formulaire n°3 ARAMIS RPT en PDF

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Département fédéral de l'environnement, des transports, de l'énergie et de la communication DETEC
Office fédéral des routes OFROU

RECHERCHE DANS LE DOMAINE ROUTIER DU DETEC Version du 09.10.2013

Formulaire N° 3 : Clôture du projet

établi / modifié le : 12 August 2014

Données de base

Projet N° : VSS2011/914

Titre du projet : Gestion coordonnées des rampes avec des limites de vitesses variables (FR)
Coordinated Ramp Metering Control with Variable Speed Limits for Swiss freeways(EN)

Echéance effective :

Textes :

Résumé des résultats du projet :

A new coordinated, traffic-responsive ramp metering algorithm with variable speed limits (VSL) considerations has been designed for Swiss freeways based on density measurements. The effectiveness of the new control strategies has been assessed by comparison with the no control case and other existing widely deployed algorithms through a "carefully calibrated with real data" detailed microscopic simulation for the morning peak of the Coppet bottleneck of A1 freeway (direction Geneva). Test results indicate that the feedback coordinated algorithm succeeds in (i) delaying the onset of breakdown, (ii) accelerating system recovery when ramp metering is unable to retain uncongested conditions in the mainline due to the violation of maximum allowable ramp waiting time and (iii) improves freeway and ramp performance compared with the no control case and state-of-the-art ramp metering algorithms. The developed strategy of coordinated ramp metering with variable speed limits is able to reduce delays for all users in the system by an average of 8-12% (considering also the drivers that have to wait at the ramps). Equitable treatment is provided for all drivers in transportation networks and no users are unduly penalized by the control strategy. The developed strategy retains high speed conditions on the mainstream freeway to the maximum possible extent (postpone freeway breakdowns and accelerate recovery times), while treating ramp users well by avoiding long queues and spillback to the city networks. The combined strategy regulates the input demand of the freeway system so that a truly operationally balanced corridor system is achieved. The project also describes in details data needs, amount of sensors and optimal sensor locations in freeway and ramps to efficiently observe level of congestion and successfully deploy an active traffic management scheme in Swiss freeways.

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Office fédéral des routes OFROU

Atteinte des objectifs :

The objectives of the project as have been introduced in the initial proposal and the Form 2 have been successfully met. This work investigated the feasibility of a coordinated ramp metering strategy with ramp constraints for waiting times at the on-ramps and no queue spill-backs to the arterials in the Swiss freeway system. The designed algorithm achieved balanced but efficient traffic conditions between the freeway users (maximizing throughput) and those waiting at the ramps (not violating maximum delay/queue constraint). This strategy can operate more efficiently when synchronized with variable speed limits (VSL) in the mainline freeway. VSL can be proved complementary to ramp metering in cases of (i) on-ramp waiting times violation and (ii) high demand off-ramps which can spill-back because of urban street congestion . The algorithm has additional positive effects related to travel time reliability and safety as it can decrease conflicts of different directions (stop and go traffic, lane changes etc) which increase the probability of an accident. This project provided very useful information to support the development of a field test in the future.

Déductions et recommandations :

An implementation of a ramp metering in Swiss freeways should definitely apply a coordinated algorithm to balance the queues in successive ramps and avoid spill-backs in the urban network. Variable speed limit can be beneficial to succeed the objectives of small delays for all users and travel time reliability. An isolated ramp metering can create strong inequities among different users and travel time uncertainty and should be avoided. Additional sensors are required to be installed before a field implementation with a low cost. Careful consideration should be given to space constraints especially when the ramps are in the proximity of the city centers. Parameter calibration of the algorithm has to be re-evaluated in a field test as micro-simulation cannot replicate in full scale real conditions.

Publications :

Ramezani, M., Yildirimoglu, M., Anderson, P. and Geroliminis, N. 2014. Development of a coordinated ramp metering algorithm with variable speed limits for Swiss Freeways (Working paper - to be submitted for publication)

Chef/cheffe de projet :

Nom : Geroliminis   Prénom : Nikolaos

Service, entreprise, institut : LUTS / ENAC / EPFL

Signature du chef/de la cheffe de projet :

Recherche dans le domaine routier du DETEC : Formulaire 3   Page 2 / 3

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Office fédéral des routes OFROU

RECHERCHE DANS LE DOMAINE ROUTIER DU DETEC

Formulaire N° 3 : Clôture du projet

Appréciation de la commission de suivi :

Evaluation :

La recherche a été conduite de manière rigoureuse et complète. Elle a permis d'atteindre les objectifs initiaux, à savoir:
- Un analyse bibliographique complète sur le thème du Rampmetering
- Le tronçon de l'A1 entre Gland et Vengeron, avec 3 entrées, a été modélisé minutieusement et calibré précisément avec Aimsun, à partir des données trafic disponibles et recueillies.
- Les différents algorithmes ont été testés et évalués précisément, en mettant bien en évidence les particularités et les limites de chaque stratégie
- La stratégie de rampmetering coordonné associé à de l'harmonisation des vitesses a démontré son efficacité générale supérieure aux autres stratégies.
- Les contraintes pour une implantation sur site sont décrites

Mise en oeuvre :

Il est recommandé de poursuivre les recherches sur la gestion coordonnées des rampes avec une harmonisation des vitesses, en implantant un tel système sur site, en coordination avec l'OFROU. Cela permettra d'affiner les paramètres de l'algorithme de gestion coordonnée des rampes et de valider les exigences relatives à la position des équipements et aux principes de fonctionnement.

Besoin supplémentaire en matière de recherche :

-

Influence sur les normes :

Intégrer le résultat de la recherche dans la mise à jour de la norme SN 640 807 (gestion des rampes) et les directives de l'OFROU.

Président/Présidente de la commission de suivi :

Nom : Maillard   Prénom : Patrick

Service, entreprise, institut : Robert-Grandpierre et Rapp SA

Signature du président/ de la présidente de la commission de suivi :

P. Maillard

Recherche dans le domaine routier du DETEC : Formulaire 3   Page 3 / 3

Index of road research reports

Stand : 15.06.2014

no. de rapport	no. de projet	titre	année
1465	ASTRA 2000/417	Erfahrungen mit der Sanierung und Erhaltung von Betonoberflächen	2014
1462	ASTRA 2011/004	Ermittlung der Versagensgrenze eines T2 Norm-Belages mit der mobiles Grossversuchsanlage MLS10	2014
1460	SVI 2007/017	Nutzen der Verkehrsinformation für die Verkehrssicherheit	2014
1459	VSS 2002/501	Leichtes Fallgewichtsgerät für die Verdichtungskontrolle von Fundationsschichten	2014
1458	VSS 2010/703	Umsetzung Erhaltungsmanagement für Strassen in Gemeinden - Arbeitshilfen als Anhang zur Norm 640 980	2014
1457	SVI 2012/006	Forschungspaket VeSPA Teilprojekt 5: Medizinische Folgen des Strassenunfallgeschehens	2014
1456	SVI 2012/002	Fotschungspaket VeSPA Teilprojekt 4: Einflüsse des Wetters auf das Strassenunfallgeschehen	2014
1455	SVI 2012/004	Forschungspaket VeSPA Teilprojekt 3: Einflüsse von Fahrzeugeigenschaften auf das Strassenunfallgeschehen	2014
1454	SVI 2012/003	Forschungspaket VeSPA Teilprojekt 2: Einflüsse von Situation und Infrastruktur auf das Strassenunfallgeschehen: Phase 1	2014
1453	SVI 2012/002	Forschungspaket VeSPA Teilprojekt 1: Einflüsse von Mensch und Gesellschaft auf das Strassenunfallgeschehen: Phase 1	2014
1452	SVI 2012/001	Forschungspaket VeSPA: Synthesebericht Phase 1	2014
1451	FGU 2010/006	Gasanalytik zur frühzeitigen Branddetektion in Tunneln	2013
1450	VSS 2002/401	Kaltrecycling von Ausbauasphalt mit bituminösen Bindemitteln	2014
1449	ASTRA 2010/024	E-Scooter - Sozial- und naturwissenschaftliche Beiträge zur Förderung leichter Elektrofahrzeuge in der Schweiz	2013
1448	SVI 2009/008	Anforderungen der Güterlogistik an die Netzinfrastruktur und die langfristige Netzentwicklung in der Schweiz. Forschungspaket UVEK/ASTRA "Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz", Teilprojekt C	2014
1447	SVI 2009/005	Informationstechnologien in der zukünftigen Gütertransportwirtschaft Forschungspaket UVEK/ASTRA "Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz", Teilprojekt E	2013
1446	VSS 2005/454	Forschungspaket Recycling von Ausbauasphalt in Heissmischgut: EP3: Stofffluss- und Nachhaltigkeitsbeurteilung	2013
1445	VSS 2009/301	Öffnung der Busstreifen für weitere Verkehrsteilnehmende	2013
1444	VSS 2007/306	Verkehrsqualität und Leistungsfähigkeit von Anlagen des leichten Zweirad- und des Fussgängerverkehrs	2013
1443	VSS 2007/305	Verkehrsqualität und Leistungsfähigkeit des strassengebundenen ÖV	2013
1442	SVI 2010/004	Messen des Nutzens von Massnahmen mit Auswirkungen auf den Langsamverkehr - Vorstudie	2013
1441_2	SVI 2009/010	Zielsystem im Güterverkehr. Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz - Teilprojekt G	2013
1441_1	SVI 2009/010	Effizienzsteigerungspotenziale in der Transportwirtschaft durch integrierte Bewirtschaftungsinstrumente aus Sicht der Infrastrukturbetreiber Synthese der Teilprojekte B3, C, D, E und F des Forschungspakets Güterverkehr anhand eines Zielsystems für den Güterverkehr	2013
1440	SVI 2009/006	Benchmarking-Ansätze im Verkehrswesen	2013
1439	SVI 2009/002	Konzept zur effizienten Erfassung und Analyse der Güterverkehrsdaten Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz von	2013

no. de rapport	no. de projet	titre	année
		Verkehrsmitteln im Güterverkehr der Schweiz TP A	
1438_2	SVI 2009/011	Ortsbezogene Massnahmen zur Reduktion der Auswirkungen des Güterverkehrs - Teil 2. Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz TP H	2013
1438_1	SVI 2009/011	Ortsbezogene Massnahmen zur Reduktion der Auswirkungen des Güterverkehrs - Teil 1. Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz TP H	2013
1437	VSS 2008/203	Trottoirüberfahrten und punktuelle Querungen ohne Vortritt für den Langsamverkehr	2013
1436	VSS 2010/401	Auswirkungen verschiedener Recyclinganteile in ungebundenen Gemischen	2013
1435	FGU 2008/007_OBF	Schadstoff- und Rauchkurzschlüsse bei Strassentunneln	2013
1434	VSS 2006/503	Performance Oriented Requirements for Bitumainous Mixtures	2013
1433	ASTRA 2010/001	Güterverkehr mit Lieferwagen: Entwicklungen und Massnahmen Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz TP B3	2013
1432	ASTRA 2007/011	Praxis-Kalibrierung der neuen mobilen Grossversuchanlage MLS10 für beschleunigte Verkehrslastsimulation auf Strassenbelägen in der Schweiz	2013
1431	ASTRA 2011/015	TeVeNOx - Testing of SCR-Systems on HD-Vehicles	2013
1430	ASTRA 2009/004	Impact des conditions météorologiques extrêmes sur la chaussée	2013
1429	SVI 2009/009	Einschätzungen der Infrastrukturnutzer zur Weiterentwicklung des Regulativs Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz TP F	2013
1428	SVI 2010/005	Branchenspezifische Logistikkonzepte und Güterverkehrsaufkommen sowie deren Trends. Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz TP B2	2013
1427	SVI 2006/002	Begegnungszonen - eine Werkschau mit Empfehlungen für die Realisierung	2013
1426	ASTRA 2010/025_OBF	Luftströmungsmessung in Strassentunneln	2013
1425	VSS 2005/401	Résistance à l'altération des granulats et des roches	2013
1424	ASTRA 2006/007	Optimierung der Baustellenplanung an Autobahnen	2013
1423	ASTRA 2010/012	Forschungspaket: Lärmarme Beläge innerorts EP3: Betrieb und Unterhalt lärmarmer Beläge	2013
1422	ASTRA 2011/006_OBF	Fracture processes and in-situ fracture observations in Gipskeuper	2013
1421	VSS 2009/901	Experimenteller Nachweis des vorgeschlagenen Raum- und Topologiemodells für die VM-Anwendungen in der Schweiz (MDATrafo)	2013
1420	SVI 2008/003	Projektierungsfreiräume bei Strassen und Plätzen	2013
1419	VSS 2001/452	Stabilität der Polymere beim Heisseinbau von PmB-haltigen Strassenbelägen	2013
1418	VSS 2008/402	Anforderungen an hydraulische Eigenschaften von Geokunststoffen	2012
1417	FGU 2009/002	Heat Exchanger Anchors for Thermo-active Tunnels	2013
1416	FGU 2010/001	Sulfatwiderstand von Beton: verbessertes Verfahren basierend auf der Prüfung nach SIA 262/1, Anhang D	2013
1415	VSS 2010/A01	Wissenslücken im Infrastrukturmanagementprozess "Strasse" im Siedlungsgebiet	2013
1414	VSS 2010/201	Passive Sicherheit von Tragkonstruktionen der Strassenausstattung	2013
1413	SVI 2009/003	Güterverkehrsintensive Branchen und Güterverkehrsströme in der Schweiz Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz Teilprojekt B1	2013
1412	ASTRA 2010/020	Werkzeug zur aktuellen Gangliniennorm	2013
1411	VSS 2009/902	Verkehrstelematik für die Unterstützung des Verkehrsmanagements in ausserordentlichen Lagen	2013
1410	VSS 2010/202_OBF	Reduktion von Unfallfolgen bei Bränden in Strassentunneln durch Abschnittsbildung	2013
1409	ASTRA 2010/017_OBF	Regelung der Luftströmung in Strassentunneln im Brandfall	2013
1408	VSS 2000/434	Vieillissement thermique des enrobés bitumineux en laboratoire	2012
1407	ASTRA 2006/014	Fusion des indicateurs de sécurité routière : FUSAIN	2012

no. de rapport	no. de projet	titre	année
1406	ASTRA 2004/015	Amélioration du modèle de comportement individuell du Conducteur pour évaluer la sécurité d'un flux de trafic par simulation	2012
1405	ASTRA 2010/009	Potential von Photovoltaik an Schallschutzmassnahmen entlang der Nationalstrassen	2012
1404	VSS 2009/707	Validierung der Kosten-Nutzen-Bewertung von Fahrbahn-Erhaltungsmassnahmen	2012
1403	SVI 2007/018	Vernetzung von HLS- und HVS-Steuerungen	2012
1402	VSS 2008/403	Witterungsbeständigkeit und Durchdrückverhalten von Geokunststoffen	2012
1401	SVI 2006/003	Akzeptanz von Verkehrsmanagementmassnahmen-Vorstudie	2012
1400	VSS 2009/601	Begrünte Stützgitterböschungssysteme	2012
1399	VSS 2011/901	Erhöhung der Verkehrssicherheit durch Incentivierung	2012
1398	ASTRA 2010/019	Environmental Footprint of Heavy Vehicles Phase III: Comparison of Footprint and Heavy Vehicle Fee (LSVA) Criteria	2012
1397	FGU 2008/003_OBF	Brandschutz im Tunnel: Schutzziele und Brandbemessung Phase 1: Stand der Technik	2012
1396	VSS 1999/128	Einfluss des Umhüllungsgrades der Mineralstoffe auf die mechanischen Eigenschaften von Mischgut	2012
1395	FGU 2009/003	KarstALEA: Wegleitung zur Prognose von karstspezifischen Gefahren im Untertagbau	2012
1394	VSS 2010/102	Grundlagen Betriebskonzepte	2012
1393	VSS 2010/702	Aktualisierung SN 640 907, Kostengrundlage im Erhaltungsmanagement	2012
1392	ASTRA 2008/008_009	FEHRL Institutes WIM Initiative (Fiwi)	2012
1391	ASTRA 2011/003	Leitbild ITS-CH Landverkehr 2025/30	2012
1390	FGU 2008/004_OBF	Einfluss der Grundwasserströmung auf das Quellverhalten des Gipskeupers im Belchentunnel	2012
1389	FGU 2003/002	Long Term Behaviour of the Swiss National Road Tunnels	2012
1388	SVI 2007/022	Möglichkeiten und Grenzen von elektronischen Busspuren	2012
1387	VSS 2010/205_OBF	Ablage der Prozessdaten bei Tunnel-Prozessleitsystemen	2012
1386	VSS 2006/204	Schallreflexionen an Kunstbauten im Strassenbereich	2012
1385	VSS 2004/703	Bases pour la révision des normes sur la mesure et l'évaluation de la planéité des chaussées	2012
1384	VSS 1999/249	Konzeptuelle Schnittstellen zwischen der Basisdatenbank und EMF-, EMK- und EMT-DB	2012
1383	FGU 2008/005	Einfluss der Grundwasserströmung auf das Quellverhalten des Gipskeupers im Chienbergtunnel	2012
1382	VSS 2001/504	Optimierung der statischen Eindringtiefe zur Beurteilung von harten Gussasphaltsorten	2012
1381	SVI 2004/055	Nutzen von Reisezeiteinsparungen im Personenverkehr	2012
1380	ASTRA 2007/009	Wirkungsweise und Potential von kombinierter Mobilität	2012
1379	VSS 2010/206_OBF	Harmonisierung der Abläufe und Benutzeroberflächen bei Tunnel-Prozessleitsystemen	2012
1378	SVI 2004/053	Mehr Sicherheit dank Kernfahrbahnen?	2012
1377	VSS 2009/302	Verkehrssicherheitsbeurteilung bestehender Verkehrsanlagen (Road Safety Inspection)	2012
1376	ASTRA 2011/008_004	Erfahrungen im Schweizer Betonbrückenbau	2012
1375	VSS 2008/304	Dynamische Signalisierungen auf Hauptverkehrsstrassen	2012
1374	FGU 2004/003	Entwicklung eines zerstörungsfreien Prüfverfahrens für Schweissnähte von KDB	2012
1373	VSS 2008/204	Vereinheitlichung der Tunnelbeleuchtung	2012
1372	SVI 2011/001	Verkehrssicherheitsgewinne aus Erkenntnissen aus Datapooling und strukturierten Datenanalysen	2012
1371	ASTRA 2008/017	Potenzial von Fahrgemeinschaften	2011
1370	VSS 2008/404	Dauerhaftigkeit von Betonfahrbahnen aus Betongranulat	2011
1369	VSS 2003/204	Rétention et traitement des eaux de chaussée	2012
1368	FGU 2008/002	Soll sich der Mensch dem Tunnel anpassen oder der Tunnel dem Menschen?	2011
1367	VSS 2005/801	Grundlagen betreffend Projektierung, Bau und Nachhaltigkeit von Anschlussgleisen	2011
1366	VSS 2005/702	Überprüfung des Bewertungshintergrundes zur Beurteilung der Strassengriffigkeit	2010
1365	SVI 2004/014	Neue Erkenntnisse zum Mobilitätsverhalten dank Data Mining?	2011

no. de rapport	no. de projet	titre	année
1364	SVI 2009/004	Regulierung des Güterverkehrs Auswirkungen auf die Transportwirtschaft Forschungspaket UVEK/ASTRA Strategien zum wesensgerechten Einsatz der Verkehrsmittel im Güterverkehr der Schweiz TP D	2012
1363	VSS 2007/905	Verkehrsprognosen mit Online -Daten	2011
1362	SVI 2004/012	Aktivitätenorientierte Analyse des Neuverkehrs	2012
1361	SVI 2004/043	Innovative Ansätze der Parkraumbewirtschaftung	2012
1360	VSS 2010/203	Akustische Führung im Strassentunnel	2012
1359	SVI 2004/003	Wissens- und Technologientransfer im Verkehrsbereich	2012
1358	SVI 2004/079	Verkehrsanbindung von Freizeitanlagen	2012
1357	SVI 2007/007	Unaufmerksamkeit und Ablenkung: Was macht der Mensch am Steuer?	2012
1356	SVI 2007/014	Kooperation an Bahnhöfen und Haltestellen	2011
1355	FGU 2007/002	Prüfung des Sulfatwiderstandes von Beton nach SIA 262/1, Anhang D: Anwendbarkeit und Relevanz für die Praxis	2011
1354	VSS 2003/203	Anordnung, Gestaltung und Ausführung von Treppen, Rampen und Treppenwegen	2011
1353	VSS 2000/368	Grundlagen für den Fussverkehr	2011
1352	VSS 2008/302	Fussgängerstreifen (Grundlagen)	2011
1351	ASTRA 2009/001	Development of a best practice methodology for risk assessment in road tunnels	2011
1350	VSS 2007/904	IT-Security im Bereich Verkehrstelematik	2011
1349	VSS 2003/205	In-Situ-Abflussversuche zur Untersuchung der Entwässerung von Autobahnen	2011
1348	VSS 2008/801	Sicherheit bei Parallelführung und Zusammentreffen von Strassen mit der Schiene	2011
1347	VSS 2000/455	Leistungsfähigkeit von Parkierungsanlagen	2010
1346	ASTRA 2007/004	Quantifizierung von Leckagen in Abluftkanälen bei Strassentunneln mit konzentrierter Rauchabsaugung	2010
1345	SVI 2004/039	Einsatzbereiche verschiedener Verkehrsmittel in Agglomerationen	2011
1344	VSS 2009/709	Initialprojekt für das Forschungspaket "Nutzensteigerung für die Anwender des SIS"	2011
1343	VSS 2009/903	Basistechnologien für die intermodale Nutzungserfassung im Personenverkehr	2011
1342	FGU 2005/003	Untersuchungen zur Frostkörperbildung und Frosthebung beim Gefrierverfahren	2010
1341	FGU 2007/005	Design aids for the planning of TBM drives in squeezing ground	2011
1340	SVI 2004/051	Aggressionen im Verkehr	2011
1339	SVI 2005/001	Widerstandsfunktionen für Innerorts-Strassenabschnitte ausserhalb des Einflussbereiches von Knoten	2010
1338	VSS 2006/902	Wirkungsmodelle für fahrzeugseitige Einrichtungen zur Steigerung der Verkehrssicherheit	2009
1337	ASTRA 2006/015	Development of urban network travel time estimation methodology	2011
1336	ASTRA 2007/006	SPIN-ALP: Scanning the Potential of Intermodal Transport on Alpine Corridors	2010
1335	VSS 2007/502	Stripping bei lärmmindernden Deckschichten unter Überrollbeanspruchung im Labormassstab	2011
1334	ASTRA 2009/009	Was treibt uns an? Antriebe und Treibstoffe für die Mobilität von Morgen	2011
1333	SVI 2007/001	Standards für die Mobilitätsversorgung im peripheren Raum	2011
1332	VSS 2006/905	Standardisierte Verkehrsdaten für das verkehrsträgerübergreifende Verkehrsmanagement	2011
1331	VSS 2005/501	Rückrechnung im Strassenbau	2011
1330	FGU 2008/006	Energiegewinnung aus städtischen Tunneln: Systemeevaluation	2010
1329	SVI 2004/073	Alternativen zu Fussgängerstreifen in Tempo-30-Zonen	2010
1328	VSS 2005/302	Grundlagen zur Quantifizierung der Auswirkungen von Sicherheitsdefiziten	2011
1327	VSS 2006/601	Vorhersage von Frost und Nebel für Strassen	2010
1326	VSS 2006/207	Erfolgskontrolle Fahrzeugrückhaltesysteme	2011
1325	SVI 2000/557	Indices caractéristiques d'une cité-vélo. Méthode d'évaluation des politiques cyclables en 8 indices pour les petites et moyennes communes.	2010
1324	VSS 2004/702	Eigenheiten und Konsequenzen für die Erhaltung der Strassenverkehrsanlagen im überbauten Gebiet	2009
1323	VSS 2008/205	Ereignisdetektion im Strassentunnel	2011

no. de rapport	no. de projet	titre	année
1322	SVI 2005/007	Zeitwerte im Personenverkehr: Wahrnehmungs- und Distanzabhängigkeit	2008
1321	VSS 2008/501	Validation de l'oedomètre CRS sur des échantillons intacts	2010
1320	VSS 2007/303	Funktionale Anforderungen an Verkehrserfassungssysteme im Zusammenhang mit Lichtsignalanlagen	2010
1319	VSS 2000/467	Auswirkungen von Verkehrsberuhigungsmassnahmen auf die Lärmimmissionen	2010
1318	FGU 2006/001	Langzeitquellversuche an anhydritführenden Gesteinen	2010
1317	VSS 2000/469	Geometrisches Normalprofil für alle Fahrzeugtypen	2010
1316	VSS 2001/701	Objektorientierte Modellierung von Strasseninformationen	2010
1315	VSS 2006/904	Abstimmung zwischen individueller Verkehrsinformation und Verkehrsmanagement	2010
1314	VSS 2005/203	Datenbank für Verkehrsaufkommensraten	2008
1313	VSS 2001/201	Kosten-/Nutzenbetrachtung von Strassenentwässerungssystemen, Ökobilanzierung	2010
1312	SVI 2004/006	Der Verkehr aus Sicht der Kinder: Schulwege von Primarschulkindern in der Schweiz	2010
1311	VSS 2000/543	VIABILITE DES PROJETS ET DES INSTALLATIONS ANNEXES	2010
1310	ASTRA 2007/002	Beeinflussung der Luftströmung in Strassentunneln im Brandfall	2010
1309	VSS 2008/303	Verkehrsregelungssysteme - Modernisierung von Lichtsignalanlagen	2010
1308	VSS 2008/201	Hindernisfreier Verkehrsraum - Anforderungen aus Sicht von Menschen mit Behinderung	2010
1307	ASTRA 2006/002	Entwicklung optimaler Mischgüter und Auswahl geeigneter Bindemittel; D-A-CH - Initialprojekt	2008
1306	ASTRA 2008/002	Strassenglätte-Prognosesystem (SGPS)	2010
1305	VSS 2000/457	Verkehrserzeugung durch Parkierungsanlagen	2009
1304	VSS 2004/716	Massnahmenplanung im Erhaltungsmanagement von Fahrbahnen	2008
1303	ASTRA 2009/010	Geschwindigkeiten in Steigungen und Gefällen; Überprüfung	2010
1302	VSS 1999/131	Zusammenhang zwischen Bindemitteleigenschaften und Schadensbildern des Belages?	2010
1301	SVI 2007/006	Optimierung der Strassenverkehrsunfallstatistik durch Berücksichtigung von Daten aus dem Gesundheitswesen	2009
1300	VSS 2003/903	SATELROU Perspectives et applications des méthodes de navigation pour la télématique des transports routiers et pour le système d'information de la route	2010
1299	VSS 2008/502	Projet initial - Enrobés bitumineux à faibles impacts énergétiques et écologiques	2009
1298	ASTRA 2007/012	Griffigkeit auf winterlichen Fahrbahnen	2010
1297	VSS 2007/702	Einsatz von Asphaltbewehrungen (Asphalteinlagen) im Erhaltungsmanagement	2009
1296	ASTRA 2007/008	Swiss contribution to the Heavy-Duty Particle Measurement Programme (HD-PMP)	2010
1295	VSS 2005/305	Entwurfsgrundlagen für Lichtsignalanlagen und Leitfaden	2010
1294	VSS 2007/405	Wiederhol- und Vergleichspräzision der Druckfestigkeit von Gesteinskörnungen am Haufwerk	2010
1293	VSS 2005/402	Détermination de la présence et de l'efficacité de dope dans les bétons bitumineux	2010
1292	ASTRA 2006/004	Entwicklung eines Pflanzenöl-Blockheizkraftwerkes mit eigener Ölmühle	2010
1291	ASTRA 2009/005	Fahrmuster auf überlasteten Autobahnen Simultanes Berechnungsmodell für das Fahrverhalten auf Autobahnen als Grundlage für die Berechnung von Schadstoffemissionen und Fahrzeitgewinnen	2010
1290	VSS 1999/209	Conception et aménagement de passages inférieurs et supérieurs pour piétons et deux-roues légers	2008
1289	VSS 2005/505	Affinität von Gesteinskörnungen und Bitumen, nationale Umsetzung der EN	2010
1288	ASTRA 2006/020	Footprint II - Long Term Pavement Performance and Environmental Monitoring on A1	2010
1287	VSS 2008/301	Verkehrsqualität und Leistungsfähigkeit von komplexen ungesteuerten Knoten: Analytisches Schätzverfahren	2009
1286	VSS 2000/338	Verkehrsqualität und Leistungsfähigkeit auf Strassen ohne Richtungstrennung	2010
1285	VSS 2002/202	In-situ Messung der akustischen Leistungsfähigkeit von Schallschirmen	2009

no. de rapport	no. de projet	titre	année
1284	VSS 2004/203	Evacuation des eaux de chaussée par les bas-cotés	2010
1283	VSS 2000/339	Grundlagen für eine differenzierte Bemessung von Verkehrsanlagen	2008
1282	VSS 2004/715	Massnahmenplanung im Erhaltungsmanagement von Fahrbahnen: Zusatzkosten infolge Vor- und Aufschub von Erhaltungsmassnahmen	2010
1281	SVI 2004/002	Systematische Wirkungsanalysen von kleinen und mittleren Verkehrsvorhaben	2009
1280	ASTRA 2004/016	Auswirkungen von fahrzeuginternen Informationssystemen auf das Fahrverhalten und die Verkehrssicherheit Verkehrspsychologischer Teilbericht	2010
1279	VSS 2005/301	Leistungsfähigkeit zweistreifiger Kreisel	2009
1278	ASTRA 2004/016	Auswirkungen von fahrzeuginternen Informationssystemen auf das Fahrverhalten und die Verkehrssicherheit - Verkehrstechnischer Teilbericht	2009
1277	SVI 2007/005	Multimodale Verkehrsqualitätsstufen für den Strassenverkehr - Vorstudie	2010
1276	VSS 2006/201	Überprüfung der schweizerischen Ganglinien	2008
1275	ASTRA 2006/016	Dynamic Urban Origin - Destination Matrix - Estimation Methodology	2009
1274	SVI 2004/088	Einsatz von Simulationswerkzeugen in der Güterverkehrs- und Transportplanung	2009
1273	ASTRA 2008/006	UNTERHALT 2000 - Massnahme M17, FORSCHUNG: Dauerhafte Materialien und Verfahren SYNTHESE - BERICHT zum Gesamtprojekt "Dauerhafte Beläge" mit den Einzelnen Forschungsprojekten: - ASTRA 200/419: Verhaltensbilanz der Beläge auf Nationalstrassen - ASTRA 2000/420: Dauerhafte Komponenten auf der Basis erfolgreicher Strecken - ASTRA 2000/421: Durabilité des enrobés - ASTRA 2000/422: Dauerhafte Beläge, Rundlaufversuch - ASTRA 2000/423: Griffigkeit der Beläge auf Autobahnen, Vergleich zwischen den Messergebnissen von SRM und SCRIM - ASTRA 2008/005: Vergleichsstrecken mit unterschiedlichen oberen Tragschichten auf einer Nationalstrasse	2008
1272	VSS 2007/304	Verkehrsregelungssysteme - behinderte und ältere Menschen an Lichtsignalanlagen	2010
1271	VSS 2004/201	Unterhalt von Lärmschirmen	2009
1270	VSS 2005/502	Interaktion Strasse Hangstabilität: Monitoring und Rückwärtsrechnung	2009
1269	VSS 2005/201	Evaluation von Fahrzeugrückhaltesystemen im Mittelstreifen von Autobahnen	2009
1268	ASTRA 2005/007	PM10-Emissionsfaktoren von Abriebspartikeln des Strassenverkehrs (APART)	2009
1267	VSS 2007/902	MDAinSVT Einsatz modellbasierter Datentransfernormen (INTERLIS) in der Strassenverkehrstelematik	2009
1266	VSS 2000/343	Unfall- und Unfallkostenraten im Strassenverkehr	2009
1265	VSS 2005/701	Zusammenhang zwischen dielektrischen Eigenschaften und Zustandsmerkmalen von bitumenhaltigen Fahrbahnbelägen (Pilotuntersuchung)	2009
1264	SVI 2004/004	Verkehrspolitische Entscheidfindung in der Verkehrsplanung	2009
1263	VSS 2001/503	Phénomène du dégel des sols gélifs dans les infrastructures des voies de communica-tion et les pergélisols alpins	2006
1262	VSS 2003/503	Lärmverhalten von Deckschichten im Vergleich zu Gussasphalt mit strukturierter Oberfläche	2009
1261	ASTRA 2004/018	Pilotstudie zur Evaluation einer mobilen Grossversuchsanlage für beschleunigte Verkehrslastsimulation auf Strassenbelägen	2009
1260	FGU 2005/001	Testeinsatz der Methodik "Indirekte Vorauserkundung von wasserführenden Zonen mittels Temperaturdaten anhand der Messdaten des Lötschberg-Basistunnels	2009
1259	VSS 2004/710	Massnahmenplanung im Erhaltungsmanagement von Fahrbahnen - Synthesebericht	2008
1258	VSS 2005/802	Kaphaltestellen Anforderungen und Auswirkungen	2009
1257	SVI 2004/057	Wie Strassenraumbilder den Verkehr beeinflussen Der Durchfahrtswiderstand als Arbeitsinstrument bei der städtebaulichen Gestaltung von Strassenräumen	2009
1256	VSS 2006/903	Qualitätsanforderungen an die digitale Videobild-Bearbeitung zur Verkehrsüberwachung	2009

no. de rapport	no. de projet	titre	année
1255	VSS 2006/901	Neue Methoden zur Erkennung und Durchsetzung der zulässigen Höchstgeschwindigkeit	2009
1254	VSS 2006/502	Drains verticaux préfabriqués thermiques pour la consolidation in-situ des sols	2009
1253	VSS 2001/203	Rétention des polluants des eaux de chausées selon le système "infilitrations sur les talus". Vérification in situ et optimisation	2009
1252	SVI 2003/001	Nettoverkehr von verkehrsintensiven Einrichtungen (VE)	2009
1251	ASTRA 2002/405	Incidence des granulats arrondis ou partiellement arrondis sur les propriétés d'ahé-rence des bétons bitumineux	2008
1250	VSS 2005/202	Strassenabwasser Filterschacht	2007
1249	FGU 2003/004	Einflussfaktoren auf den Brandwiderstand von Betonkonstruktionen	2009
1248	VSS 2000/433	Dynamische Eindringtiefe zur Beurteilung von Gussasphalt	2008
1247	VSS 2000/348	Anforderungen an die strassenseitige Ausrüstung bei der Umwidmung von Standstreifen	2009
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