ΠΟΛΥΤΕΧΝΕΙΟ ΚΡΗΤΗΣ

ΤΜΗΜΑ ΜΗΧΑΝΙΚΩΝ ΠΑΡΑΓΩΓΗΣ ΚΑΙ ΔΙΟΙΚΗΣΗΣ

Coordinated ramp metering for large-scale motorways

(Συντονισμένος έλεγχος ραμπών εισόδου σε αυτοκινητοδρόμους μεγάλης κλίμακας)

Διατριβή που υπεβλήθη για την μερική ικανοποίηση των απαιτήσεων για την απόκτηση Μεταπτυχιακού Διπλώματος Ειδίκευσης

Υπό

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Η διατριβή του Ιωάννη Μαργώνη εγκρίνεται

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Ευχαριστίες

Θα ήθελα πάρα πολύ να ευχαριστήσω τον καθηγητή κύριο Μάρκο Παπαγεωργίου που με εμπιστεύτηκε και μου έδωσε την ευκαιρία να συμμετέχω στο Εργαστήριο Δυναμικών Συστημάτων και Προσομοίωσης. Επίσης τα θερμότερά μου ευχαριστώ στον επιβλέπων καθηγητή μου, λέκτορα Ιωάννη Παπαμιχαήλ, για την απεριόριστη βοήθεια που προσέφερε καθ' όλη την διάρκεια της εκπόνησης της μεταπτυχιακής διατριβής αλλά και γιατί με αντιμετώπισε και μου συμπεριφέρθηκε σαν φίλος σε όλη τη διάρκεια της συνεργασίας μας.

Ακόμα θα ήθελα να ευχαριστήσω την οικογένειά μου για την ηθική και οικονομική συμπαράσταση όλα αυτά τα χρόνια των σπουδών μου. Σε περίοπτη θέση στη καρδιά μου έχω όλους τους φίλους και φίλες που απέκτησα αυτά τα χρόνια και τις ανεκτίμητες από κάθε άποψη εμπειρίες που ζήσαμε μαζί.

Δε θα ήθελα να αμελήσω να αναφέρω τον Απόστολο Κότσιαλο που αν και δεν προλάβαμε να συνεργαστούμε για μεγάλο χρονικό διάστημα βοήθησε και αυτός με τον τρόπο του στην παρούσα εργασία. Μέρος της παρούσας δουλειάς χρηματοδοτήθηκε από την Ευρωπαϊκή Επιτροπή στα πλαίσια του ερευνητικού προγράμματος EURAMP (IST-2002-23110).

Σύντομο Βιογραφικό

Ο Μαργώνης Ιωάννης γεννήθηκε τον Σεπτέμβριο του 1980 στην Άρτα. Αφού πέρασε από Λάρισα, Ludwigsburg (Γερμανία), Άρτα, κατέληξε στα Χανιά όπου και σπούδασε στο τμήμα Μηχανικών Παραγωγής και Διοίκησης του Πολυτεχνείου Κρήτης. Αποφοίτησε το 2004 με διπλωματική εργασία με θέμα «Πλοήγηση, Τηλεπλοήγηση της αυτοκινούμενης ρομποτικής πλατφόρμας Hellenak και ανίχνευση εμποδίων». Συνέχισε τις σπουδές του στο μεταπτυχιακό πρόγραμμα σπουδών του τμήματος στον τομέα της Επιχειρησιακής Έρευνας και εργάστηκε στο Εργαστήριο Δυναμικών Συστημάτων και Προσομοίωσης σαν επιστημονικός συνεργάτης. Έχει διατελέσει υπεύθυνος εργαστηρίου ως βοηθός στο προπτυχιακό μάθημα «Δυναμικός Προγραμματισμός» που διδάσκεται στο τμήμα Μηχανικών Παραγωγής και Διοίκησης από τον καθηγητή Μάρκο Παπαγεωργίου και έχει συμμετάσχει σε ερευνητικά προγράμματα.

Περίληψη

Οι οδικές αρτηρίες αντιμετωπίζουν ολοένα και αυξανόμενα προβλήματα καθώς η κινητικότητα προσώπων και αγαθών ακολουθεί σταθερά αυξητική πορεία. Το αποτέλεσμα είναι να παρουσιάζονται κυκλοφοριακές συμφορήσεις ακόμα και σε αυτοκινητοδρόμους υψηλής ικανότητας, με επακόλουθα καθυστερήσεις, μειωμένη οδική ασφάλεια, αυξημένη κατανάλωση καυσίμων και σοβαρή ατμοσφαιρική ρύπανση. Η συνεχής επέκταση της υπάρχουσας υποδομής δεν μπορεί πλέον να εξαλείψει πλήρως την κυκλοφοριακή συμφόρηση και τις αρνητικές συνέπειές της για λόγους οικονομικούς, οικολογικούς ή και απλά έλλειψης χώρου. Μια εναλλακτική και ταυτόχρονα εφικτή προσέγγιση για την επίλυση των κυκλοφοριακών προβλημάτων, η οποία δέχθηκε ισχυρή ώθηση με τις αλματώδεις εξελίξεις στην τεχνολογία των επικοινωνιών και των ηλεκτρονικών υπολογιστών (τηλεματική), είναι η ορθολογική και πλήρης αξιοποίηση και χρήση της υπάρχουσας υποδομής μέσω της ανάπτυξης και υλοποίησης σύγχρονων μορφών ελέγχου και διαχείρισης.

Η παρούσα μελέτη ασχολείται με το συντονισμένο έλεγχο της κυκλοφορίας δικτύων αυτοκινητοδρόμων μεγάλης κλίμακας. Έχουν προταθεί και εφαρμόζονται διάφορες στρατηγικές και μέθοδοι ελέγχου της κυκλοφορίας τέτοιων δικτύων. Από τις πιο δημοφιλείς και αποτελεσματικές μεθόδους κρίνεται ο έλεγχος των ραμπών εισόδου στους αυτοκινητόδρομους. Οι στρατηγικές ελέγχου των ραμπών εισόδου αποσκοπούν στον προσδιορισμό της ροής οχημάτων που θα επιτραπεί να εισέλθει από την κάθε ράμπα εισόδου στον αυτοκινητόδρομο στη διάρκεια ενός διακριτού βήματος ελέγχου. Η αποτελεσματικότητά τους μπορεί να αποδειχθεί μαθηματικά και αναλύεται στο 1ο κεφάλαιο. Αυτή οφείλεται κυρίως στη δυνατότητα που έχουν να ρυθμίζουν τον αριθμό των οχημάτων που μπορεί να εισέλθει στον αυτοκινητόδρομο. Ρυθμίζοντας την εισροή υπάρχει η δυνατότητα να αποφευχθεί μια πιθανή συμφόρηση με αποτέλεσμα να υπάρχει καλύτερη ροή και μικρότερη καθυστέρηση συνολικά παρά το χρόνο που θα περιμένουν μερικοί οδηγοί στην ράμπα εισόδου. Επίσης, επειδή μια πιθανή συμφόρηση μπορεί να μεταδοθεί αρκετά προς τα πίσω και να φράξει και κάποια ράμπα εξόδου εμποδίζοντας έτσι την έξοδο κάποιων

οχημάτων, η αποφυγή της συμφόρησης μέσω του ελέγχου της εισόδου των οχημάτων από τις ράμπες εισόδου, δύναται να αποφύγει και αυτή την κατάσταση.

Οι στρατηγικές ελέγχου των ραμπών εισόδου σε αυτοκινητοδρόμους είναι αρκετά διαδεδομένες και πολλές έχουν αναπτυχθεί και εφαρμοστεί σε διάφορα μέρη του κόσμου. Οι στρατηγικές αυτές μπορούν να κατηγοριοποιηθούν είτε σε σταθερού χρόνου είτε σε στρατηγικές που χρησιμοποιούν μετρήσεις σε πραγματικό χρόνο. Αυτές μπορούν να χωριστούν σε τοπικές στρατηγικές και σε στρατηγικές συντονισμένου ελέγχου. Στο 2ο κεφάλαιο παρουσιάζονται κάποιες από τις διαθέσιμες στρατηγικές ελέγχου ραμπών εισόδου. Οι στρατηγικές σταθερού χρόνου χρησιμοποιούν ιστορικά δεδομένα και υπολογίζουν την στρατηγική εκ των προτέρων. Οι πιο συνηθισμένες στρατηγικές τοπικού ελέγχου που χρησιμοποιούν μετρήσεις σε πραγματικό χρόνο είναι η στρατηγική ζήτησης – ικανότητας (demand – capacity), η στρατηγική ποσοστού κατάληψης (occupancy) που είναι ουσιαστικά στρατηγικές ελέγχου ανοιχτού βρόχου απόρριψης διαταραχής καθώς και η ALINEA που είναι μια τοπική στρατηγική βασισμένη σε ισχυρές και εύρωστες μεθόδους αυτομάτου ελέγχου με ανατροφοδότηση. Στρατηγικές συντονισμένου ελέγχου είναι η πολυμεταβλητή στρατηγική ρύθμισης METALINE, ο αλγόριθμος Bottleneck, οι αλγόριθμοι Zone και Stratified Zone Metering, οι αλγόριθμοι Helper Ramp και Linked Ramp και άλλοι. Επίσης ενώ οι προηγούμενες στρατηγικές προσπαθούν να αντιδράσουν σε μια ήδη διαμορφωμένη κατάσταση υπάρχουν και στρατηγικές που είναι σχεδιασμένες με βάση τη θεωρία βέλτιστου ελέγχου και ανιχνεύουν τα αίτια μιας συμφόρησης πριν λάβει χώρα και εν συνεχεία προσδιορίζουν τον βέλτιστο τρόπο αντίδρασης. Μια τέτοια στρατηγική είναι το AMOC, μια στρατηγική μη-γραμμικού βέλτιστου ελέγχου που βασίζεται σε ένα ρεαλιστικό μοντέλο της κυκλοφοριακής ροής. Η στρατηγική AMOC περιγράφεται παρακάτω καθώς και στο 4ο κεφάλαιο.

Για την μελέτη ενός φυσικού φαινομένου όπως η κυκλοφοριακή ροή χρειάζεται να χρησιμοποιηθεί κάποιο μοντέλο. Στην περίπτωση του φαινομένου της κυκλοφοριακής ροής σε δίκτυα αυτοκινητοδρόμων ευρείας κλίμακας, τα μαθηματικά πρότυπα που την περιγράφουν μπορούν να ταξινομηθούν σε τρεις κατηγορίες ανάλογα με το βαθμό ακρίβειας της περιγραφής. Στην πρώτη κατηγορία ανήκουν τα μικροσκοπικά μοντέλα τα οποία παρακολουθούν την ατομική κίνηση καθενός οχήματος ξεχωριστά καθώς ταξιδεύει μέσα στο δίκτυο. Στη δεύτερη κατηγορία κατατάσσονται τα μεσοσκοπικά μοντέλα τα οποία παρακολουθούν και επιβλέπουν την κίνηση ομάδων οχημάτων που έχουν κάποια κοινά χαρακτηριστικά. Η τρίτη κατηγορία, τα μακροσκοπικά μοντέλα, περιγράφουν την κυκλοφοριακή ροή σαν ένα ρευστό που χαρακτηρίζεται από μακροσκοπικές μεταβλητές, όπως η κυκλοφοριακή ροή, η πυκνότητα και η μέση ταχύτητα των οχημάτων. Στην παρούσα μελέτη, για την μοντελοποίηση της κυκλοφορίας χρησιμοποιείται το λογισμικό μακροσκοπικής προσομοίωσης

METANET. Η προσομοίωση της κυκλοφοριακής ροής βασίζεται σε ένα μοντέλο 2ης τάξης. Το δίκτυο αναπαρίσταται σαν προσανατολισμένος γράφος όπου οι σύνδεσμοι αντιπροσωπεύουν μέρη αυτοκινητοδρόμων. Οι κόμβοι τοποθετούνται σε σημεία αλλαγής της γεωμετρίας, διασταύρωση ή ένωση δύο αυτοκινητοδρόμων ή ένωση αυτοκινητοδρόμων με ράμπα εισόδου ή εξόδου. Υπάρχουν 4 τύποι συνδέσμων: σύνδεσμοι αυτοκινητοδρόμων, σύνδεσμοι ραμπών εισόδου, σύνδεσμοι ραμπών εξόδου και σύνδεσμοι αποθήκευσης και προώθησης. Στους κόμβους μοντελοποιείται η κατανομή της ροής, η ανάντη επίδραση της πυκνότητας και η κατάντη επίδραση της ταχύτητας. Τα κριτήρια που χρησιμοποιούνται για τον υπολογισμό της απόδοσης κάθε στρατηγικής και υπολογίζονται από το METANET, είναι ο Συνολικός Χρόνος Ταξιδιού (ΣΧΤ), ο Συνολικός Χρόνος Αναμονής Εισόδου (ΣΧΑΕ), ο Συνολικός Χρόνος Αναμονής στις ουρές των συνδέσμων Αποθήκευσης και Προώθησης (ΣΧΑΑΠ), ο Συνολικός Χρόνος (ΣΧ), η Συνολική Διανυθείσα Απόσταση (ΣΔΑ) και η Συνολική Ποσότητα Καυσίμων (ΣΠΚ). Αναλυτική περιγραφή του μοντέλου και των κριτηρίων γίνεται στο 3ο κεφάλαιο.

Η στρατηγική ελέγχου AMOC εφαρμόζει συντονισμένο έλεγχο στις ράμπες εισόδου. Το πρόβλημα ελέγχου του δικτύου αυτοκινητοδρόμων μορφοποιείται σαν ένα μη-γραμμικό πρόβλημα βέλτιστου ελέγχου διακριτού χρόνου με περιορισμούς. Η κυκλοφοριακή ροή θεωρείται σαν μια διαδικασία που ελέγχεται μέσω της ροής σε κάθε ράμπα εισόδου του δικτύου χρησιμοποιώντας κατάλληλα συστήματα φωτεινής σηματοδότησης που είναι εγκατεστημένα σε αυτές. Λαμβάνοντας υπόψη την τρέχουσα κατάσταση του συστήματος και τις προβλέψεις των διαταραχών, βελτιστοποιεί ένα κατάλληλο κριτήριο κόστους και υπολογίζει τις βέλτιστες τροχιές ελέγχου με βάση το μη-γραμμικό μοντέλο της κυκλοφοριακής ροής του δικτύου. Καθορίζει, δηλαδή, ποιες είναι οι επιτρεπτές ροές για τις ράμπες εισόδου σε όλο το δίκτυο.

Παρόλο που οι τροχιές ελέγχου που προσδιορίζονται από το AMOC είναι βέλτιστες, η υλοποίηση τους δεν διατηρεί αυτή την ιδιότητα. Οι λόγοι για τους οποίους αυτό συμβαίνει είναι: i) η εκτίμηση της αρχικής κατάστασης του συστήματος δεν είναι ακριβής είτε ελλείψει αρκετών δεδομένων είτε λόγω περιορισμένης ακρίβειας των αλγορίθμων εκτίμησης, ii) η πρόβλεψη των διαταραχών έχει πεπερασμένη ακρίβεια αφού έχουν στοχαστικό χαρακτήρα και άρα η πρόβλεψη τους αναπόφευκτα περιλαμβάνει λάθη που μεταδίδονται στο μοντέλο της κυκλοφοριακής ροής και άρα το πρόβλημα βελτιστοποίησης που επιλύει το AMOC δεν ανταποκρίνεται στο πραγματικό πρόβλημα αλλά σε μια προσέγγιση αυτού, iii) η πεπερασμένη ακρίβεια εκτίμησης των παραμέτρων του μοντέλου της κυκλοφοριακής ροής ή αλλαγή των παραμέτρων κατά τη διάρκεια εφαρμογής του ελέγχου, και iv) κάποιο απρόβλεπτο συμβάν όπως κάποιο ατύχημα. Για την αντιμετώπιση αυτών των προβλημάτων εφαρμόζεται η τεχνική του κυλιόμενου ορίζονται και εισάγετε μια ιεραρχική δομή ελέγχου. Στην περίπτωση ιεραρχικού συντονισμένου ελέγχου η ιεραρχική δομή αποτελείται από τρία επίπεδα: το επίπεδο εκτίμησης/πρόβλεψης, το επίπεδο βελτιστοποίησης και το επίπεδο ελέγχου. Το πρώτο επίπεδο έχει ως στόχο τον καθορισμό σε πραγματικό χρόνο των αρχικών συνθηκών του συστήματος και των παραμέτρων του μοντέλου. Πραγματοποιεί ακόμη μια πρόβλεψη των διαταραχών που πρόκειται να επενεργήσουν στη διάρκεια της περιόδου πρόβλεψης. Στο δεύτερο επίπεδο χρησιμοποιείται η στρατηγική ελέγχου AMOC. Σαν είσοδο δέχεται την τρέχουσα κυκλοφοριακή κατάσταση του δικτύου, τις παραμέτρους του μοντέλου και τις προβλέψεις των διαταραχών για τον χρονικό ορίζοντα της βελτιστοποίησης. Το AMOC, επιλύοντας το μη-γραμμικό πρόβλημα βέλτιστου ελέγχου διακριτού χρόνου, προσδιορίζει τις βέλτιστες τροχιές ελέγχου και τις αντίστοιχες βέλτιστες τροχιές της κατάστασης του δικτύου. Τα αποτελέσματα περνάνε ως είσοδος στο επόμενο επίπεδο, όπου δύναται είτε να εφαρμοστούν απευθείας στις ελεγχόμενες ράμπες είτε να χρησιμοποιηθούν ως στόχοι που πρέπει να πετύχει η μέθοδος τοπικού ελέγχου ALINEA για μια συγκεκριμένη περίοδο εφαρμογής. Αυτό γίνεται γιατί ο τοπικός ελεγκτής έχει τη δυνατότητα να αντιδράσει πιο άμεσα σε περίπτωση που λόγω κάποιου συμβάντος οι κυκλοφοριακές συνθήκες αλλάξουν πριν η στρατηγική ελέγχου ενημερωθεί ή να εξισορροπήσει τυχόν σφάλματα στους υπολογισμούς της στρατηγικής που μπορεί να οφείλονται στη στοχαστική φύση της πρόβλεψης της ζήτησης ή στην πεπερασμένη ακρίβεια εκτίμησης των παραμέτρων του μοντέλου.

Ως βασικό δίκτυο για τη μελέτη της κυκλοφορίας και την επίδραση του ελέγχου σε αυτήν χρησιμοποιείται το περιαστικό δίκτυο αυτοκινητοδρόμων του Άμστερνταμ. Το κύριο μέρος του δικτύου αποτελεί ο περιφερειακός δακτύλιος A10. Ο A10 περιλαμβάνει δύο σήραγγες, τη σήραγγα Coen και τη σήραγγα Zeeburg. Επίσης στα βόρεια συνδέεται με τον αυτοκινητόδρομο A8, στα νοτιοδυτικά με τον A4, στα νότια με τον A2 και νοτιοανατολικά με τον A1. Το δίκτυο υπόκειται καθημερινά σε συμφόρηση η οποία είναι ιδιαίτερα μεγάλη στο βορειοδυτικό τμήμα του A10 ενώ είναι λιγότερη στο ανατολικό τμήμα. Το δίκτυο μοντελοποιήθηκε και για τις δύο κατευθύνσεις που σημαίνει ότι 143 km χωρίστηκαν σε 654 συνδέσμους (249 σύνδεσμοι αυτοκινητοδρόμων, 231 σύνδεσμοι αποθήκευσης και προώθησης και 174 εικονικοί σύνδεσμοι). Οι σύνδεσμοι των αυτοκινητοδρόμων αποτελούνται από 291 τμήματα με το μήκος τους να κυμαίνεται από 400 έως 800 μέτρα (μέσο μήκος 491,4m). Για το μοντέλο του δικτύου έγινε αρχικά ποσοτική επικύρωση των παραμέτρων όπου μια ομάδα παραμέτρων αρχικά εκτιμήθηκε και στη συνέχεια επικυρώθηκε. Στη συνέχεια έγινε ποιοτική επικύρωση του μοντέλου με σκοπό να μπορέσει να αναπαραστήσει πειστικά την πραγματική δυναμική του συστήματος. Για την παρούσα μελέτη χρησιμοποιήθηκε μόνο το κομμάτι του δακτυλίου του A10 που έχει αριστερόστροφη φορά. Το συγκεκριμένο κομμάτι έχει μήκος περίπου 32 km και περιλαμβάνει 21 ράμπες εισόδου και 20 ράμπες εξόδου στις οποίες συμπεριλαμβάνονται και οι συνδέσεις με τους αυτοκινητοδρόμους A8, A4, A3 και A1. Ο δακτύλιος χωρίζεται σε 76 διακριτά τμήματα με μέσο μήκος 421 m. Αυτό σημαίνει ότι το διάνυσμα κατάστασης έχει διάσταση 173. Αν υποθέσουμε ότι ελέγχονται όλες οι ράμπες εισόδου τότε το διάνυσμα ελέγχου έχει διάσταση 21 και το διάνυσμα των διαταραχών έχει διάσταση 41. Παρατηρείται ότι το μοντέλο προσομοιώνει ικανοποιητικά το φαινόμενο της κυκλοφοριακής ροής στο δίκτυο αυτό και μπορεί να χρησιμοποιηθεί για το σχεδιασμό μιας στρατηγικής ελέγχου αλλά και για την μετέπειτα αξιολόγηση αυτής.

Στην εργασία εφαρμόστηκε η μέθοδος τοπικού ελέγχου ALINEA, η στρατηγική AMOC και ο ιεραρχικός έλεγχος στο δίκτυο του Amsterdam και τα αποτελέσματά τους συγκρίθηκαν μεταξύ τους αλλά και με την περίπτωση όπου δεν εφαρμόζεται κανένας έλεγχος. Οι προσομοιώσεις έγιναν με τη χρήση πραγματικών δεδομένων για τη ζήτηση και τις ροές στις εξόδους. Τα δεδομένα αφορούσαν έναν χρονικό ορίζοντα 4 ωρών. Χρησιμοποιώντας ένα διακριτό βήμα του μοντέλου ίσο με 10 sec προκύπτουν 1440 βήματα ως χρονικός ορίζοντας της προσομοίωσης. Στη περίπτωση όπου δεν εφαρμόζεται κανένας έλεγχος ο ΣΧΤ προκύπτει ίσος με 14268 οχήματα*ώρες. Στο δίκτυο έχει αναπτυχθεί συμφόρηση σε πολλά σημεία που μπλοκάρει αρκετές ράμπες εισόδου όπου και σχηματίζονται μεγάλες ουρές που αργούν να διαλυθούν. Στη συνέχεια έγινε η προσομοίωση με τις παραπάνω μεθόδους για 10 διαφορετικά σενάρια τα οποία είτε θεωρούν ότι ελέγχονται μόνο οι αστικές ράμπες εισόδου στον αυτοκινητόδρομο είτε οι σύνδεσμοι μεταξύ των αυτοκινητοδρόμων είτε όλες ανεξαιρέτως οι ράμπες. Τα σενάρια διαφοροποιούνται στο μήκος των ουρών που επιτρέπεται να αναπτυχθούν στους συνδέσμους μεταξύ των αυτοκινητοδρόμων. Η ALINEA καταφέρνει να βελτιώσει στα περισσότερα από τα σενάρια τις κυκλοφοριακές συνθήκες αρκετά. Όσο αυξάνεται η δυνατότητα για δημιουργία ουρών στους συνδέσμους μεταξύ των αυτοκινητοδρόμων τα αποτελέσματα βελτιώνονται. Τα καλύτερα αποτελέσματα προέκυψαν για τα σενάρια με το μέγιστο επιτρεπόμενο μήκος ουράς όπου παρατηρήθηκε βελτίωση στον ΣΧΤ μέχρι και 46%. Για ένα μέσο επιτρεπόμενο μήκος ουράς που είναι και ένα πιο πιθανό σενάριο η βελτίωση είναι περίπου 19%. Παρόλα αυτά, ακόμα κι έτσι σχηματίζεται συμφόρηση και έχουμε και ουρές που στον A4 φτάνουν μέχρι και 1200 οχήματα. Όσον αφορά την ισοτιμία που επιτυγχάνεται στην αντιμετώπιση των οδηγών που εισέρχονται στον αυτοκινητόδρομο, πιο δίκαιη κατανομή των ουρών και των καθυστερήσεων πραγματοποιείται στα σενάρια που έχουν ένα μέσο επιτρεπόμενο μήκος ουρών. Η εφαρμογή του AMOC δίνει θεαματικά αποτελέσματα. Η βελτίωση σε όλα τα σενάρια κυμαίνεται από 22% έως και 50% με τη μεγαλύτερη βελτίωση στο ΣΧΤ να εμφανίζεται όταν επιτρέπεται η δημιουργία μεγάλων ουρών στους συνδέσμους μεταξύ των αυτοκινητοδρόμων. Ωστόσο η λύση αυτή είναι ανοιχτού βρόχου και δεν θα μπορούσε να παρατηρηθεί σε μια εφαρμογή στην πραγματικότητα. Τα αποτελέσματα όμως εξακολουθούν να είναι χρήσιμα και μπορούν να χρησιμοποιηθούν ως ένα άνω όριο για την αποτελεσματικότητα οποιασδήποτε στρατηγικής ελέγχου. Στην εφαρμογή του ιεραρχικού ελέγχου με τη μέθοδο του κυλιόμενου ορίζοντα αρχικά ορίστηκε ο χρόνος του ορίζοντα εφαρμογής και του ορίζοντα πρόβλεψης. Οι τιμές που χρησιμοποιήθηκαν είναι 10 λεπτά (ή 60 βήματα της προσομοίωσης) και 60 λεπτά (ή 360 βήματα της προσομοίωσης) αντίστοιχα. Στη συνέχεια έγινε εφαρμογή του ιεραρχικού ελέγχου με τις βέλτιστες τροχιές ελέγχου που προέκυψαν από το επίπεδο βελτιστοποίησης να εφαρμόζονται από το επίπεδο ανάθεσης καθηκόντων απευθείας στις ελεγχόμενες ράμπες εισόδου και συγκρίθηκε με την περίπτωση όπου γίνεται χρήση της τοπικής στρατηγικής ALINEA με χρήση των βέλτιστων τροχιών ελέγχου ως στόχους που πρέπει να ικανοποιηθούν από αυτή. Τα αποτελέσματα με τη χρήση της ALINEA στο επίπεδο ανάθεσης καθηκόντων υπερτερούσαν όταν έγινε εφαρμογή με υποεκτίμηση ή υπερεκτίμηση της ζήτησης στο επίπεδο πρόβλεψης. Αυτό οφείλεται στο γεγονός ότι με τη βοήθεια του τοπικού ελεγκτή η μέθοδος έχει τη δυνατότητα να ανταποκριθεί καλύτερα σε πιθανά σφάλματα στη πρόβλεψη της ζήτησης ή της κατάστασης του δικτύου. Στη συνέχεια όλες οι προσομοιώσεις έγιναν με χρήση της ALINEA στο επίπεδο ανάθεσης καθηκόντων. Τα αποτελέσματα που προέκυψαν ήταν πολύ καλά. Στα σενάρια όπου υπήρξε η δυνατότητα εξυπηρέτησης μεγάλων ουρών στις ράμπες εισόδου, τα αποτελέσματα πλησίασαν αυτά της λύσης ανοιχτού βρόχου. Η βελτίωση που επιτεύχθηκε κυμάνθηκε από περίπου 10% έως και 50% σε σχέση με την περίπτωση όπου δεν εφαρμόζεται κανένας έλεγχος. Τα αποτελέσματα αν συγκριθούν με αυτά του ελέγχου ανοιχτού βρόχου με το AMOC είναι χειρότερα, όπως είναι λογικό. Ωστόσο όσο μεγαλύτερες είναι οι επιτρεπόμενες ουρές η διαφορά ελαχιστοποιείται μέχρι που για τα σενάρια με τις μέγιστες δυνατές επιτρεπόμενες ουρές τα αποτελέσματα σχεδόν ταυτίζονται με αυτά του ελέγχου ανοιχτού βρόχου. Τα σενάρια με ένα μέσο μήκος επιτρεπόμενων ουρών αποδείχτηκε να είναι αρκετά πιο δίκαια σε σχέση με τα υπόλοιπα. Παρατηρήθηκε ότι η επιβολή περιορισμών μέγιστης ουράς μπορεί να θεωρηθεί σαν ένας τρόπος να γίνει πιο ισότιμη η στρατηγική απέναντι στους οδηγούς που εισέρχονται στον αυτοκινητόδρομο από διαφορετικές ράμπες κατανέμοντας τις καθυστερήσεις. Επίσης φάνηκε ότι η ισοτιμία και η αποτελεσματικότητα μιας στρατηγικής είναι μερικώς ανταγωνιστικά κριτήρια. Σε σχέση με την εφαρμογή απλής ALINEA, η εφαρμογή του ιεραρχικού ελέγχου είναι σαφώς καλύτερη. Ακόμα και στη χειρότερη περίπτωση ο ιεραρχικός έλεγχος κυμάνθηκε στα ίδια επίπεδα με την ALINEA. Βεβαίως όταν υπάρχει διαθέσιμος χώρος για την δημιουργία ουρών στις ράμπες εισόδου ο ιεραρχικός έλεγχος καταφέρνει να βελτιώσει τις κυκλοφοριακές συνθήκες πάρα πολύ και σε αρκετές περιπτώσεις αποφεύγεται η δημιουργία συμφόρησης. Επίσης ο ιεραρχικός έλεγχος αποδεικνύεται να είναι και πιο δίκαιος προς την κατανομή των καθυστερήσεων στους οδηγούς από τις υπόλοιπες στρατηγικές.

Συμπερασματικά μπορεί να ειπωθεί ότι η χρήση της τοπικής στρατηγικής ανάδρασης ALINEA ήταν επιτυχής και κατάφερε να μειώσει αισθητά τον ΣΧΤ, καταφέρνοντας να διαλύσει την συμφόρηση μέχρι ενός σημείου που στις περισσότερες περιπτώσεις εξαρτάται και από την δυνατότητα δημιουργίας ουρών. Το κύριο όμως πρόβλημα της δημιουργίας μεγάλης ουράς στον Α4 δεν ήταν δυνατόν να αποφευχθεί. Τα αποτελέσματα του AMOC είναι θεαματικά αλλά αντιπροσωπεύουν μια ιδανική κατάσταση κάτι που δεν ισχύει ποτέ σε πραγματικές εφαρμογές. Ωστόσο μπορούν να χρησιμοποιηθούν ως ένα άνω όριο για την απόδοση κάθε στρατηγικής ελέγχου. Ο ιεραρχικός έλεγχος με το AMOC στο επίπεδο βελτιστοποίησης και την ALINEA στο επίπεδο ανάθεσης καθηκόντων αποδίδει καλύτερα από ότι η μη συντονισμένη χρήση της τοπικής στρατηγικής ελέγχου. Τα αποτελέσματα της μεθόδου κρίνονται περισσότερο από ικανοποιητικά. Στη χειρότερη περίπτωση, όπου δεν επιτρέπεται η δημιουργία ουρών στους συνδέσμους των αυτοκινητοδρόμων, τα αποτελέσματα της μεθόδου είναι τουλάχιστον όσο καλά και της ALINEA και στην καλύτερη περίπτωση, όπου υπάρχει η δυνατότητα για εξυπηρέτηση μεγάλων ουρών, τα αποτελέσματα είναι σχεδόν το ίδιο καλά με την λύση ανοιχτού βρόχου του AMOC.

Με την συνεχή πρόοδο των υπολογιστών, η υπολογιστική ισχύς που απαιτείται για την εφαρμογή της μεθόδου είναι όλο και λιγότερο σημαντική. Από την παρούσα μελέτη αναδύθηκε η ανάγκη για την εισαγωγή ελέγχου και στις ράμπες που ενώνουν αυτοκινητόδρομους. Η χρήση ελέγχου στις ράμπες εισόδου από τα αστικά δίκτυα βελτίωσαν κάπως την κατάσταση αλλά το μεγαλύτερο ρόλο έπαιξε η χρήση των ραμπών που ενώνουν αυτοκινητόδρομους. Με τη δυνατότητα δημιουργίας ουρών έως και 200 οχημάτων στις ράμπες που ενώνουν αυτοκινητόδρομους ο ιεραρχικός έλεγχος κατάφερε να βελτιώσει τις συνθήκες κατά 48%. Οι τοπικές αρχές διστάζουν συχνά να επιβάλλουν έλεγχο σε αυτές τις ράμπες αλλά και χωρίς έλεγχο σχηματίζονται ουρές σε αυτές και μάλιστα μεγαλύτερες. Η βελτίωση που μπορεί να επιφέρει η εισαγωγή ενός τέτοιου μέτρου μπορεί να μετριάσει και τις αναμενόμενες αντιδράσεις του κοινού στον έλεγχο των ραμπών που ενώνουν αυτοκινητόδρομους. Σαν επόμενο βήμα θα μπορούσε να αναπτυχθεί μια στρατηγική που θα μιμείται την συμπεριφορά του ιεραρχικού ελέγχου χωρίς όμως να είναι απαραίτητη η πρόβλεψη της ζήτησης και των ποσοστών στροφής στις ράμπες εξόδου.

Abstract

Motorway networks around the world have to deal with increasing problems because the movement of persons and goods is constantly growing. As a result congestion appears even on motorways with high capacity, which leads to delays, reduced safety, increase in fuel consumption and severe environmental pollution. The constant expansion of the existing infrastructure is not able to address the problem and its negative consequences; the reasons are economic, environmental or just lack of space. An alternative and feasible approach to the traffic problems is the rational and full exploitation and use of the existing infrastructure through the development and implementation of modern control and management methods.

This study is concerned with the coordinated control of large-scale motorway networks through ramp metering. Ramp metering strategies aim to determine the vehicle flow, which should be allowed to enter the mainstream of a motorway from every on-ramp in a period of time.

A nonlinear model-predictive hierarchical control approach is presented for coordinated ramp metering of motorway networks. The utilized hierarchical structure consists of three layers: the estimation/prediction layer, the optimization layer and the direct control layer. The previously design optimal control tool AMOC is incorporated in the second layer while the local feedback control strategy ALINEA is used in the third layer.

For the modelling and simulation of the traffic process the macroscopic simulation program METANET is used. Simulation results are presented for the Amsterdam ring-road. ALINEA, a well-known and widely used local ramp metering control method based on powerful and robust automatic control methods, AMOC, an optimal control strategy employing a non-linear traffic flow model to calculate the optimal control trajectories by minimizing a suitable cost criterion, and the proposed Hierarchical Control approach are compared to the no-control case. Hierarchical Control outperforms uncoordinated local ramp metering with ALINEA and its efficiency converges to the one obtained by the optimal open-loop solution of AMOC. Hierarchical Control is also able to

produce good results even in situations where the available predictions are not accurate. It is shown that metering of all on-ramps, including motorway-to-motorway intersections, leads to the optimal utilization of the available infrastructure.

1 Introduction to Ramp Metering

1.1 Introduction

Motorways originally were conceived and designed with the aim of providing virtually unlimited mobility to the users. With the constant increase in cars new motorways had to be built or the old ones had to be expanded. However the cost, both economical and environmental, is very high and it is not allowing the motorways capacity to grow quick enough. The lack of available space is also a problem. Except that, it has become obvious that the existing infrastructure in most cases is actually more than sufficient and is able to accommodate the demand except for special occasions resulting in congestions. These exceptions can be either non-recurrent, like an accident that shrinks the motorway's capacity, or recurrent like morning or evening peak hours.

It has become apparent that it is possible to ameliorate the traffic conditions by implementing some kind of control on the motorways. Various solutions have been proposed like the use of speed limits, variable message signs (VMS), introduction of tolls, ramp metering or other approaches that integrate two or more methods. Ramp metering is probably the most efficient mean to this end. Several control strategies that implement ramp metering have been developed (see chapter 2) and manage to improve traffic conditions in exchange for short delays usually at the on-ramps.

Ramp metering aims at improving the traffic conditions by appropriately regulating the inflow from the on-ramps to the motorway mainstream and is deemed as one of the most effective control measures for motorway network traffic. In Kotsialos and Papageorgiou (2005b) and Papageorgiou (2006) the reasons why ramp metering is effective in ameliorating traffic conditions is thoroughly analysed. In the following sections these reasons will be presented.

1.2 A Basic Property

Let's consider a traffic network (Figure 1-1). It is obvious that if a time interval of a day, for example, is taken, any vehicle that enters the network will also leave. In other words the demand over a certain time is equal with the exit flows as no vehicle disappears or appears out of nothing in the network. If a time interval T is introduced with a discrete time index $k = 1, 2, \ldots, K$ and the total demand (independent of control actions) is represented as $d(k)$, the exit flows as $s(k)$ and the total number of vehicles in the network at time k with $N(k)$ then the time spent in the network is represented by

$$T_s = T\sum_{k=1}^{K}\left[N(0) + T\sum_{\kappa=0}^{k-1} d(k) - T\sum_{\kappa=0}^{k-1} s(k)\right]. \tag{1.1}$$

The aim is to minimize the time spent in the network. Since the first two terms of the outer sum are independent of the control measures, minimization of T_s is equivalent of the maximization of

$$S = T^2\sum_{k=1}^{K}\sum_{\kappa=0}^{k-1} s(k) = T^2\sum_{k=0}^{K-1}(K-k)s(k). \tag{1.2}$$

This means that the time-weighted outflows have to be maximized in order to minimize the time spent in the network. The time-weighted outflows are maximized if the vehicles are able to leave the network as early as possible. It is clear that congestion is not helping and any control measure should aim to achieve the early exit of the vehicles.

Figure 1-1: A general traffic network.

1.3 *Why Ramp Metering?*

1.3.1 First Answer

In Figure 1-2 two cases for an on-ramp are considered. In the first case no control measures are used, in the second case ramp metering is implemented. It is known that in case of congestion the motorway outflow is 5-10% lower than the motorway's capacity. By applying a ramp metering strategy to maintain capacity flow on the mainstream a queue is formed on the on-ramp but nevertheless an amelioration of the total time spent, including the ramp waiting time, is achieved. The amelioration ΔT_s (in %) is given by equation (1.3), where q_{in} is the upstream flow, d the ramp demand, q_{con} the mainstream outflow in presence of congestion and q_{cap} the motorway capacity.

$$\Delta T_s = \frac{q_{cap} - q_{con}}{q_{in} + d - q_{con}} 100 \tag{1.3}$$

For example, if the total demand exceeds the motorway capacity by 20% ($q_{in} + d = 1.2 q_{cap}$) and the capacity drop due to congestion is 5% ($q_{con} = 0.95 q_{cap}$) then from equation (1.3) $\Delta T_s = 20\%$, an improvement of 20%. This is a good demonstration of the importance of ramp metering.

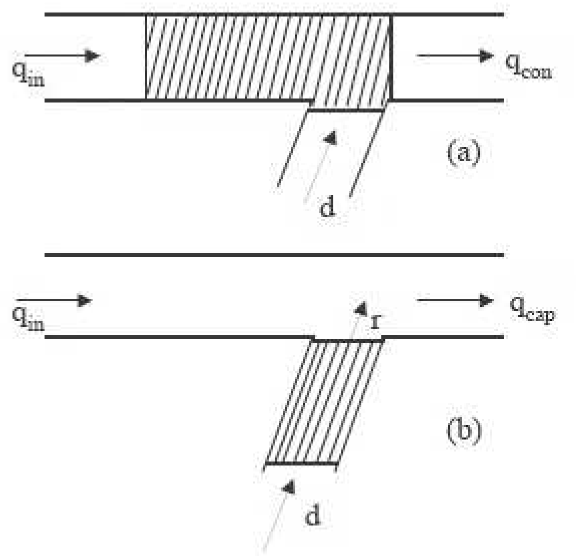

Figure 1-2: Two cases of an on-ramp: (a) without ramp metering, (b) with ramp metering. The grey areas represent congestion zones.

1.3.2 Second Answer

In Figure 1-3 two cases for a motorway stretch are considered. The motorway stretch includes an on-ramp and an off-ramp. In the first case no control measures are used, in the second case ramp metering is implemented. An assumption is made that $q_{con} = q_{cap}$ in order to concentrate on the effect of ramp metering in this case and clearly separate with the previous case. A portion of vehicles are exiting the mainstream at the off-ramp with a rate γ $(0 < \gamma < 1)$. Since the off-ramp is blocked by congestion in the first case the exit flow will be given by equation (1.4) while equation (1.5) holds for the second case where the off ramp is not blocked.

$$s^{nc} = \frac{\gamma}{1-\gamma}\left(q_{cap} - d\right) \tag{1.4}$$

$$s^{rm} = \gamma q_{in} \tag{1.5}$$

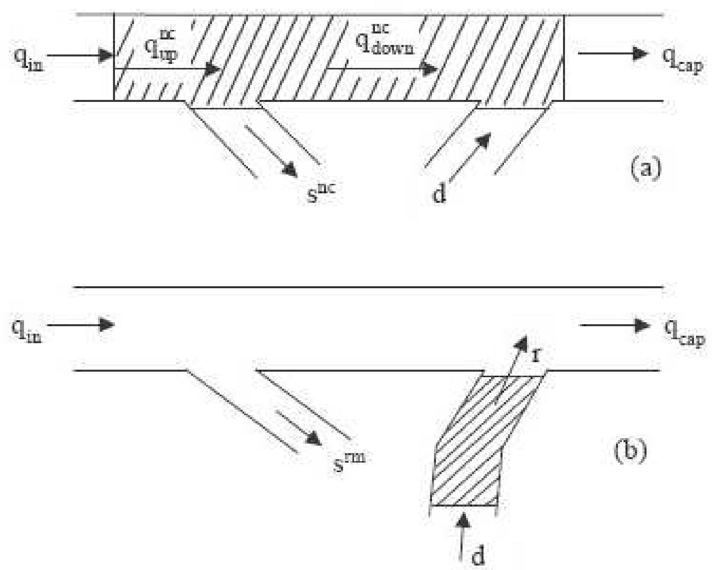

Figure 1-3: Two cases of a motorway stretch: (a) without ramp metering, (b) with ramp metering. The grey areas represent congestion zones.

When a congestion has been formed it is implied that $\left(1-\gamma\right)q_{in} + d > q_{cap}$. This leads to

$$\left(1-\gamma\right)q_{in} > q_{cap} - d \Rightarrow q_{in} > \frac{q_{cap} - d}{\left(1-\gamma\right)} \Rightarrow \gamma q_{in} > \frac{\gamma}{\left(1-\gamma\right)}q_{cap} - d \Rightarrow s^{rm} > s^{nc}.$$

Hence, ramp metering increases the outflow, thus, decreasing the total time spent in the system. The amelioration in this case has been shown to be given by :

$$\Delta T_s = \gamma 100 . \tag{1.6}$$

This means that with an exit rate of $\gamma = 0.05$ the improvement is $\Delta T_s = 5\%$. If more than one off-ramp is blocked by the congestion it is obvious that the amelioration from the introduction of ramp metering can be even higher.

1.3.3 Further impacts

If the results of both section 1.3.1 and 1.3.2 are examined, it is intelligible that the improvement of the traffic conditions can be even better.

Other impacts of ramp metering can be the better utilisation of the reserve capacity on parallel arterials. The users of the road infrastructure choose their respective routes in a way that minimizes their individual travel times. Introduction of ramp metering may change the travel times of some routes and in response some drivers may change their routes to take advantage (or to avoid a disadvantage) of the new situation Figure 1-4. As their behaviour can be predicted, the introduction of ramp metering may be used to impose a desired distribution of the traffic flow in the overall network.

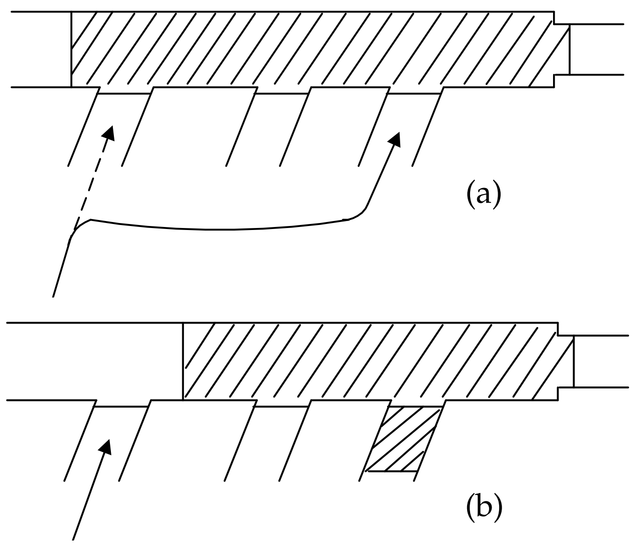

Figure 1-4: Two cases of a motorway stretch: (a) without ramp metering, (b) with ramp metering. The grey areas represent congestion zones.

Also, several studies have shown that introduction of ramp metering leads to an increase of traffic safety. The merging behaviour at intersections is safer and because of less congestion fewer lane changes are performed and driver stress is less, which means reduced accidents. Furthermore the efficiency of the network increases leading to reduced pollutant emissions and to economic benefits due to smaller delays in the transportation of persons and various goods.

1.3.4 When not to use Ramp Metering

Ramp metering is able to improve traffic conditions when introduced in a traffic network but there are some cases were it is not able to help the current situation and may even have negative impact.

A condition where ramp metering is not certain to improve traffic conditions is when a congestion forms due to a bottleneck usually caused by a lane drop or an incident. In such a case, if the congestion spills back in the network, to impose ramp metering on an on-ramp that is further upstream has no effect on the cause of the congestion and may even hold back vehicles that would have exited the motorway from an off-ramp before the bottleneck.

A similar case is when congestion propagates upstream from an off-ramp that is not able to accommodate all the vehicles exiting the mainstream. In this case the metering of an upstream on-ramp, as in the previous case, may not be useful as it will hold back vehicles without having any effect on the congestion.

2 A Review of Ramp Metering Strategies

2.1 Introduction

Motorways around the world are not able to fulfil their original purpose of providing an efficient and reliable way of transportation of goods and persons because of congestion. The problem of congestion occurs when traffic demand is higher than the one that the infrastructure is able to cope with and can be recurrent or non-recurrent. Congestion results in delays, reduced safety, increased pollution and reduced utilization of the motorways' capacity at the moment where it is most needed.

The solution to the problem of congestion can not simply be the expansion of the existing infrastructure or the construction of new; economic cost, environmental implications and lack of space are some of the reasons. The constantly increasing number of vehicles is bound to bring any new or expanded motorway soon to its limits.

Taken under consideration the fact that the consequence of congestion is the reduced capacity of the motorway, which means the infrastructure is not fully taken advantage of, it becomes obvious that there is the need to have a control method in order the whole capacity of a motorway. Ramp metering is the most efficient means to this end (Papageorgiou and Kotsialos 2002).

This review aims at presenting the available ramp metering strategies, how they operate, how and where they are implemented.

2.2 Classification of Ramp Metering Strategies

Ramp metering strategies can be classified in a number of ways. In Jin and Zhang (2001) the algorithms are categorized as isolated (local) or coordinated.

Local ramp metering methods decide the metering rate of a ramp based on the local conditions. Depending on the strategy, measurements of flow, density and occupancy - among others – upstream, downstream or on the ramp, are taken under consideration. The second category, coordinated strategies, is divided in three subcategories, cooperative, competitive and integral. Cooperative algorithms try to address the problem of congestion by computing the metering rate for each on-ramp based on local information and making further adjustments based on information coming from other ramps; competitive algorithms compute more than one metering rate for each ramp based on both local and global conditions and select the most restrictive one; integral algorithms aim at optimizing an objective function that is either explicitly or implicitly affecting the control action.

From the control systems point of view, we have either fixed-time strategies or traffic responsive strategies. In the first case, metering rates are computed off-line based mostly on historical data and are fixed for particular times-of-day; in the second case the rates are subject to constant change and are computed in real time based on the motorways' current state. The strategies can either be local or coordinated.

It is not the intention of this review to classify the available ramp metering strategies. Their classification is used merely for organizational reasons.

2.3 Available Ramp Metering Strategies

Ramp metering strategies have been developed and used on various locations, mainly in North America and Europe, for many years. Other strategies proved to be efficient and others not. During the years most of the strategies have evolved as has the infrastructure of motorway networks and also ramp meters.

The information about the ramp metering strategies that are presented next originates mostly from previous reviews (Bogenberger and May 1999; Jin and Zhang 2001; Papageorgiou and Kotsialos 2002; Kotsialos and Papageorgiou 2004a; Hadi 2005; Kotsialos et al. 2005;).

2.3.1 Fixed-Time Strategies

Fixed-time ramp metering strategies, as mentioned before, are simple static models that are computed off-line using only historical data. Fixed-time strategies are fixed to clock time.

Various approaches to derive a fixed-time ramp metering strategy have been suggested. Most of the formulations proposed lead to linear-programming or quadratic-programming problems. These problems can easily be solved via various computer programs available.

The downside to fixed-time strategies is that their results are based on historical data. Historical data are valuable and can give a notion of what to expect but are not always accurate as demands can change within a time-of-day or vary from day to day. Demands also may change in the long term causing the optimized settings to 'age'. Another weak point is that the drivers' response to the strategy is difficult to foresee and can not be taken under consideration in advance. If the drivers behave differently then the strategy implemented will not be efficient. Incidents and other disturbances may render a fixed-time strategy useless because they are not taken into account. All that can cause either underutilization or overload to the motorway and stress the need for strategies that consider and react to real-time traffic conditions.

2.3.2 Reactive Strategies

2.3.2.1 Local Strategies

Demand – Capacity Strategy

The Demand-Capacity (DC) strategy (Masher et al. 1975) uses mainstream measurements of flow and occupancy upstream of the on-ramp. The goal is to add as much ramp flow as necessary to the upstream flow to match the known downstream capacity, as long as the measured upstream occupancy is undercritical. In case the upstream occupancy becomes overcritical the ramp flow is reduced to a minimum flow, which is also the minimum flow allowed to avoid ramp closure.

The strategy reads:

$$r(k) = \begin{cases} q_{cap} - q_{in}(k-1) & , \quad o_{in}(k-1) \le o_{cr} \\ r_{\min} & , \quad o_{in}(k-1) > o_{cr} \end{cases} \tag{2.1}$$

where $r(k)$ is the allowed ramp flow at time k, $q_{in}(k-1)$ is the last measured upstream motorway flow, $o_{in}(k-1)$ is the last measured upstream motorway occupancy, q_{cap} is the downstream motorway capacity, $r_{\min}$ is the minimum admissible ramp flow and o_{cr} is the downstream critical occupancy.

It is clear from the formulation of the DC strategy that it is a feed-forward (Figure 2-1) disturbance-rejection scheme, which is generally known to be sensitive to various disturbances.

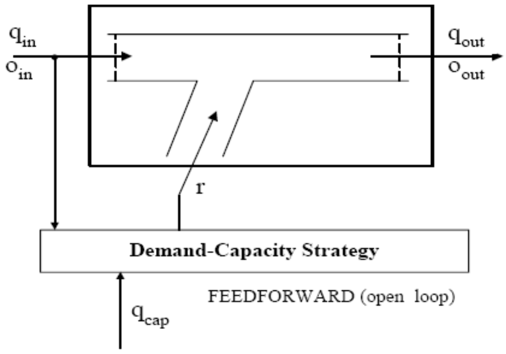

Figure 2-1: Demand-Capacity (DC) strategy

Occupancy Strategy

The Occupancy (OCC) strategy (Masher et al. 1975) approximates the left-hand side of the fundamental diagram (Figure 2-2) via a straight line. It uses measurements of the ramp's upstream occupancy. The upstream flow is calculated as $q_{in} = \frac{v_f \cdot o_{in}}{g}$ where v_f is the free speed and g is known as the g-factor.

By replacing q_{in} in the DC strategy equation we get the OCC strategy:

$$r(k) = \begin{cases} K_1 - K_2 \cdot o_{in}(k-1) & , \quad o_{in}(k-1) \le o_{cr} \\ r_{\min} & , \quad o_{in}(k-1) > o_{cr} \end{cases} \tag{2.2}$$

where $K_1 = q_{cap}$, $K_2 = \frac{v_f}{g}$ and $r(k)$ is between $r_{\min}$ and $r_{\max}$, where $r_{\max}$ is the ramp's estimated flow capacity.

It is clear that the OCC strategy is, like the DC strategy, a feed-forward scheme based on occupancy. Because of the linearity assumption of the fundamental diagram and the estimated values of v_f and g, this strategy is even more inaccurate than the DC strategy.

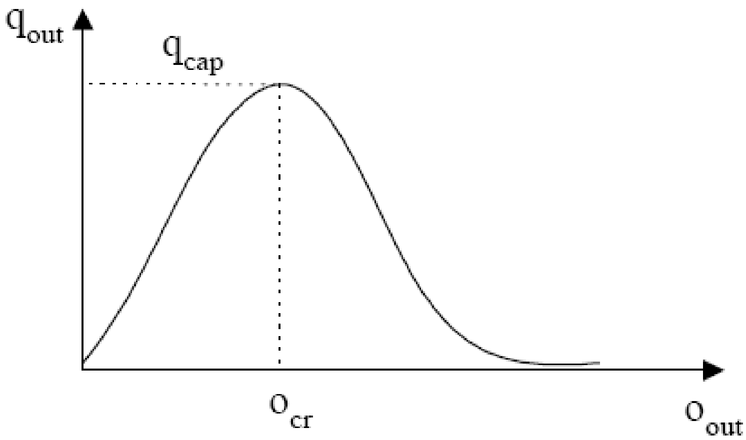

Figure 2-2: Fundamental diagram.

ALINEA

ALINEA (Papageorgiou et al. 1991) stands for Asservissement Linéaire d’Entrée Auotroutière and is a local feedback ramp metering strategy (Figure 2-3) based on powerful and robust automatic control methods. The control law is

$$r(k) = r(k-1) + K_R\left[\hat{o} - o_{out}(k-1)\right] \tag{2.3}$$

where $r(k)$ is the metering rate at time k, $K_R > 0$ is a regulator parameter, $\hat{o}$ is the set (desired) value for the downstream occupancy (typically $\hat{o} = o_{cr}$) and o_{out} is the measured downstream occupancy.

ALINEA has been implemented at various sites with very good results. Comparative field evaluations demonstrated the clear superiority of ALINEA compared to the DC (Demand – Capacity) and OCC (Occupancy) strategies (Papageorgiou et al. 1997).

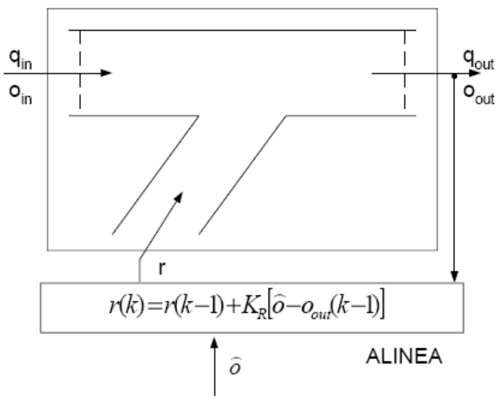

Figure 2-3: ALINEA strategy

Apart from its basic form, there have been a number of modifications and extensions of ALINEA suggested by Smaragdis and Papageorgiou (2003). These include Flow-Based ALINEA (FL-ALINEA), Upstream-Occupancy Based ALINEA (UP-ALINEA), Upstream-Flow Based ALINEA (UF-ALINEA) and Ramp-Queue Control (X-ALINEA/Q), where X can be any of the aforementioned ALINEAs. Another development is Adaptive ALINEA (AD-ALINEA) presented by Smaragdis et al. (2004).

Fuzzy Logic Algorithm

Fuzzy logic ramp metering control has been implemented in both Seattle and Zoetermeer with good results. According to Bogenberger and May (1999) in the case of Seattle it showed improved results in comparison to the existing bottleneck algorithm that lead to the conversion of the existing control strategy (bottleneck algorithm) to fuzzy logic control.

The algorithm as it is implemented in Seattle uses 7 inputs, 5 measurements of occupancy and 2 of speed at locations on the ramp, at the merging point and also upstream and downstream of it. Then the classic fuzzy logic process is realized, that means the measured values undergo fuzzification, are run through a rule base and after defuzzification a metering rate is produced.

2.3.2.2 Coordinated Strategies

METALINE

METALINE is a multivariable regulator control strategy and may be viewed as a generalization and extension to ALINEA. It is developed on the basis of linear quadratic (LQ) optimization theory (Papageorgiou et al. 1990b). Although a motorway traffic system is a nonlinear system, LQ control can be applied after linearization around a steady-state of the nonlinear system.

METALINE has been implemented and tested either by simulation or at the field at various sites such as the Boulevard Peripherique in Paris, in Milwaukee. The results showed METALINE to be successful in improving traffic conditions.

Two alternative types of METALINE have been considered, a classical LQ-control law (equation (2.4)) and a linear quadratic integral (LQI) control law (equation (2.5)), with the latter being the one recommended due to easier implementation (Papageorgiou et al. 1990b).

$$\mathbf{r}(k) = \mathbf{r}(k-1) - \mathbf{K}_1\left[\mathbf{o}(k) - \mathbf{o}(k-1)\right] \tag{2.4}$$

$$\mathbf{r}(k)=\mathbf{r}(k-1)-\mathbf{K}_1\left[\mathbf{o}(k)-\mathbf{o}(k-1)\right]+\mathbf{K}_2\left[\hat{\mathbf{O}}-\mathbf{O}(k)\right] \tag{2.5}$$

where $\mathbf{r}$ is the vector of controllable on-ramp volumes, $\mathbf{o}$ is the vector of the measured occupancies on the motorway stretch, $\mathbf{O}$ is a subset of $\mathbf{o}$ that includes occupancy locations for which pre-specified set values $\hat{\mathbf{O}}$ may be given and $\mathbf{K}_1$, $\mathbf{K}_2$ are the constant gain matrices of the regulators and must be suitably designed.

METALINE applies LQ and LQI control on a nonlinear system that undergoes linearization, as mentioned before. This means that the gain matrices may be optimal for the approximated linear system but will be suboptimal for the nonlinear system. The results of METALINE's application depend on how well the nonlinear system is approximated by the linear system. The gain matrices require careful tuning that is specific to the location. An example of a study for the application of METALINE at a stretch on the A10-West in Amsterdam can be found in Diakaki and Papageorgiou (1994).

Bottleneck Algorithm

The bottleneck algorithm was developed by the Washington Department of Transportation (WDOT) and is implemented at the Seattle area. The results of the use of the algorithm showed a decrease in travel time and accident rates without causing big delays at each metered ramp.

The algorithm is of competitive manner. It uses a two-level structure, the local and the global level. At the local level, metering rates are calculated so that the measured upstream demand plus the ramp flow equals the downstream capacity, in other words the DC strategy is used. At the global level, when a bottleneck is identified, a volume reduction for the area is calculated based on flow conservation and is distributed to upstream ramps that are in the bottleneck area of influence according to predetermined weights. The most restrictive of the two calculated rates is then chosen.

After the ramp metering rate is specified, further adjustments are made for high occupancy vehicles (HOV) and also to avoid queue spillback on the arterial street network.

Minnesota's Zone & Stratified Zone Metering Algorithm

The zone algorithm was implemented at the Twin Cities area in Minnesota. Periodical evaluations of the metering system have shown improvements in traffic conditions. Nevertheless, after a study ordered by the Minessota's

Department of Transportation (Mn/DOT) in 2000, it was decided to develop a new algorithm that is now used and is known as stratified zone metering.

The original zone algorithm segments a motorway into zones with variable lengths. Each zone has usually an upstream free-flow area and ends downstream in a bottleneck area. The goal of the algorithm is to have the traffic volume that enters the zone to be no more than the volume that can leave the zone. The metering rate for each ramp is selected from six distinct predefined rates varying from no metering rate to a full cycle length. To account for localized congestion a second metering rate is calculated based on local detector data. The most restrictive rate is then chosen.

One of the downsides of the zone algorithm is that it does not take under consideration on-ramp queues resulting in long waiting times and spillback to local streets. The new, modified, algorithm is accounting for long queues and delays and even tries to share the delays across corridor ramps.

Helper Ramp Algorithm

The helper ramp algorithm was introduced in 1981 in the Denver area. In 1988 and 1999 evaluations of the strategy were conducted and the results showed that centralized control was effective only in the case when speeds were less than 90 km/h. During the years of its implementation there have been minor adjustments to the strategy.

The algorithm consists of a local traffic responsive algorithm combined with a centralized algorithm that is able to override local control in the case that specific congestion thresholds are reached. The controlled ramps are divided into groups, with each group having 1 to 7 ramps.

The local strategy selects for each ramp one of 6 available predefined metering rates based on measurements of the upstream occupancy. In case of excessive queue build-up on the ramps, it is detected and the metering rate is changed one level per time interval to clear them. A smoothing function makes sure there are no wide swings in metering rates.

The centralized strategy monitors each ramp. When a ramp's metering rate is at the most restricting level or the queue on it exceeds a certain threshold, local control is overridden. If the ramps state does not change for three consecutive time intervals the metering rate of the next upstream ramp is then reduced by one level. As long as the problem exists this process is repeated and moves upstream one ramp each time interval until all ramps in the group are overridden. In that case if the problem still consists the process is continued in the next upstream group. The coordinated control state stops and is changed back to the local control strategy when all ramps return to a normal state.

Linked Ramp Algorithm

The linked ramp algorithm operates in the area of San Diego since 1968. Until 1994 the San Diego Ramp Metering System (SDRMS) was partially coordinated but that changed and the meters operate as local traffic responsive control.

The base of the SDRMS is the demand-capacity theory. Historical ramp flow and origin-destination information is used to assign the capacity of each roadway segment to the mainline and to all the influencing upstream ramps. A target flow rate is then determined for each segment based on historical data and the minimum ramp metering rates. A 16-level metering rate system with linearly distributed rates between the minimum and maximum values is used. The rate to be implemented is decided locally according to the upstream measured flow. If the measured flow exceeds the target flow rate then the lowest metering rate is used. A second rate is calculated based on occupancy measurements to compensate for the case of low flow due to congestion. The most restricting rate is used.

When a ramp's metering rate is one of its lowest three possible rates the next upstream ramp is signalled to begin metering at the same rate or less. The situation is constantly re-evaluated and it is possible to move to next ramp if necessary. It is even possible to move on to the next area of influence.

Sperry Algorithm

The Sperry ramp metering algorithm is implemented in northern Virginia and was developed by the Virginia Department of Transportation. The first ramp meters were installed in 1985. Since then no expansion of the system has taken place.

The algorithm has two modes, non-restrictive metering and restrictive metering. The latter case, restrictive metering, is the default state and is implemented when traffic conditions require it. It uses a demand-capacity equation, which tries to keep centralized demand below capacity nevertheless trying to have fair-play between the ramps. The motorway is divided in control sections with several on and off ramps and up to ten meters. The algorithm starts at the furthest downstream ramp calculating its rate and moving upstream, one ramp at a time. Non-restrictive metering is implemented when spillback of the ramp queue to the arterial network occurs. The metering rate is then increased until the spillback is contained.

Compass Algorithm

The compass algorithm is implemented in Toronto since 1975. The algorithm can be operated both manually and in automatic mode.

In the manual mode the metering rate can be selected from 17 different rates for each ramp. The automatic mode consists of both a local and a global strategy. The strategy's main characteristics are the control section, control period, control algorithm and queue override. A control section consists of motorway segments that have an influence of a downstream point. A control period defines when the system should activate and deactivate the automatic metering control. The control algorithm can either be local or global. The local strategy chooses the metering rate from a look-up table based on local mainline occupancy, downstream mainline occupancy, upstream mainline volume and other predefined parameters. The global strategy computes the metering rates off-line. The most restrictive of the two rates is selected. In the case of queue spillback the metering rates are overridden and are increased by one level until occupancy falls under a predefined threshold level.

System Wide Adaptive Ramp Metering

The System Wide Adaptive Ramp Metering (SWARM) algorithm is in development since 1996. It also uses a 2 level structure, of local and global control. The main difference to other algorithms is that the metering rates are decided based on predictions made with use of Kalman filtering on detector data.

SWARM1 is the algorithm responsible for the forecasting of a density trend at each detector location for the next time interval. To achieve this, a process of linear regression and Kalman filtering is used on data collected in previous time intervals. The predicted density is then compared to the saturation density to calculate an excess density that is used to prevent congestion. After a few calculations the algorithm returns either volume reduction or volume excess values for each detector location. These values are then distributed to upstream ramps within a predefined area of influence according to weighting factors and a metering rate is produced.

SWARM2 is a local algorithm, which assigns metering rates to each ramp based on each ramp's upstream density.

The most restricting rate of the two is selected for implementation as long as it is between predefined minimum and maximum values.

2.3.2.3 Nonlinear Optimal Ramp Metering Strategies

Advanced Motorway Optimal Control

Advanced Motorway Optimal Control (AMOC) formulates the coordinated ramp metering problem as a discrete-time dynamic optimal control problem with constrained control variables which can be solved numerically over a given optimization horizon K_p. Motorway traffic flow is considered to be the process controlled via the various ramp meters installed at on-ramps.

AMOC is described in great detail in chapter 4.

2.3.2.4 Other Strategies

Other ramp metering algorithms already in use or under development include dynamic metering control algorithm, linear programming algorithms, BALL Aerospace/FHWA corridor control algorithm, advanced real-time metering system (ARMS), coordinated and/or local metering using artificial neural networks (ANN), metering model of non-recurrent congestion and others.

3 Modelling of traffic flow on motorway networks

3.1 Introduction

The study of natural phenomena, like traffic flow, is made easier by the existence of mathematical models that describe them. There can exist more than one model that describes a phenomenon. Each one can be more or less accurate and detailed and covers different needs.

The mathematical models for traffic flow can most of the times be classified in three categories based on their level of accuracy; microscopic models, mesoscopic models and macroscopic models. Microscopic traffic flow models keep track of every individual car movement in the network, which accounts for great complexity. Mesoscopic models observe groups of vehicles with similar characteristics. Macroscopic traffic flow models have a different approach. They consider traffic flow as a fluid that can be described with variables like flow, density and speed.

Modelling of traffic flow on motorway networks is a useful tool for several traffic engineering tasks. It can be used for the development and evaluation of traffic control strategies, for the evaluation of the impact of new constructions and the comparison of alternatives, for the evaluation of the impact of capacity reducing events (e.g. road works, accidents) or increased demand, for the prediction and surveillance of the traffic state in complex networks.

When a model is chosen for the simulation of a phenomenon, there are various aspects to consider. Speed and accuracy are usually competitive, available data and needed results are other factors. Microscopic and mesoscopic models are more detailed but therefore need more computational power; macroscopic models are simpler and much faster to compute. Macroscopic models are probably better suited for the simulation of traffic flow on motorway networks. Their lack of detail has not a negative effect on results and they are much faster, which is more important in case of real time applications.

The first macroscopic modelling theory for traffic flow on a highway stretch is usually called the LW model because of a paper by Lighthill and Whitham (1955) that laid the foundations of the kinematic wave theory. A more accurate second-order model was proposed by Payne (1971) and was later extended by Papageorgiou et al. (1990a) to improve some aspects of the model particular in merging areas such as on-ramps or lane-drops.

The importance of traffic flow modelling and the relationship with traffic control is studied by Kotsialos and Papageorgiou (2001b). In the present research the macroscopic model METANET (Messmer and Papageorgiou 1990; DSSL and Messmer 2000) is used for the simulation of traffic flow on motorway networks and the development of control strategies.

3.2 The METANET traffic flow model

The METANET model for motorway network simulation is based on a purely macroscopic modelling approach. The motorway network is described as a graph with the use of network links and network nodes. The network links represent motorway stretches and the nodes are placed at places where a change in the geometry occurs, for example at junctions or lane drops.

3.2.1 Modelling of network links

The simulation of traffic behaviour in the network links uses an approach that is based on Payne's (1971) model with the extensions introduced later by Papageorgiou et al. (1990a). The model's variables are the traffic density ρ (veh/km/lane), the mean speed v (km/h), and the traffic volume (or flow) q (veh/h).

The time and space arguments are discretized. The discrete time step is denoted by T. Motorway links are denoted by m and are divided into N_m segments of equal length L_m. Each segment i of link m at discrete time $t = kT$, $k = 0,...,K$, where K is the time horizon, is then macroscopically characterized via the following variables: the traffic density $\rho_{m,i}(k)$ (veh/lane/km) is the number of vehicles in segment i of link m at time $t = kT$ divided by L_m and by the number of lanes Λ_m; the mean speed $\upsilon_{m,i}(k)$ (km/h) is the mean speed of the vehicles included in segment i of link m at time $t = kT$; and the traffic volume or flow $q_{m,i}(k)$ (veh/h) is the number of vehicles leaving segment i of link m during the time period $\left[kT,(k+1)T\right]$, divided by T.

There are 4 types of network links: motorway links, on-ramp links, off-ramp links and store and forward links.

As stated before, each link m has to be divided into N_m segments of equal length L_m. The following relationship has to hold true:

$$L_m > v_{f,m} \cdot T\,, \tag{3.1}$$

where $v_{f,m}$ is the free speed and T the simulation time step. This relation ensures that a vehicle travelling with free speed through the segment will not pass it during the simulation time step. Typical segment length is between 300 and 800 meters for a simulation time step of 10 seconds and free speed around 100 km/h.

3.2.1.1 Motorway links

For every segment i the following equations are used:

Continuity Equation:

$$\rho_{m,i}(k+1) = \rho_{m,i}(k) + \frac{T}{L_m \cdot \lambda_m}\left[q_{m,i-1}(k) - q_{m,i}(k)\right], \tag{3.2}$$

$$q_{m,i}(k) = \rho_{m,i}(k) \cdot v_{m,i}(k) \cdot \lambda_m\,. \tag{3.3}$$

Speed Equation:

$$\begin{aligned} v_{m,i}(k+1) \quad = \quad & v_{m,i}(k) + \frac{T}{\tau}\left[V\left(\rho_{m,i}(k)\right) - v_{m,i}(k)\right] \\ + \quad & \frac{T}{L_m} v_{m,i}(k) \cdot \left[v_{m,i-1}(k) - v_{m,i}(k)\right] - \frac{\nu T\left[\rho_{m,i+1}(k) - \rho_{m,i}(k)\right]}{\tau L_m\left[\rho_{m,i}(k) + \kappa\right]}\,. \end{aligned} \tag{3.4}$$

Fundamental Diagram (Figure 3-1):

$$V\left(\rho_{m,i}(k)\right) = v_{f,m} \cdot \exp\left[-\frac{1}{a_m}\left(\frac{\rho_{m,i}(k)}{\rho_{cr,m}}\right)^{a_m}\right]. \tag{3.5}$$

τ, ν and κ are parameters that have the same value for all network links. λ_m represents the number of lanes of link m. The values for free flow speed $v_{f,m}$, for the critical density $\rho_{cr,m}$ and for the exponent a_m are specific for the fundamental diagram of each link m. While free speed and critical density are required as a user input, the parameter a_m is internally computed using one of the following equations depending on the data available:

$$a_m = -\frac{1}{\ln\left(\frac{q_{cap,m}}{v_{f,m}\rho_{cr,m}}\right)}, \tag{3.6}$$

$$\ln\left(\frac{q_{cap60,m}}{q_{cap,m}}\frac{\rho_{cr,m}}{60}\right) = \frac{1}{a_m}\left(1-\left(\frac{60}{\rho_{cr,m}}\right)^{a_m}\right), \tag{3.7}$$

$$\ln\left(\frac{q_{cap60,m}}{60v_{f,m}}\right) = -\frac{1}{a_m}\left(\left(\frac{60v_{f,m}}{\rho_{cr,m}}\right)^{a_m}\right)\frac{1}{e}. \tag{3.8}$$

When two or more links merge at a network node and the leaving links have less or equal lanes than the incoming, the merging phenomenon occurs and has to be considered. In this case the following term is added to equation (3.4):

$$-\frac{\delta T}{L_m\lambda_m}\frac{q_\mu(k)v_{m,l}(k)}{\rho_{m,l}(k)+\kappa} \tag{3.9}$$

where δ is a global parameter.

In case the leaving lanes are more than the incoming, dedicated lanes exist. If the inflow is below the capacity of the leaving link or links, equation (3.9) is not applied else the exceeding flow is used as q_μ.

Lane drops are other phenomena that have to be considered. In this case the speed is reduced and has to be accounted for in equation (3.4). The following term, where $\Delta\lambda$ is the number of lanes being dropped, is added to equation (3.4):

$$-\frac{\phi T}{L_m \lambda_m} \frac{\Delta\lambda \cdot \rho_{m,l_m}(k)}{\rho_{cr,m}} v_{m,l_m}(k)^2 . \tag{3.10}$$

Incidents have also to be considered. To define an incident, the time, duration and location have to be specified as well as the severity (capacity reduction). Equation (3.3) is modified as follows

$$q_{acc} = (1-u) q_{cap,m} \lambda_m , \tag{3.11}$$

$$q_{m,i}(k) = \min\left\{\rho_{m,i}(k) v_{m,i}(k) \lambda_m , q_{acc}\right\} , \tag{3.12}$$

with u representing the severity of the incident, $u = 0$ means in fact no blocking and $u = 1$ means complete blocking.

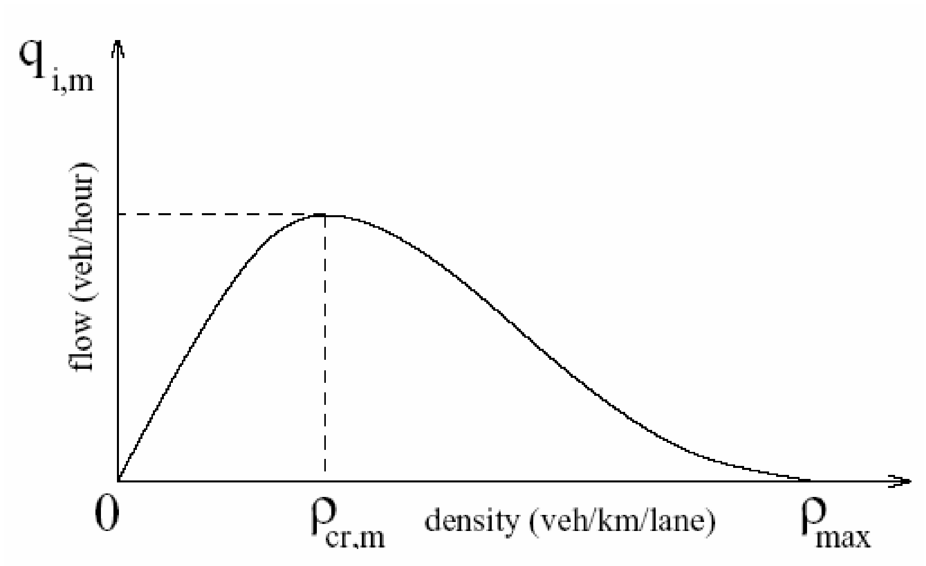

Figure 3-1: Fundamental diagram.

3.2.1.2 Store and Forward links

Store and forward links (SAF) do not describe traffic flow as accurate as motorway links. The traffic that enters a SAF link is added at the end of a link queue w_{saf} after a time delay $T_{lag,saf}$

$$w_{saf}\left(k+1\right)=w_{saf}\left(k\right)+T\left[q_{\text{inflow},saf}\left(k\right)-q_{saf}\left(k\right)\right]. \tag{3.13}$$

The outflow q_{saf} of a SAF link is modelled with the following equations

$$\begin{aligned} q_{saf} &= r_{saf}\, q_{\max,saf} \\ q_{\max,saf} &= \min\left\{\frac{q_{\text{inflow},saf}+w_{saf}}{T}, q_{poss,saf}\right\} \end{aligned} \tag{3.14}$$

where $q_{\text{inflow},saf}$ is the delayed by time $T_{lag,saf}$ flow that enters the SAF link, w_{saf} is the length of the existing waiting queue, $q_{\max,saf}$ is the current maximum outflow from the link, $q_{poss,saf}$ is the current outflow capacity of the link and $r_{saf}\in\left[0,1\right]$ is the metering rate.

The outflow capacity $q_{poss,saf}$ is defined according to the downstream density ρ_{μ}

$$q_{poss,saf}=\begin{cases} Q_{\max,saf}\lambda_{saf} & , \quad \rho_{\mu}<\rho_{cr,\mu} \\ Q_{\max,saf}\lambda_{saf}\, p & , \quad \rho_{\mu}\geq\rho_{cr,\mu} \end{cases} \tag{3.15}$$

with $Q_{\max,saf}$ being the geometrical capacity and $0\leq p\leq 1$ a factor that reduces the flow allowed to leave the SAF and is calculated by:

$$p=1-\frac{\rho_{\mu}-\rho_{cr,\mu}}{\rho_{\max}-\rho_{cr,\mu}} \tag{3.16}$$

A traffic density ρ_{saf} is calculated for the link, which may affect the traffic volume entering the SAF from the upstream node. This density is calculated as follows:

$$\rho_{saf}=\rho_{\max}\frac{\left(w_{saf}+n_{d,saf}\right)L}{l_{saf}\lambda_{saf}} \tag{3.17}$$

where $\rho_{\max}$ is a global parameter representing the maximum permissible traffic density, $n_{d,saf}$ is the number of vehicles that have entered the SAF but haven't reached the queue yet due to the internal travel time, l_{saf} is the length of the link,

λ_{saf} is the number of lanes and L is the mean vehicle length that its default value is set to 0.006 km.

3.2.1.3 Origin links

Origin links are considered the furthest upstream links of a motorway and the on-ramps. They act as boundary conditions for the model and are modelled with a simple queuing model (Figure 3-2) in conjunction with inflow limitation. The queue is built as follows:

$$w_o(k+1) = w_o(k) + T \cdot \left[d_o(k) - q_o(k) \right] \tag{3.18}$$

with

$$\begin{aligned} q_o &= r_o \cdot q_{\max,o} \\ q_{\max,o} &= \min\left\{ d_o + \frac{w_o}{T}, q_{poss,o} \right\} \end{aligned} \tag{3.19}$$

where d_o is the demand flow at origin o, w_o is the length of the existing waiting queue, $q_{\max,o}$ is the current maximum outflow from the origin into the network, $q_{poss,o}$ is the current outflow capacity of the origin link and $r_o \in [0,1]$ is the metering rate.

The outflow capacity $q_{poss,o}$ is defined according to the downstream density ρ_μ

$$q_{poss,o} = \begin{cases} Q_{\max,o} \cdot \lambda_o & , \quad \rho_\mu < \rho_{cr,\mu} \\ Q_{\max,o} \cdot \lambda_o \cdot p & , \quad \rho_\mu \geq \rho_{cr,\mu} \end{cases} \tag{3.20}$$

with $Q_{\max,o}$ being the geometrical capacity and $0 \leq p \leq 1$ a factor that reduces the flow allowed to leave the origin link and is calculated in the same way as for SAF links:

$$p = 1 - \frac{\rho_\mu - \rho_{cr,\mu}}{\rho_{\max} - \rho_{cr,\mu}}. \tag{3.21}$$

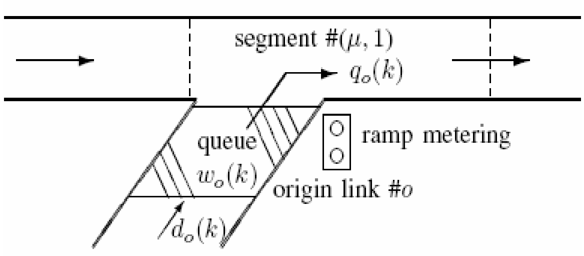

Figure 3-2: The origin-link queue model.

A similar approach applies to motorway-to-motorway (mtm) interchanges. The evolution of the origin queue w_o is described by an additional state equation (conservation of vehicles). Due to the complex nonlinear and dynamic nature of the macroscopic model the critical density of a simulated motorway is not fully determined by the considered fundamental diagram. Thus the motorway flow $q_{\mu,1}$ in merge segments is maximized if the corresponding density $\rho_{\mu,1}$ takes values around a factual density $\rho_{f-cr,\mu}$, which is determined via simulations, and not the critical density $\rho_{cr,\mu}$ provided by the fundamental diagram of that link.

3.2.1.4 Destination links

Destination links are considered the furthest downstream links of a motorway and the off-ramps. These accept the traffic volume of the network and forward it to the environment. As is the case with origin links, destination links act as boundary conditions to the model. It is assumed that the environment has infinite capacity. Nevertheless the outflow of the network is limited by the ability of the upstream motorway link.

3.2.2 Modelling of network nodes

3.2.2.1 Flow Distribution

In general, traffic enters a node n through a number of input links and is distributed to a number of output links. The incoming flow is merged in the node and then distributed to the leaving links as expressed by equations (3.22) and (3.23) respectively.

$$Q_n(k) = \sum_{\mu \in I_n} q_{\mu,N_\mu}(k) \tag{3.22}$$

$$q_{m,0} = \beta_n^m(k) Q_n(k) \quad \forall m \in O_n \,. \tag{3.23}$$

$Q_n(k)$ is the total traffic volume entering node n at period k. The turning rates β_n^m specify the portion of $Q_n(k)$ that leaves the node through link m, I_n is the set of links entering node n and O_n is the set of links leaving.

3.2.2.2 Upstream Influence of Density

In each segment, the dynamic evolution of speed is influenced by the density of the next downstream segment as is obvious from equation (3.4). In case the segment is not the last in the link, the downstream density can easily be obtained. But in the case of the last segment l_m in a link m of l_m segments, a density ρ_{m,l_m+1} has to be calculated.

In the case of only one leaving link from the node the value of the downstream density is the value of the density of the adjacent downstream segment. But in the case of two or more leaving links this value has to be calculated by considering the density value of the adjacent downstream segment of all leaving links. This is done by taking an appropriate weighted average of these values:

$$\rho_{m,l_m+1} = \frac{\sum_{\mu \in O_n} \rho_{\mu,1}^2}{\sum_{\mu \in O_n} \rho_{\mu,1}} \quad \forall m \in I_n \tag{3.24}$$

where $\rho_{\mu,1}$ is the density of the first segment of a leaving link μ. By use of this equation a quadratic weighting of the leaving links densities is performed. This way the fact that heavily loaded stretches contribute more than proportionally to spillback is taken into account. A congestion of one of the leaving links is often sufficient to produce spillback into the input link, as is usually observed in real world.

3.2.2.3 Downstream Propagation of Speed

In each segment, the dynamic evolution of speed is also influenced by the mean speed of the upstream segment as is stated by the speed equation (3.4). Again, in case of a segment not being the first in a link the upstream mean speed is easily obtained from the adjacent upstream segment. But in case of the first segment in a link m a speed $v_{m,0}$ has to be determined.

In case of only one input link at a node this value is easily obtained from the speed of last segment of the input link. But in case of several input links the value of the speed has to be calculated by considering the speed in all incoming links. This is done by taking the mean over the speeds v_μ at the end of the incoming links μ weighted by the according incoming flow:

$$v_{m,0} = \frac{\sum_{\mu \in I_n} v_\mu \cdot Q_\mu}{\sum_{\mu \in I_n} Q_\mu} \quad \forall m \in O_n \,. \tag{3.25}$$

3.2.3 Performance criteria

To assess the performance of traffic control strategies and compare them with each other there is the need of introducing some performance criteria. There are various such criteria. The most important criteria are described below. The macroscopic simulator METANET is able to compute these criteria during simulation and present them together with the rest of the results.

3.2.3.1 Total Travel Time

Total travel time (TTT) τ_G (veh*h) is comprised of the sum of travel time of vehicles in the normal links $\tau_{G,N}$ and in the SAF links $\tau_{G,SAF}$. It is calculated as follows:

$$\tau_G = \tau_{G,N} + \tau_{G,SAF} = T \sum_k \sum_m L_m \lambda_m \sum_i \rho_{mi}(k) + T \sum_k \sum_{saf} n_{d,saf} \,. \tag{3.26}$$

where $n_{d,saf}$ represents the number of vehicles that have entered the SAF link but have not exited yet.

3.2.3.2 Total Waiting Time at network origins

The Total Waiting Time (TWTO) $\tau_{W,O}$ (veh*h) criterion represents the waiting time at all network origins over the simulation horizon. It is calculated by

$$\tau_{W,O} = T\sum_{k}\sum_{o} w_o\left(k\right) \qquad (3.27)$$

with O being the total number of network origins.

The waiting time at the origins is the result of existing queues. The queue may be created by congestion spillback from the downstream part of the network or due to excessive demand or because of metering control measures.

3.2.3.3 Total Waiting Time at SAF links

The Total Waiting Time at SAF links (TWTSAF) $\tau_{W,SAF}$ (veh*h) criterion represents the waiting times at all SAF links in the network over the simulation horizon and is calculated by

$$\tau_{W,SAF} = T\sum_{k}\sum_{saf} w_{saf}\left(k\right). \qquad (3.28)$$

As is the case with origins, the waiting time at SAF links is caused by queues created for similar reasons as for origin links.

3.2.3.4 Total Time Spent

The Total Time Spent (TTS) τ_S (veh*h) in the network is calculated as the sum of TTT, TWTO and TWTSAF:

$$\tau_S = \tau_G + \tau_{W,O} + \tau_{W,SAF}. \qquad (3.29)$$

3.2.3.5 Total Distance Travelled

The Total Distance Travelled (TDT) L_G (veh*km) is the distanced travelled by all vehicles during the simulation horizon and is calculated as the sum of the distance travelled in the normal links and in the SAF links:

$$L_G = L_{G,N} + L_{G,SAF} = \sum_{k} T\sum_{m}\sum_{i} q_{mi}\left(k\right)L_m + \sum_{k} T\sum_{saf} q_{saf}\left(k\right)L_{saf} \qquad (3.30)$$

where q_{saf} is the flow entering the SAF link.

3.2.4 Total Amount of Fuel Consumed

The Total Amount of Fuel Consumed (TFC) V_G (veh*l) criterion represents the amount of fuel that is consumed by the vehicles travelling in the network. It is calculated as the sum of the consumption in normal links, SAF links and the origin links.

$$V_G = V_{G,N} + V_{G,O} + V_{G,SAF} \tag{3.31}$$

with

$$V_{G,N} = \sum_k \frac{T}{100} \sum_m L_m \sum_i q_{m,i}(k) \cdot \begin{cases} b + \dfrac{c}{v_{m,i}(k)} + a\left(v_{m,i}(k) - 60\right)^2 & , \quad v_{m,i}(k) > 60 \\ b + \dfrac{c}{v_{m,i}(k)} & , \quad v_{m,i}(k) \le 60 \end{cases} \tag{3.32}$$

$$V_{G,O} = \sum_k \frac{T}{100} \sum_o w_o(k) v_o(k) \cdot \begin{cases} b + \dfrac{c}{v_o(k)} + a\left(v_o(k) - 60\right)^2 & , \quad v_o(k) > 60 \\ b + \dfrac{c}{v_o(k)} & , \quad v_o(k) \le 60 \end{cases} \tag{3.33}$$

$$V_{G,SAF} = \sum_k \frac{T}{100} \sum_{saf} b \cdot q_{saf}(k) \cdot L_{saf} + c \cdot w_{saf} \tag{3.34}$$

where v_o is a virtual speed value calculated as $v_o(k) = \dfrac{q_o(k)}{\rho_{queue} \lambda_o}$ where ρ_{queue} is considered fixed at 100 veh/km. The coefficients a, b, c have the following meaning:

	Consumption term	units
a	Speed-dependent per mileage	l/km/veh*(km/h)$^{-2}$*100
b	Speed-independent per mileage	l/km/veh*100
c	per time (e.g. when queuing)	l/h/veh*100

In the macroscopic simulator METANET the values used for a, b and c respectively are 0.0016, 4.49 and 122.

3.3 The METANET Simulation Program

METANET is a program for motorway network simulation based on a purely macroscopic modelling approach. This leads to relatively low computational effort, which is independent of the load (number of vehicles) in the simulated network and allows also for a real-time use of the model. The overall modelling approach allows for simulation of all kinds of traffic conditions (free, dense, and congested) and of capacity-reducing events (incidents) with prescribed characteristics (location, intensity, and duration).

METANET may be applied to existing or hypothetical, multi-origin, multi-destination, multi-route motorway networks with arbitrary topology and geometric characteristics including bifurcations, junctions, on-ramps and off-ramps. By use of a special modelling option (store-and-forward links), METANET provides also the possibility to consider non-motorway links in a simplified way.

METANET considers the application of traffic control measures (some of them were covered in the previous sections), such as collective and/or individual route guidance as well as ramp metering and motorway-to-motorway control, at arbitrary network locations. Several options are offered for describing or prescribing the average route choice behaviour of drivers groups with particular destinations. Route guidance and dynamic traffic assignment considerations in METANET are based on the notion of splitting rates at bifurcation nodes rather than on path assignment. Among other advantages, this approach enables consideration of route guidance or traffic assignment for a part of the network (rather than the whole network) if so desired by the user.

Simulation results are provided in terms of macroscopic traffic variables such as traffic density, traffic volume, and mean speed at all network locations as well as in terms of travel times on selected routes. This is done on a configurable output time interval that is chosen usually significantly longer than the simulation time step (typically 5 to 20 s). Visualisation of results is provided both by time trajectories of selected variables and by graphical representation of the whole network. Global evaluation indexes such as total travel time, total travelled distance, total fuel consumption, total waiting time at network origins, total disbenefit of routed drivers, etc. are also calculated.

4 Optimal Control and Hierarchical Optimal Control

4.1 Introduction

In this chapter, an approach to the coordinated ramp metering problem is presented. The optimal control theory and the corresponding numerical solution algorithms are used. An Advanced Motorway Optimal Control (AMOC) algorithm has been developed (Kotsialos et al. 2002) with satisfactory results (Kotsialos and Papageorgiou 2004b; Kotsialos and Papageorgiou 2004c). The AMOC strategy has been cast into a hierarchical control structure and a rolling horizon scheme is used further enhancing its efficiency (Kotsialos 2004; Kotsialos and Papageorgiou 2005a, Kotsialos et al. 2005).

4.2 Advanced Motorway Optimal Control

AMOC formulates the coordinated ramp metering problem as a discrete-time dynamic optimal control problem with constrained control variables which can be solved numerically over a given optimization horizon K_p. Motorway traffic flow is considered to be the process controlled via the various ramp meters positioned at on-ramps. AMOC employs the same equations as METANET to model the traffic flow and uses a well known feasible-direction non-linear optimization algorithm (Papageorgiou and Marinaki 1995) for the numerical solution of the problem.

In general a process is described by its state vector $\mathbf{x}$, control variables $\mathbf{u}$ and the uncontrollable external disturbances $\mathbf{d}$. In this case, the state vector $\mathbf{x}$ (equation (4.1)) is comprised of the densities $\rho_{m,i}$ and the mean speeds $v_{m,i}$ of every segment i of every link m and the queues w_o of every origin o. The control vector $\mathbf{u}$ consists of the ramp metering rates r_o of every on-ramp o under control. The disturbance vector $\mathbf{d}$ consists of the demands d_o at every origin of the network and all the turning rates β_n^m at the networks bifurcations. The disturbance trajectories are not controllable but are presumed known or at least predictable. The prediction can either be based on historical data or on real-time estimations (Wang et al. 2003; Wang et al. 2006).

$$\mathbf{x}(k+1)=\mathbf{f}\left[\mathbf{x}(k),\mathbf{u}(k),\mathbf{d}(k)\right] \quad \mathbf{x}(0)=\mathbf{x}_0 \tag{4.1}$$

The formulation of a dynamic problem requires a suitable cost criterion. The cost criterion can be any of the criteria presented in section 3.2.3. Minimization of a different cost criterion leads to a different optimal control trajectory. In the case of AMOC the goal is to eliminate congestion on the motorway but without having major queue build up on the on-ramps. The most relevant criterion thus is the TTS (Total Time Spent) (equation (3.29)). In Papageorgiou and Kotsialos (2002) it has been shown that minimization of the TTS is equivalent to the maximization of the time-weighted total network outflow. The final form of the cost criterion is

$$J=T\sum_k\left\{\sum_m\sum_i\rho_{m,i}(k)L_m\Lambda_m+\sum_o\left[w_o(k)+a_f\left[r_o(k_1)-r_o(k_1-1)\right]^2+a_w\psi\left[w_o(k)\right]^2\right]\right\} \tag{4.2}$$

with

$$\psi\left[w_o(k)\right]=\max\left\{0,w_o(k)-w_{o,\max}\right\} \tag{4.3}$$

where a_f, a_w are weighting factors. The first two terms of equation (4.2) correspond to the TTS, the term with weight a_f is included in the cost criterion to suppress high-frequency oscillations of the optimal control trajectories and the term with weight a_w is included in the cost criterion in order to enable the control strategy to limit the queue lengths at the origins to the desired level. To adjust the weight factors a_f and a_w trial-and-error method is used. The aim is to strike a balance between acceptable time-variations in the optimal control trajectories and queue constraint violations on one hand and efficiency and fast convergence to the optimum on the other hand. The control sample time T_1 may be different than the model sample time T. As a result if we assume T_1 to be a multiple of T then $T_1 = z_1 T$ with $z_1 \in \mathbb{N}$. Then $k_1 = \text{integer}\left[\frac{k}{z_1}\right]$.

The theory of non-linear optimal control that lies behind AMOC is described in great detail in Kotsialos et al. (2002b).

4.3 Hierarchical Control

The control strategy AMOC accepts as input the current situation on the network - which is considered as the initial state - and the predictions of the disturbances. Based on the traffic flow model of the network and by optimizing the cost criterion the strategy calculates the optimal control trajectories. In other words, AMOC defines how the available traffic control actuators have to operate.

The solution of AMOC is optimal but of an open-loop nature. This means that the application of the solution might lead to traffic states different than the calculated ones. The reasons are various:

i. The initial state estimation $\mathbf{x}(0)$ may be erroneous. A dense network of detectors that provide enough information for a reliable state estimation diminishes this problem to a minor issue (Wang and Papageorgiou 2005). In the Amsterdam network that is used for the evaluation of the strategy and is presented in chapter 5 it is safe to assume that the system state is always known because the distance between loop detectors is 500m.
ii. Errors associated with the prediction of the future disturbances. AMOC computes the optimal solution assuming that future disturbances are known, but errors in the prediction of the on-ramp demands and off-ramp turning rates are unavoidable. This means that the result of the optimization does not correspond entirely to the real problem.
iii. The model parameters with which AMOC determines the optimal solution may not be absolutely correct. Change of weather conditions or other reasons can lead to a mismatch between the parameters of the model and the real parameters. This means that however good the knowledge of future disturbances is, the evolution of the traffic states is possible to be different than the one predicted.
iv. Errors due to unpredictable incidents in the network. Incidents may introduce bottlenecks resulting in capacity reduction which would

create a mismatch between the real and the anticipated flow at the incident area.

In order to address the likely problem of the actuators not achieving to implement the optimal solution as calculated by AMOC a hierarchical control scheme is chosen (Figure 4-1) similar to that proposed in Papageorgiou (1984). To address any mismatch between the predicted and actual system behaviour due to the estimation, prediction and modelling errors, a receding (or rolling) horizon approach (model-predictive control) is employed.

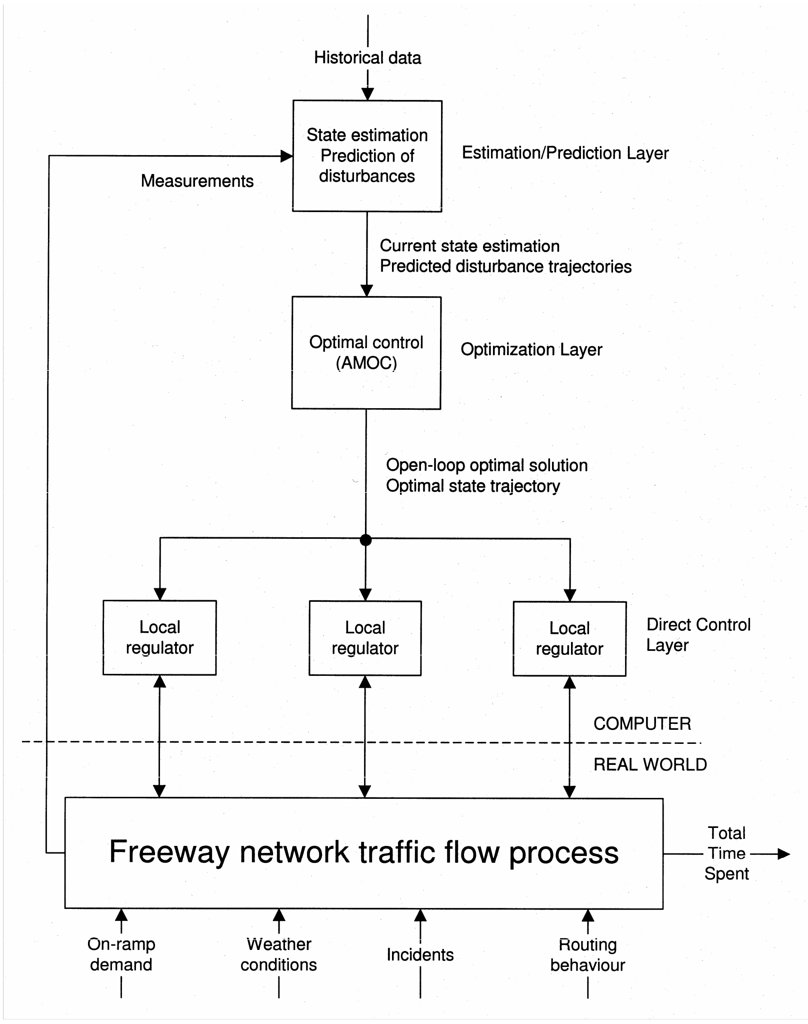

Figure 4-1: Hierarchical control structure.

The hierarchical control structure consists of three layers. The Estimation/Prediction Layer, the Optimization Layer and the Direct Control Layer.

4.3.1 Estimation/Prediction Layer

The Estimation/Prediction Layer's aim is to decide in real-time the initial state of the system, the parameters of the model and make a prediction of the disturbances for a period in the future.

The inputs to the layer are:

i. Information about incidents. In case of an incident the system is informed about where it has taken place and its severity. This data can be given to the system by a technician at the control center or by an automated incident detection system. Automated incident detection is not an easy task; a lot of data from the sensors are required.
ii. Historical data. They are used by the disturbance prediction algorithms.
iii. Real-time measurements from any kind of sensors. The measurements can be the mean speed, traffic flow and occupancy.

The output of the layer is the current state estimation, the predicted trajectories of the disturbances and the model parameters vector.

AMOC is based on a macroscopic description of the traffic flow. This means the current state is defined by the traffic density $\rho_{m,i}$. (veh/km/lane) and the mean speed $v_{m,i}$ (km/h) for segment i of link m, and queues w_o of the on-ramps or SAF links o. Thus the state vector for N links with N_m segments and W on-ramps will be

$$\mathbf{x} = \left[\rho_{1,1} v_{1,1} \dots \rho_{1,N_1} v_{1,N_1} \dots \rho_{N,1} v_{N,1} \dots \rho_{N,N_N} v_{N,N_N} w_1 \dots w_W \right]^T . \tag{4.4}$$

An algorithm that estimates the current system state has to deliver the state vector $\mathbf{x}(k)$ at the present time k which we consider $k = 0$. This is a classical estimation problem. A lot of effective tools exist in the automated control theory field with Kalman filter being the most prominent. In this case the extended Kalman filter has to be used as the problem encountered is non linear. In Wang and Papageorgiou (2005) an estimation approach using the extended Kalman filter is presented.

The inputs to the traffic flow that cannot be controlled and originate from the network environment are called disturbances. The detail in which the disturbances are described depends on the nature of the disturbances as well as from the model. In the model used, the primary disturbances that are of interest are the demand at the networks origins and the turning rates at the networks destinations. Other disturbances such as speed at the origins and density at exits are not so important and can be omitted. All disturbances can be expressed with the vector $\mathbf{d} = \left[d_1 ... d_O \beta_1^{m_1} ... \beta_B^{m_B} \right]^T$ with $d_o, o = 1, ..., O$ being the demand at the networks O origins and β_n^m the turning rates at the networks B bifurcations. The problem of demand prediction can be addressed by various approaches (Okutani and Stephanedes 1984; Lin 2001; Smith et al. 2002). The turning rates can be determined based on historical data.

To estimate the parameters of the model is not an easy task. It is time consuming and has to be done for various weather conditions so as to use the right set of parameters in each case. The models parameter estimation does not need to be in real-time but should be done in regular time steps to adjust to changes in the behavior of the users of the network.

4.3.2 Optimization Layer

The Optimization Layer is the most important part of the hierarchical control structure. It accepts as input the current situation of the network expressed by the vector $\mathbf{x}(0)$, the parameters of the macroscopic network model – in this case the parameters of METANET – and the predictions of the disturbances $\mathbf{d}$. The inputs span over an application horizon K_P in discrete time steps. Based on this input data, the control strategy solves the optimal control problem and produces the optimal control trajectory (translated into optimal on-ramp outflows) and the corresponding optimal state trajectory. These trajectories are forwarded as input to the next layer as goals that have to be accomplished by the local controllers.

The optimal control strategy applied at the optimization layer level is, in this case, AMOC, that was described in detail in a section 4.2. AMOC's solution of the optimal control problem is a decision on a strategic level and is forwarded to the local controllers to implement the decision on a tactical level.

4.3.3 Direct Control Layer

The purpose of the Direct Control Layer is to implement the optimal control strategy that has been decided in the previous layer. It accepts as input the optimal control and state trajectories calculated by AMOC that fully describe the traffic condition as it is supposed to develop over the application horizon K_P. Given these optimal trajectories the decision problem in this layer consists in implementing an appropriate control strategy at every local regulator.

For each on-ramp o with merging segment $(\mu,1)$ (Figure 3-2) a local regulator can be applied with control sample time $T_c = z_c T$, $z_c \in \mathbb{N}$ (e.g. $T_c = 30\sec = 3T$) in order to calculate the controlled on-ramp outflow $q_o^r(k_c)$ for the next control interval. The purpose of using r as a superscript in q_o^r is to differentiate the on-ramp's o outflow calculated from the regulator, from the outflow calculated from the maximum queue considerations (equation (4.8)); the latter is indicated with the use of w as superscript. The average quantities $\bar{\rho}_{\mu,1}^*(k_c) = \sum_{z=k}^{k+z_c-1} \rho_{\mu,1}^*(z) \big/ z_c$, $\bar{q}_{\mu,1}^*(k_c) = \sum_{z=k}^{k+z_c-1} q_{\mu,1}^*(z) \big/ z_c$ and $\bar{q}_o^*(k_c) = \sum_{z=k}^{k+z_c-1} q_o^*(z) \big/ z_c$, can be defined, where the *-index denotes optimal values delivered by AMOC.

Two cases can be distinguished for later comparison. The optimal control trajectories can be directly applied to the traffic process or the state trajectories can be passed on to local regulators as set-points.

In the first case the optimal control trajectories correspond to optimal ramp flows and the direct application to the traffic process implies

$$q_o^r(k_c) = \bar{q}_o^*(k_c). \tag{4.5}$$

In the second case, the Direct Control Layer is actually introduced. The optimal state trajectories are passed on to local regulators as set-points for each controlled on-ramp. In this case the local regulators employed are either ALINEA or flow-based ALINEA (FL-ALINEA) (Papageorgiou et al. 1991; Smaragdis and Papageorgiou 2003) (see also section 2.3.2.1). The ALINEA local regulator with set-point $\tilde{\rho}_{\mu,1}$ reads

$$q_o^r(k_c) = q_o^r(k_c - 1) + K_r\left[\tilde{\rho}_{\mu,1} - \rho_{\mu,1}(k_c)\right] \tag{4.6}$$

where K_r is the feedback gain factor. The flow-based ALINEA with set-point $\tilde{q}_{\mu,1}$ reads

$$q_o^r(k_c) = q_o^r(k_c - 1) + K_f\left[\tilde{q}_{\mu,1} - q_{\mu,1}(k_c)\right] \tag{4.7}$$

where K_f is the feedback gain factor. The calculated q_o^r is bounded by the maximum ramp flow Q_o and a minimum admissible ramp flow $q_{o,\min}^r$. In order to avoid the wind-up phenomenon, the term $q_o^r\left(k_c-1\right)$ used in both equations (4.6) and (4.7), is also bounded accordingly.

Creation of long ramp queues can be avoided with the application of a queue control policy (Smaragdis and Papageorgiou 2003) in conjunction with every local metering strategy (equations (4.5) - (4.7)). The queue control law takes the form

$$q_o^w\left(k_c\right)=-\frac{1}{T_c}\left[w_{o,\max}-w_o\left(k_c\right)\right]+d_o\left(k_c-1\right) \tag{4.8}$$

where $w_{o,\max}$ is the maximum admissible ramp queue. The final on-ramp outflow is then

$$q_o\left(k_c\right)=\max\left\{q_o^r\left(k_c\right),q_o^w\left(k_c\right)\right\}. \tag{4.9}$$

The flows $\overline{q}_{\mu,1}^*$ are preferable as set-points for local regulation because they are directly measurable without the uncertainty caused by modelling. However, flows do not uniquely characterize the traffic state, as the same flow may be encountered under non-congested or congested traffic conditions. Moreover, whenever AMOC optimal results indicate capacity flow at specific ramp-merge areas, the corresponding flow set-point would be equal to AMOC's flow capacity value; it is known, however, that the real flow capacity in a merge area may vary quite substantially from day to day due to reasons that are not well understood while the critical density (or occupancy), at which capacity flow occurs, seems to be more stable. For these reasons, a flow set-point $\tilde{q}_{\mu,1}=\overline{q}_{\mu,1}^*\left(k_c\right)$ is used (in conjunction with FL-ALINEA), only if $\overline{\rho}_{\mu,1}^*\left(k_c\right)\leq\rho_{f-cr,\mu}$ and $\overline{q}_{\mu,1}^*\left(k_c\right)\leq 0.9q_{\mu,cap}$, i.e. only if the optimal flows are well below the critical traffic conditions. If $\overline{\rho}_{\mu,1}^*\left(k_c\right)\geq\rho_{f-cr,\mu}$ and $\overline{q}_{\mu,1}^*\left(k_c\right)\leq 0.9q_{\mu,cap}$ then the AMOC optimal results tolerate an overcritical traffic state and hence ALINEA is applied with set point $\tilde{\rho}_{\mu,1}=\overline{\rho}_{\mu,1}^*\left(k_c\right)$; in all other cases ALINEA with $\tilde{\rho}_{\mu,1}=\rho_{f-cr,\mu}$ is applied in order to guarantee maximum flow even in presence of various model-parameter or disturbance-prediction mismatches. Additionally, no matter which is the outcome of these rules, whenever the on-ramp queue calculated by AMOC is equal to zero, ALINEA with $\tilde{\rho}_{\mu,1}=\rho_{f-cr,\mu}$ is applied in order to guarantee that the real demand arriving at the ramp will be allowed to enter the motorway; this is done in order to avoid cases where an underestimation of the demand in AMOC would lead to an on-ramp flow that is lower than the one that the network can accommodate, thus leading to a ramp queue and corresponding driver delays without a real reason. In all of the above cases the factual critical density is used which is determined via simulations.

4.3.4 Rolling Horizon Technique

As mentioned before, the core of the hierarchical strategy is AMOC which calculates the optimal solution that minimizes the cost criterion based on the estimation of the disturbances over an application horizon K_P. The optimal state trajectory $\mathbf{x}^*(k)$ is used to adjust the parameters of the local regulators. This optimal solution incorporates errors made in the estimation of the initial state vector $\mathbf{x}(0)$, in the estimation of the model's parameters and in the prediction of the disturbances. In order to reduce the influence of the accumulated errors a periodical renewal of the initial state $\mathbf{x}(0)$ and of the prediction of disturbances has to be made. This is done for a period $K_A \leq K_P$. At any application of AMOC the current state estimation is used as the initial condition $\mathbf{x}(0)$ and with the predicted disturbances the optimal control trajectories are calculated over a horizon of K_P but are used only for a horizon K_A. After the application period K_A the optimal control problem is solved again with updated state estimation and disturbance predictions. Thus the control loop is closed and AMOC is not any more of an open-loop nature but has feedback. This control scheme is generally known as rolling or receding horizon optimal control or Model Predictive Control (MPC). An issue associated with this kind of control is the computation time required for the calculation of the open-loop optimal solution. A long optimization horizon K_P has the advantage of taking into consideration the system dynamics and the control consequences early in time but having as disadvantage the required computation time. Shorter K_P may require less time but increases the possibility of myopic control actions. On the other hand the update period K_A results in improved feedback for AMOC when shorter but it also means more frequent time consuming tasks such as the state estimation, the disturbance prediction and the optimization procedure. In conclusion as a general rule the control actions have the tendency to be more efficient with increasing K_P and decreasing K_A.

5 The Amsterdam Network

5.1 Introduction

As a test bed for the network-wide ramp metering hierarchical strategy the road network around Amsterdam has been chosen (Figure 5-1).

The main part of the network consists of the A10 ring-road (Figure 5-2). The A10 contains two tunnels, the Coen Tunnel at the North-West and the Zeeburg Tunnel at the East and has four main connections with other motorways, A1 at the South-East, A2 in the South, A4 at South-West and A8 in the North. In the south there is also the A9 which forms a bypass for traffic between the North-East on the one hand and the centre of the country as well as the region between Amsterdam and The Hague including Schipol airport on the other.

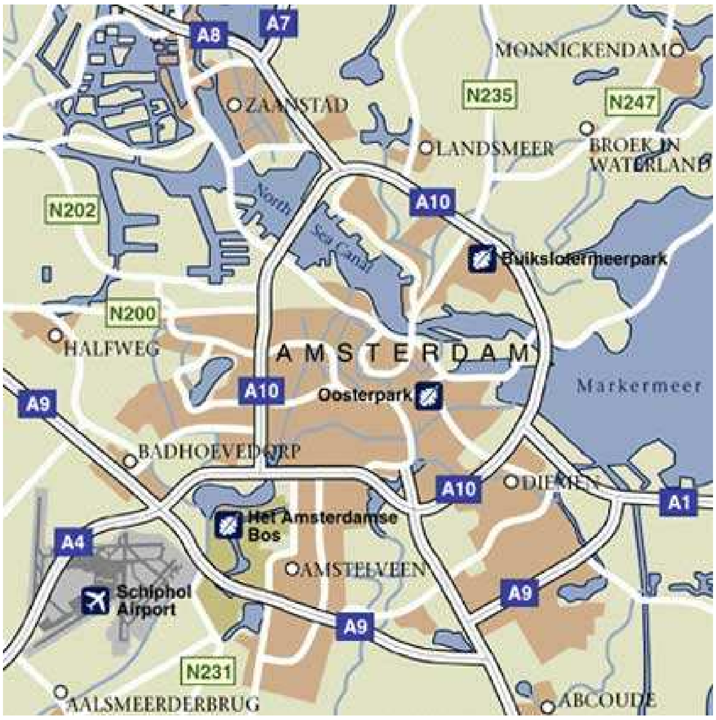

Figure 5-1: A map of the Amsterdam area

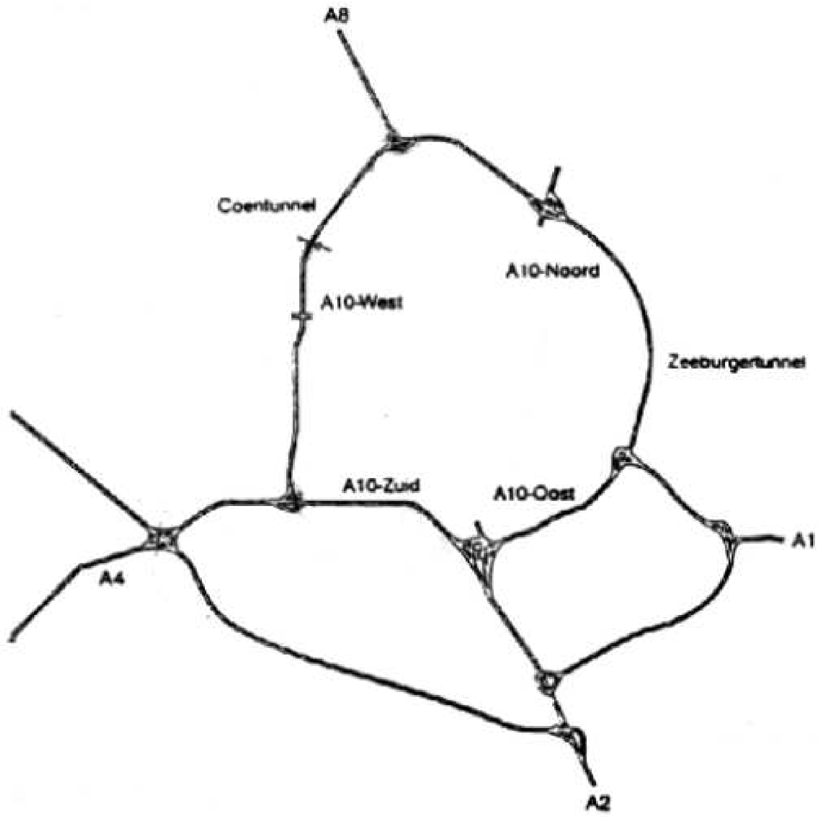

Figure 5-2: The motorway network around Amsterdam

5.2 The Network Model

The whole network has been modelled for both directions. That means 143 km divided in 654 links (249 motorway links, 231 SAF links and 174 dummy links). The motorway links consist of 291 segments of length between 400 and 800 meters (average length of 491,4m) (Figure 5-3).

This network model has been used for an extensive validation of the parameters of the traffic flow model against real data. The process of the validation had two phases, the quantitative and qualitative phase (Kotsialos 2004; Kotsialos et al. 2002).

In the quantitative approach, a group of parameters that reflect particular characteristics of a given motorway stretch were at first estimated and then verified. This process was performed for four different motorway stretches. The resulting parameters were the same for all stretches except for the critical density (Table 5-1) (Kotsialos et al. 1997; Kotsialos 2004; Kotsialos et al. 2002).

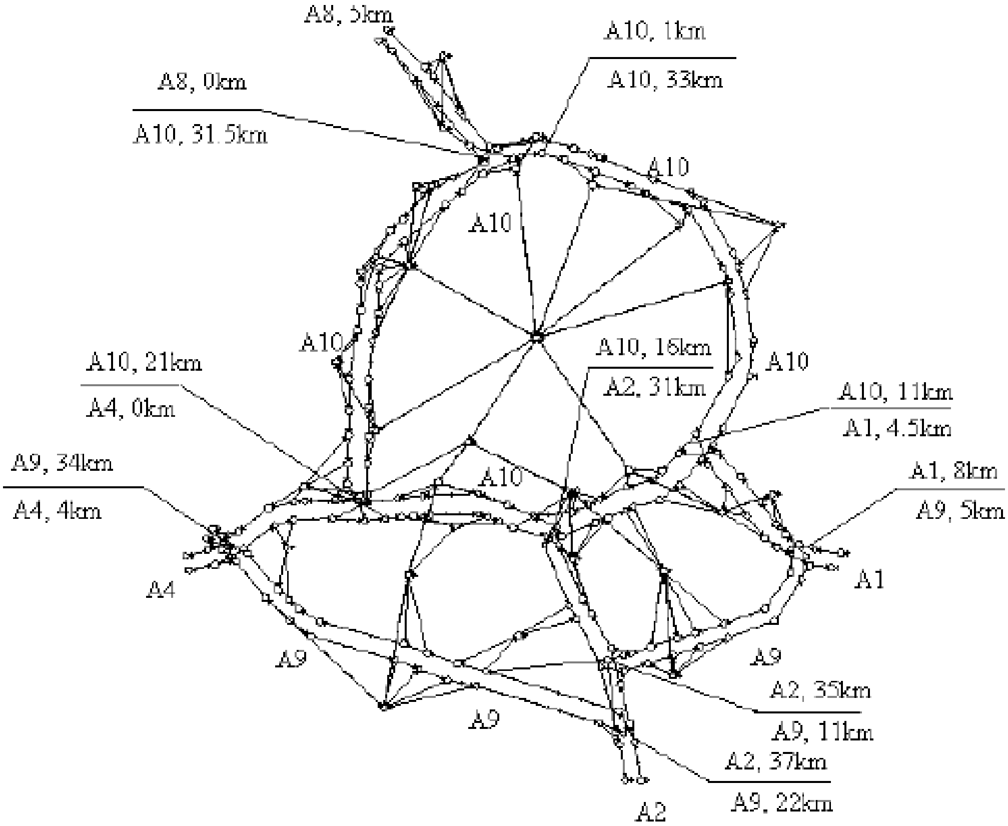

Figure 5-3: The Amsterdam network model

Table 5-1: Values of the common parameters

Parameter	**Value**
α_m	2.34
$v_{f,m}$ (km/h)	102
τ (seconds)	18
δ	0.012
ν (km^2/h)	60
κ (veh/km)	40
$v_{\min}$ (km/h)	7.5
$\rho_{\max}$	180

In the qualitative model validation the aim was to address traffic conditions for the entire network. The model should be able to capture the network-wide dynamics of traffic congestion. In other words the goal was for the model to be able to predict the location, duration and propagation of congestion as encountered in real data. These often meant the manual calibration of parameters via repeated computer simulations and comparison of the results with real data (Kotsialos 2004; Kotsialos et al. 2002).

5.3 The Amsterdam Test Model

For the simulation and testing of the optimal control strategy only a part of the larger network model of the Amsterdam area was used. In particular, for the purposes of the study, the counter-clockwise direction of the A10 was used (Figure 5-4). This part of the network is approximately 32 km long. It has 21 on-ramps and 20 off ramps including in both cases the connections with motorways A1, A2, A4 and A8. It is assumed that it is possible to implement ramp metering at every on-ramp, even at the motorway-to-motorway (mtm) ramps. The ring road is divided in 76 segments with an average length of 421m. As a result, the state vector has a dimension of 173 (76 segments with variables for density ρ and mean speed v, and 21 ramps with variables for queue w). When ramp metering is applied to all on-ramps and mtm ramps the control vector is 21-dimensional and the disturbance vector is 41 dimensional (demands for 21 on-ramps and turning rates for 20 off-ramps).

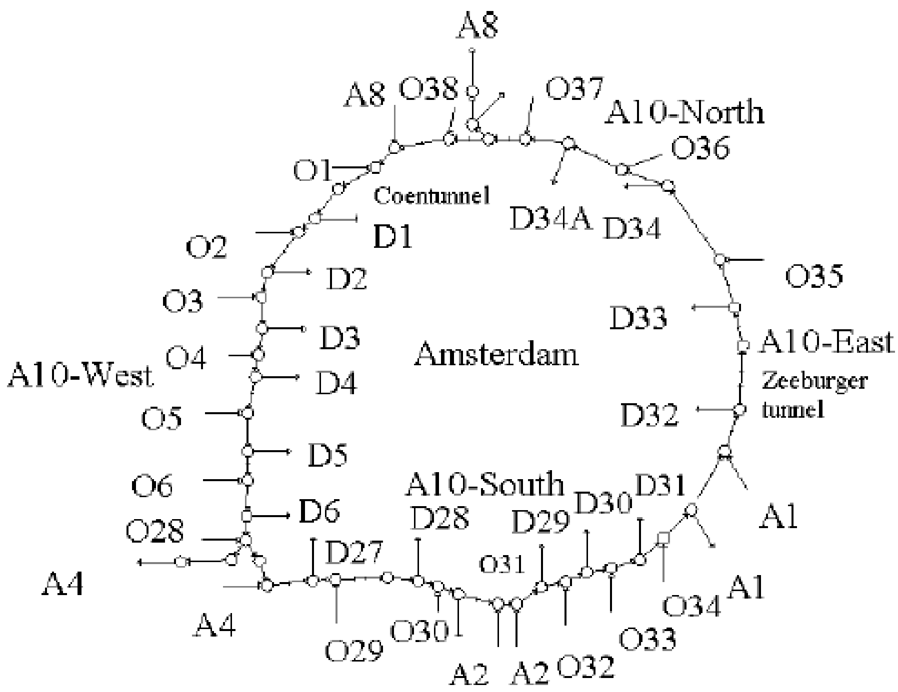

Figure 5-4: The counter-clockwise direction of the Amsterdam ring road.

6 Simulation Results

6.1 Introduction

The application of ALINEA as a stand alone local controller, of AMOC and of the Hierarchical control structure is presented in chapter. The simulation was realized in the METANET simulator for the counter-clockwise direction of the Amsterdam ring-road that is described in section 5.3.

The simulation was performed using real (measured) time-dependent demand and turning rate trajectories as input. The simulation spans over a time horizon of 4 hours. It spans from 16:00 until 20:00 of an evening in June 1996. This time period includes the evening peak hour. With a time step of $T = 10\,\text{sec}$, a simulation horizon of $K = 1440$ steps is considered which results in a large-scale optimization problem with 254160 variables for a control sample time of 1 minute and all on-ramps, including mtm ramps, metered.

6.2 The no-control case

The no-control case will be used as the basic reference against which all control scenarios will be compared. In this case no control measures are applied. As a result heavy congestion appears in the motorway and large queues build up at the on-ramps. The congestion begins shortly after the start of the simulation because of the excessive demand and the uncontrolled entrance of vehicles into the motorway. This congestion appears at the point where the A1 connects with the A10 and is spread upstream blocking the A4 and a large part of A10. At the time this congestion tends to dissolve, a new congestion appears and moves upstream catching up with the previous congestion that never comes to a complete resolution. This way the A4 entrance to the A10 is blocked and the congestion spills back to A4 through the mtm on-ramp of A4. On several on-ramps long queues are built. The TTS is used as a performance criterion. For the no-control case it has a value equal to 14168 veh*h.

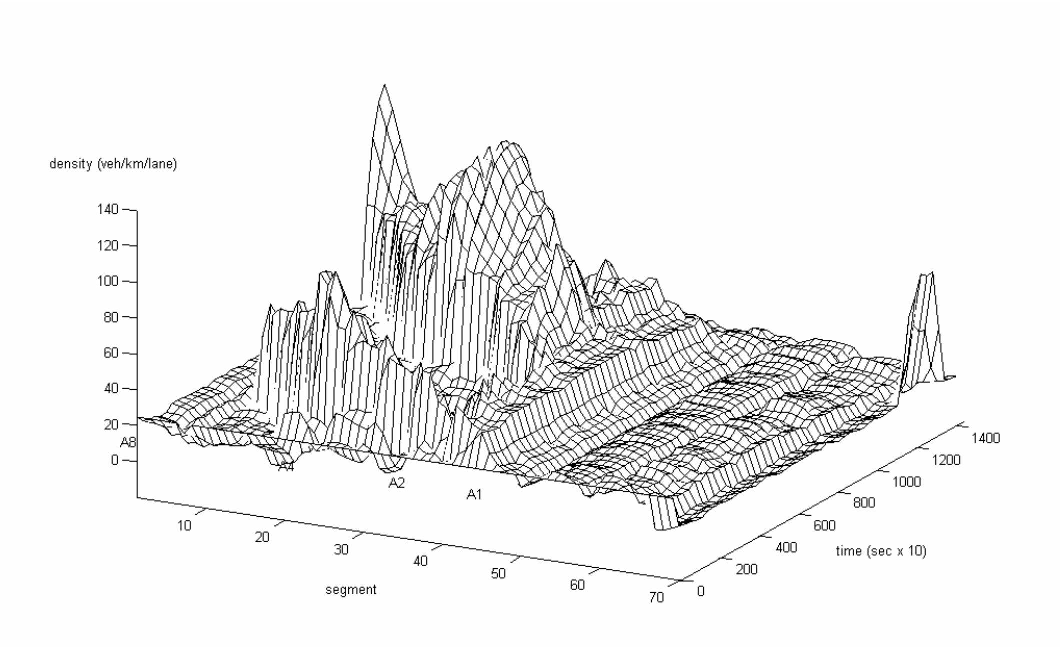

Figure 6-1: No-control case density profile.

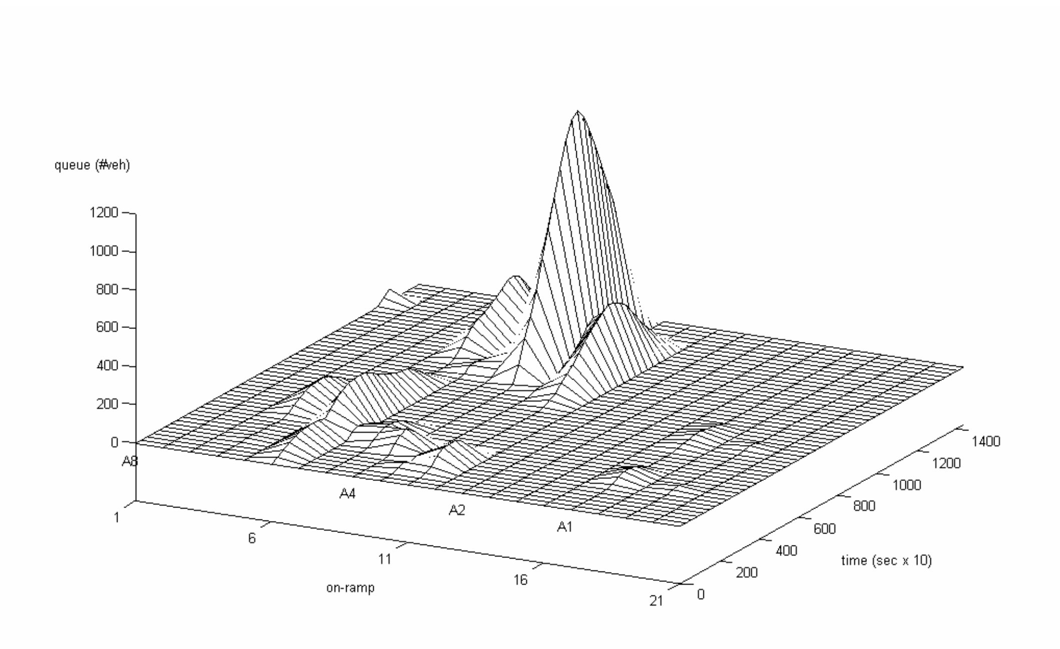

Figure 6-2: No-control case ramp queue profile.

6.3 Description of the Simulation Scenarios

On-ramps can act as a buffer for the storage of vehicles. In times where the density of the mainstream is near the critical density and congestion may occur, holding back some of the vehicles that aim to enter the motorway may prevent the creation of congestion. When the density falls back under a predefined level the vehicles may enter the motorway. However, holding back vehicles on the on-ramps leads to queue build-up on the ramps and drivers may become disquiet if they are waiting too long. Except that, the geometrical characteristics of the on-ramps usually do not allow the build-up of long queues. Another issue is that long queues may spillback on the urban network and cause congestion.

For the purpose of this study 10 scenarios were examined. The main difference of the scenarios concerns the length of the queue that is allowed on the urban on-ramps and mtm ramps. Urban on-ramps usually due to space limitation are not able to accommodate a large number of vehicles. On the other hand mtm ramps usually have a lot of space available and are able to serve more vehicles but authorities are reluctant to the prospect of applying ramp metering to those ramps. Scenario 1 is used as a reference scenario and the assumption is made that space is not an issue. That means that both the urban on-ramps and the mtm on-ramps are able to accommodate an infinite number of vehicles. In scenario 2, a more pragmatical view is adopted; no mtm ramps are used and urban on-ramps can store no more than 30 vehicles. In scenarios 3, 4, 5 and 6 mtm ramps are used with a storage capacity of 100, 200, 300 and 400 vehicles respectively with urban on-ramps having a capacity of 30 vehicles. Scenarios 7, 8, 9 and 10 use only mtm ramps with 100, 200, 300 and 400 vehicles capacity, in order to be able to assess the importance of metering mtm ramps in contrast to urban on-ramps. In Table 6-1 the scenarios are presented.

Table 6-1: The scenarios examined.

Scenario	Allowed queues for urban on-ramps when controlled (# veh)	Allowed queues for mtm on-ramps when controlled (# veh)
1	∞	∞
2	30	not controlled
3	30	100
4	30	200
5	30	300
6	30	400
7	not controlled	100
8	not controlled	200
9	not controlled	300
10	not controlled	400

6.4 *Application of ALINEA*

6.4.1 Efficiency

ALINEA may be used at each ramp as a stand-alone strategy without any kind of coordination. The set-point for each controlled on-ramp o is set equal to the factual critical density of the corresponding link μ, i.e. $\tilde{\rho}_{\mu,1} = \rho_{f-cr,\mu}$, in order to maximize the local motorway throughput. After exhaustive simulation checking, this factual critical density is found to be $\rho_{f-cr,\mu} = 1.1\rho_{cr,\mu}$. The application of ALINEA has lead to an improvement of the TTS for all scenarios presented in Table 6-1 compared to the no-control case.

In particular in scenario 1 ALINEA has a TTS of 7563 veh*h, an improvement of almost 47%. The density profile (Figure 6-3) is almost flat which means ALINEA manages to prevent congestion. A look at the queue profile (Figure 6-4) however, shows the existence of a large queue at the A1 mtm on-ramp. The result of this queue would be a spillback of the congestion to A1. Except that, as a queue is built almost exclusively on the A1 mtm on-ramp it is unfair towards those drivers.

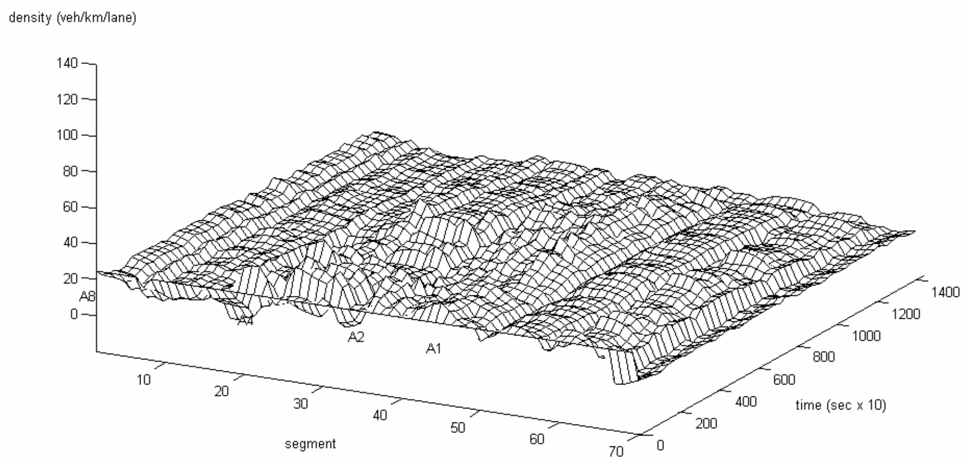

Figure 6-3: ALINEA scenario 1 density profile.

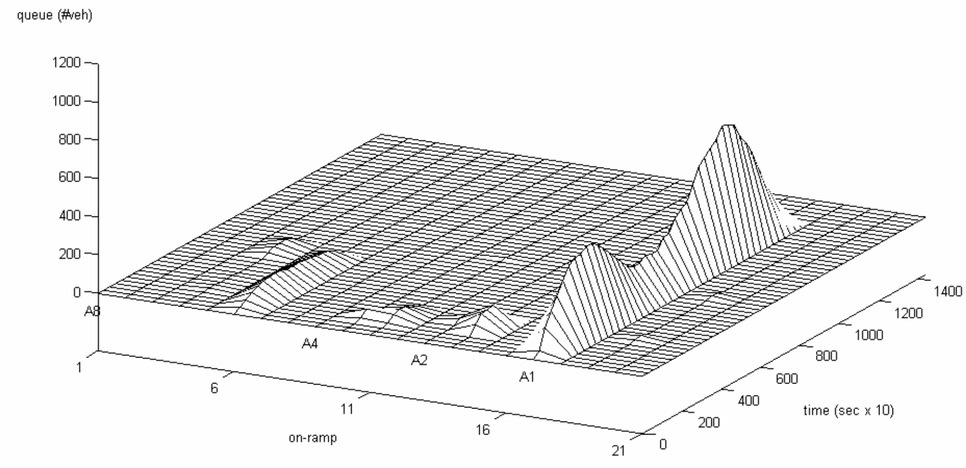

Figure 6-4: ALINEA scenario 1 queue profile.

When scenario 2 is considered, the amelioration of the traffic conditions is just around 5.5%. The density profile (Figure 6-5) and the queue profile (Figure 6-6) reveal that ALINEA is much less efficient in this case. Although a maximum queue constraint of 30 vehicles is imposed on the on-ramps it is clear that the queues become much bigger. Especially on the A4 large queues are formed reaching 1200 veh although ramp metering is not applied there. The TTS in this case is 13402 veh*h.

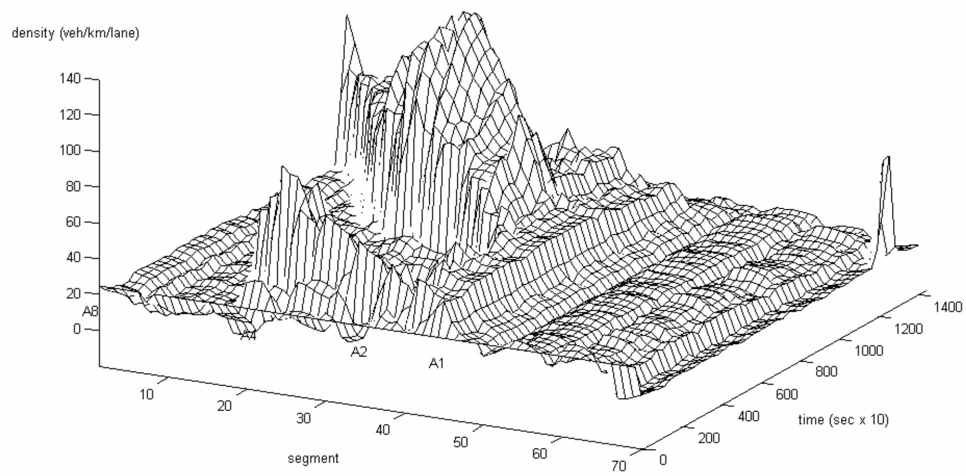

Figure 6-5: ALINEA scenario 2 density profile.

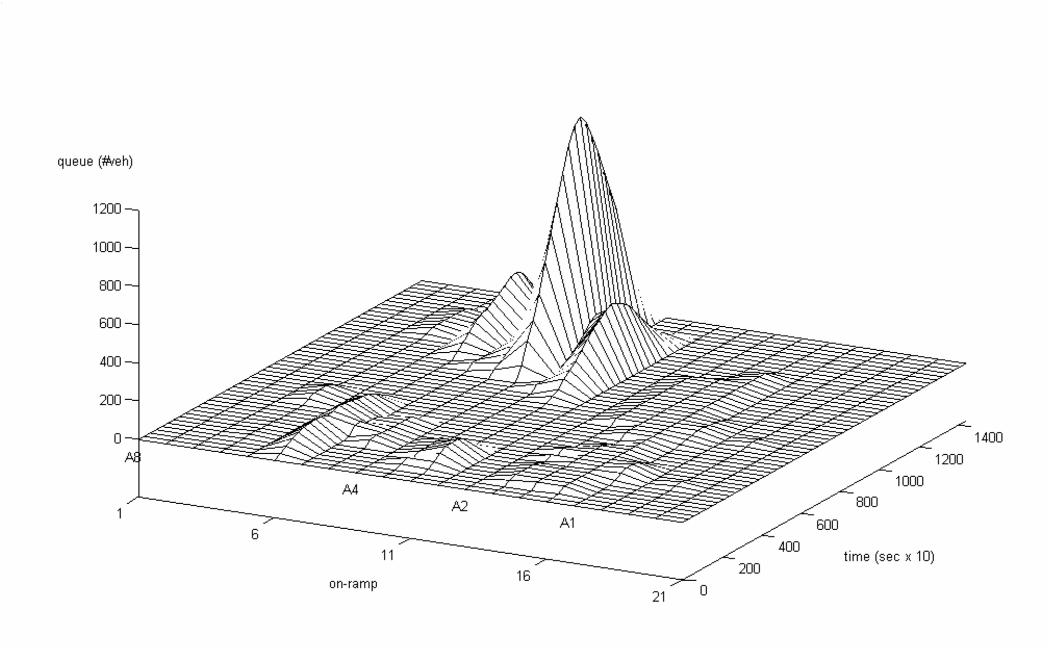

Figure 6-6: ALINEA scenario 2 queue profile.

In Table 6-2 the results for all the scenarios are presented. It becomes clear that by controlling only the urban on-ramps the potential for improving the traffic conditions is very small. It is necessary to control the mtm on-ramps as well. By increasing the admissible ramp queue for the mtm on-ramps the results are getting much better. From Figure 6-7 it becomes apparent how small the impact of the urban on-ramps control is on the resulting improvement. The dotted line represents the TTS value that would have been achieved if the storage capacity of both urban and mtm on-ramps were infinite.

Table 6-2: Results of the application of ALINEA and improvement compared to the no-control case.

Scenario	ALINEA TTS (veh*h)	Improvement compared to the no-control case in %
1 (∞/∞)	7563	46,6%
2 (30/-)	13402	5,4%
3 (30/100)	12583	11,2%
4 (30/200)	11515	18,7%
5 (30/300)	8526	39,8%
6 (30/400)	7648	46,0%
7 (-/100)	12802	9,6%
8 (-/200)	12050	15,0%
9 (-/300)	8580	39,4%
10 (-/400)	7649	46,0%

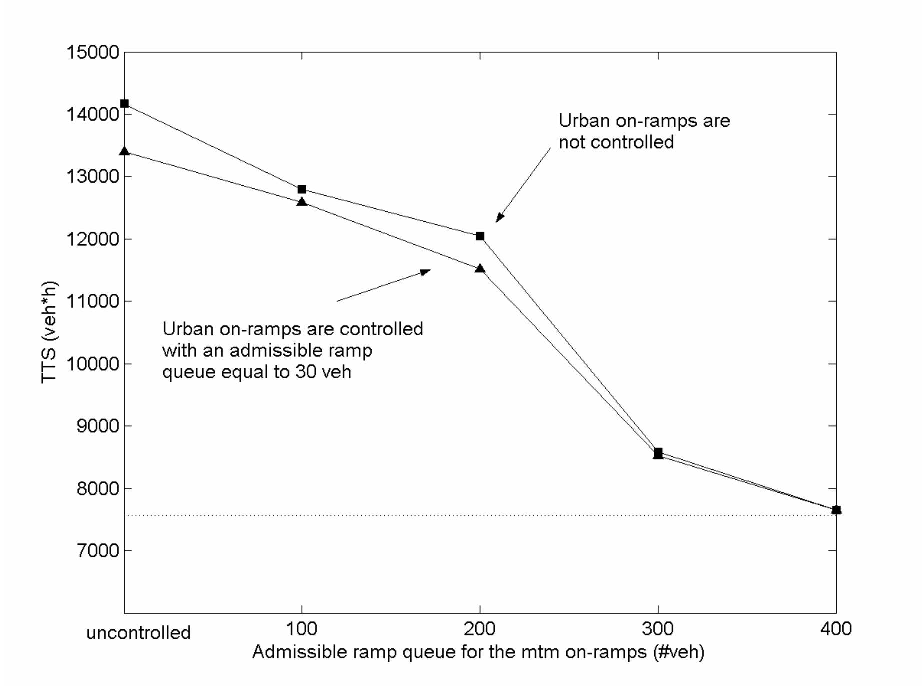

Figure 6-7: TTS values when ALINEA is applied for the different scenarios.

The density and queue profile for scenario 3 can be seen on Figure 6-8 and Figure 6-9 respectively.

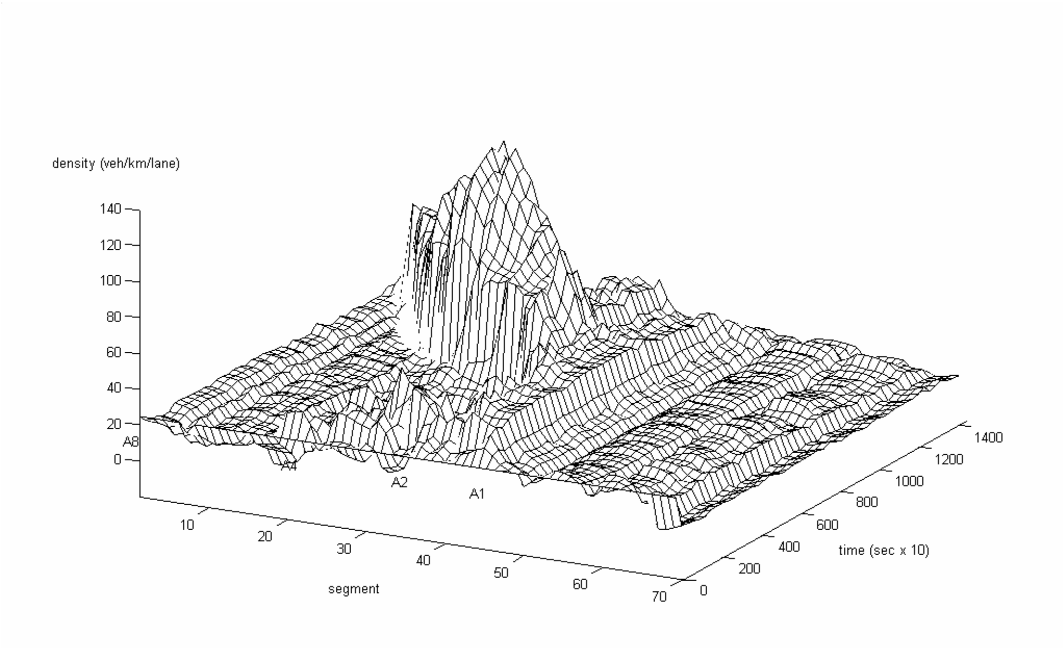

Figure 6-8: ALINEA scenario 3 density profile.

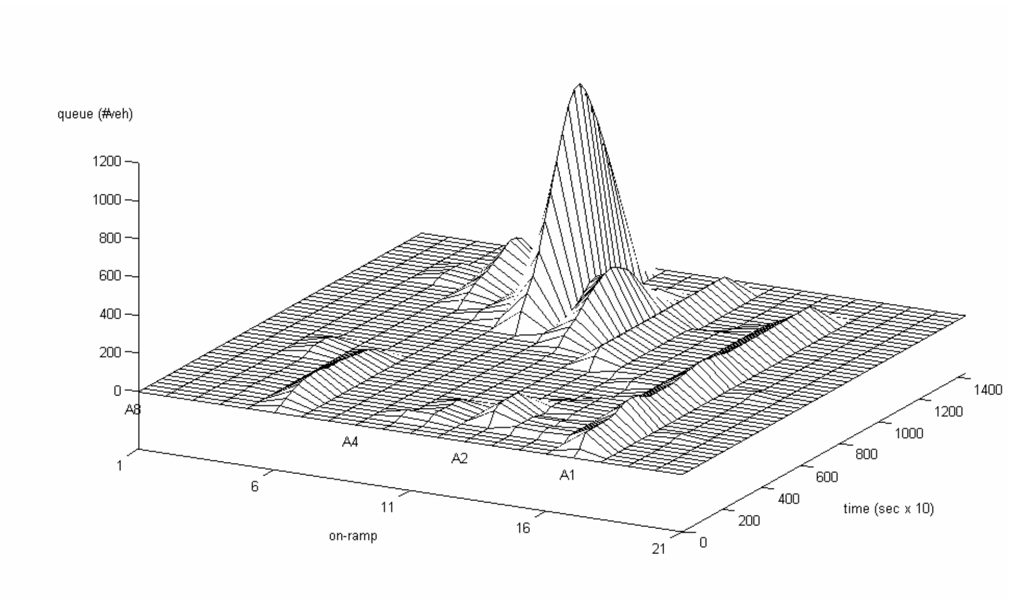

Figure 6-9: ALINEA scenario 3 queue profile.

Scenario 4 has a maximum admissible queue of 30 vehicles on the urban on-ramps and 200 vehicles on the mtm on-ramps. In the case of the ALINEA application the TTS value for scenario 4 is 11515 veh*h. This corresponds to a 19% improvement compared to the no-control case. Compared to scenario 1 though it is clear that the maximum queue constraint on both urban and mtm on-ramps has its toll on the results. The density profile (Figure 6-10) shows clearly that the congestion is not avoided although smaller than the no-control case.

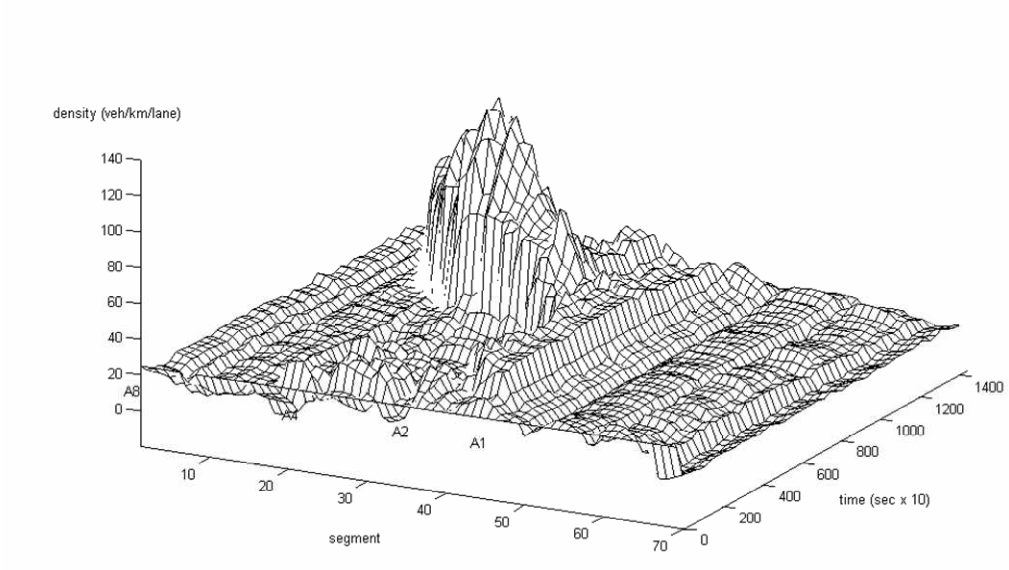

Figure 6-10: ALINEA scenario 4 density profile.

In Figure 6-11 it can be seen that the queue at A1 reaches its maximum admissible value for the entire simulation horizon. This leads to a congestion creation that travels upstream and spreads ramp queues in the critical area between the junctions of A1 and A4 with A10. The A2 also lies in this critical area and it can be seen that it reaches its maximum allowed queue, like A1, for almost half the simulation time. The congestion reaches A4 where the queue can not be avoided and it even surpasses the allowed maximum and reaches 935 veh.

In the next pages the density and queue profiles for scenarios 5 through 10 are presented (Figure 6-12 to Figure 6-23). It becomes obvious when studying the figures that with increasing admissible queues on the mtm ramps the congestion is decreasing.

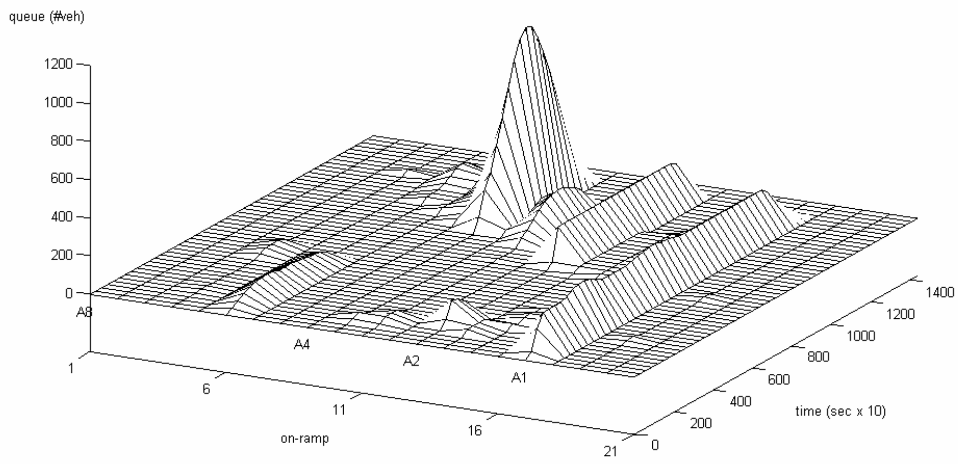

Figure 6-11: ALINEA scenario 4 queue profile.

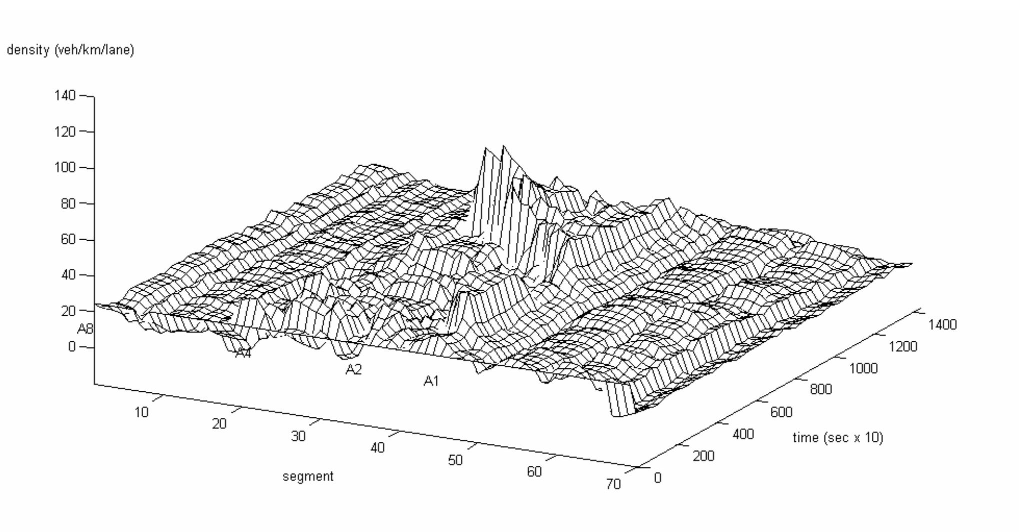

Figure 6-12: ALINEA scenario 5 density profile.

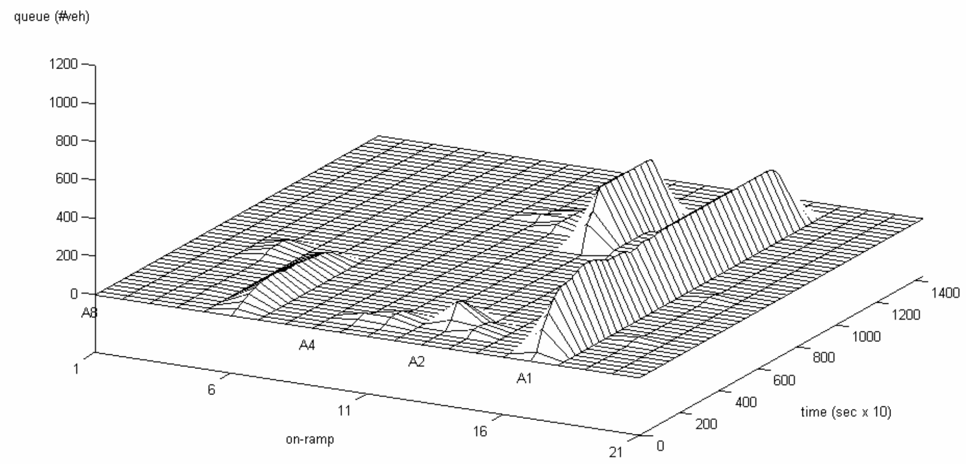

Figure 6-13: ALINEA scenario 5 queue profile.

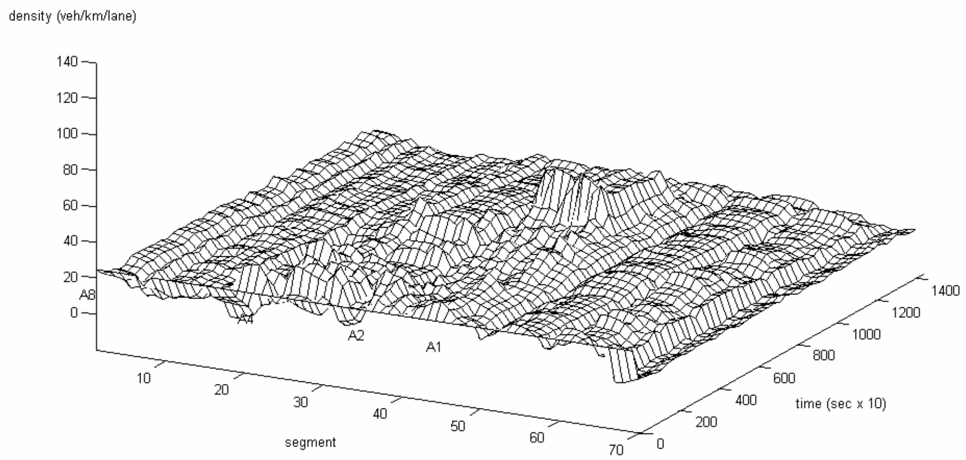

Figure 6-14: ALINEA scenario 6 density profile.

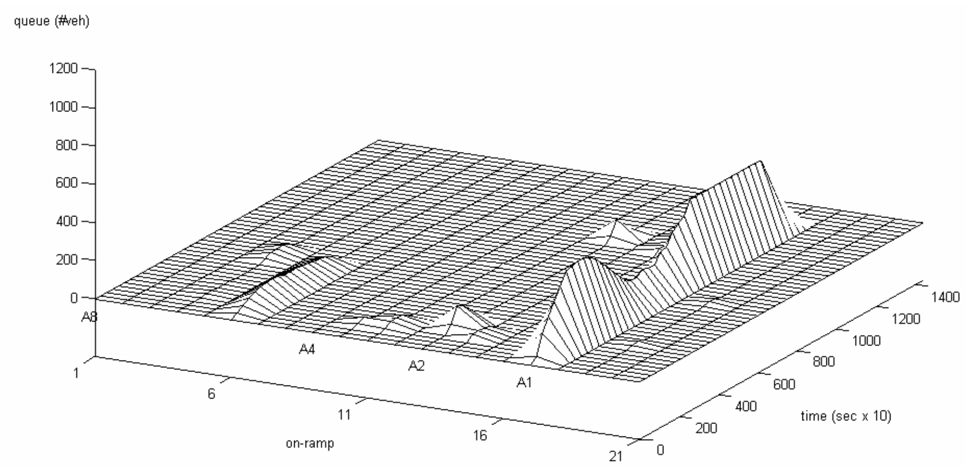

Figure 6-15: ALINEA scenario 6 queue profile.

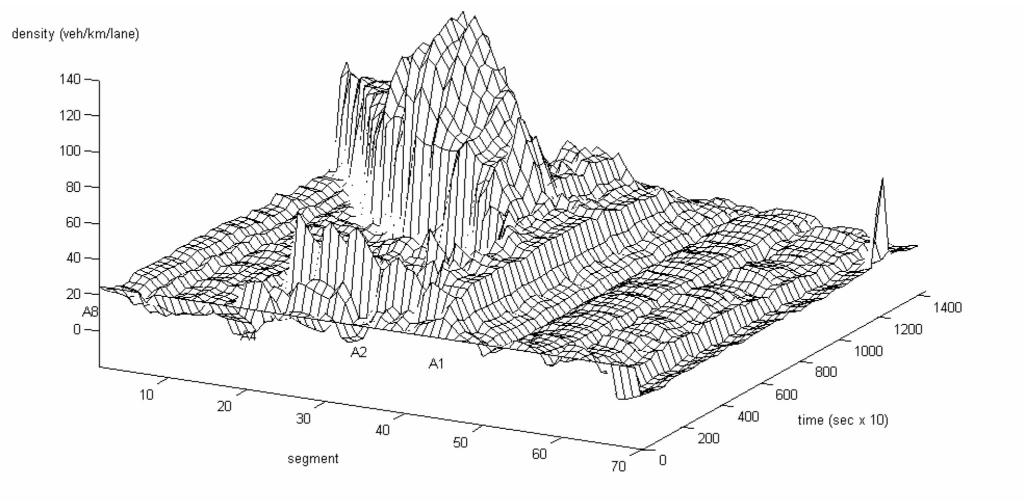

Figure 6-16: ALINEA scenario 7 density profile.

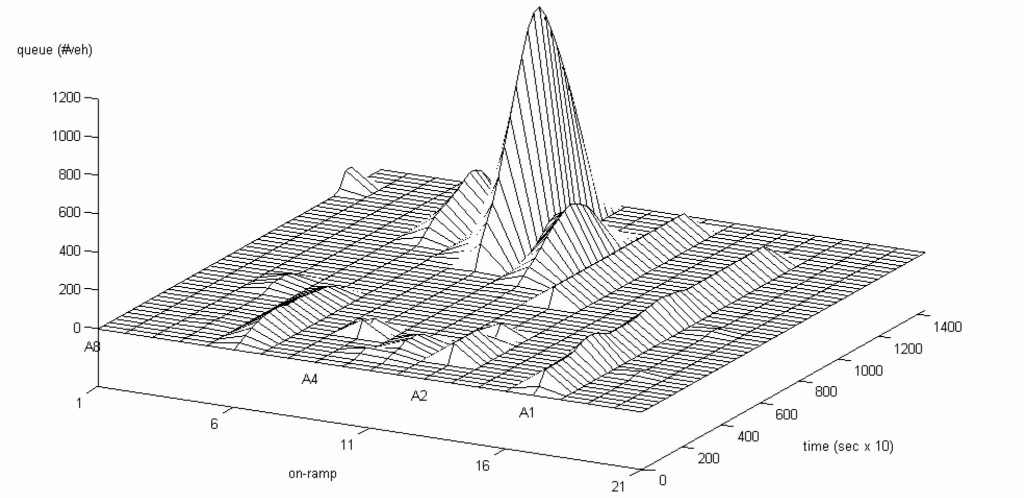

Figure 6-17: ALINEA scenario 7 queue profile.

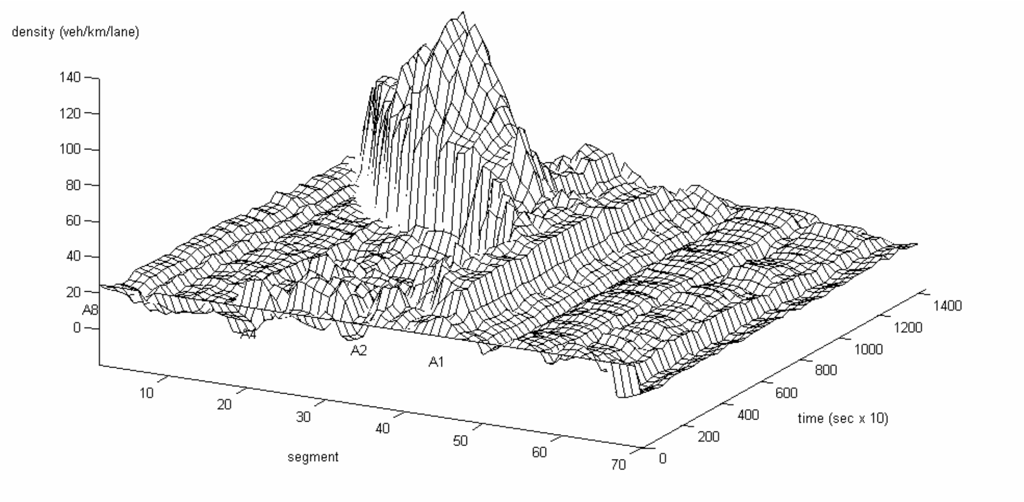

Figure 6-18: ALINEA scenario 8 density profile.

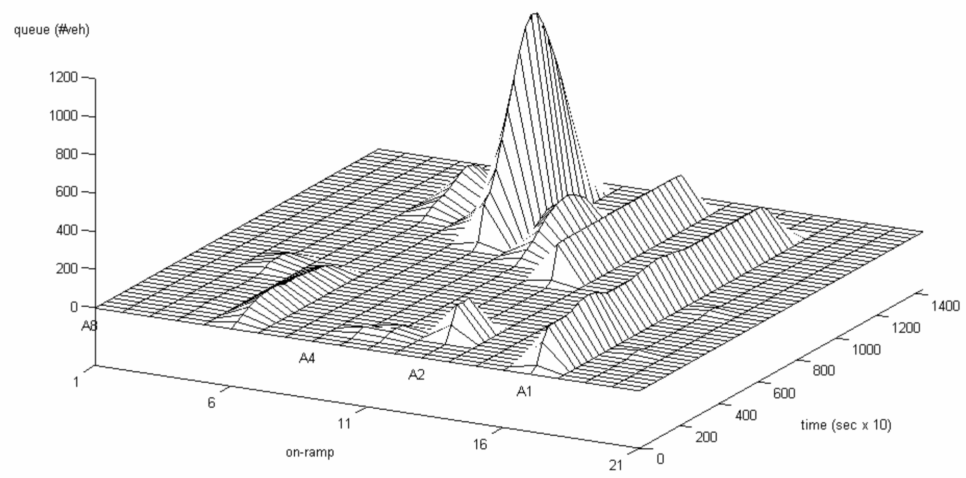

Figure 6-19: ALINEA scenario 8 queue profile.

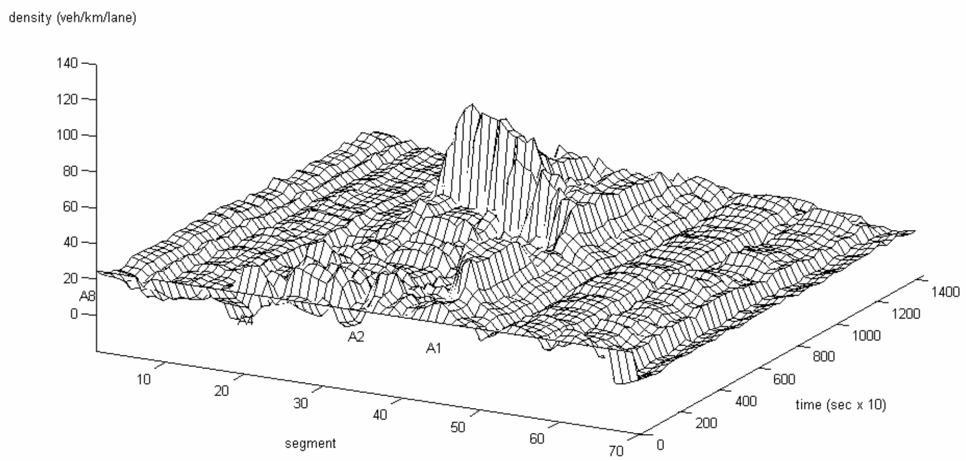

Figure 6-20: ALINEA scenario 9 density profile.

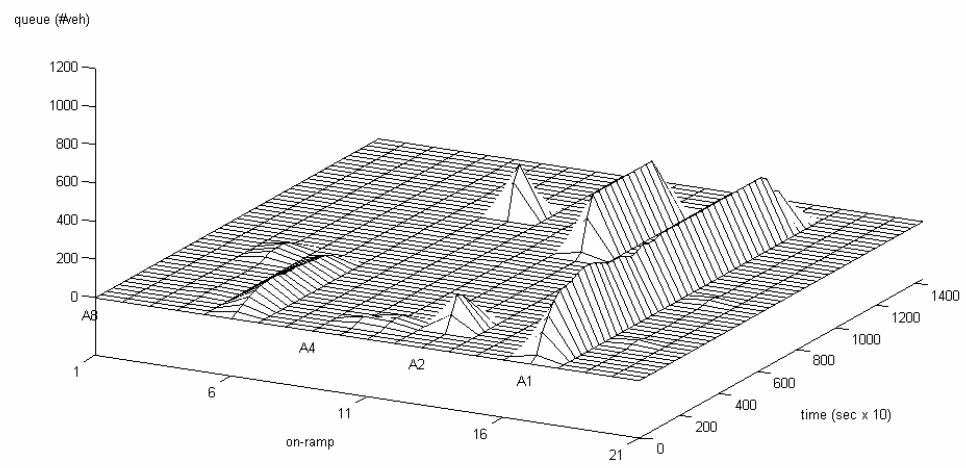

Figure 6-21: ALINEA scenario 9 queue profile.

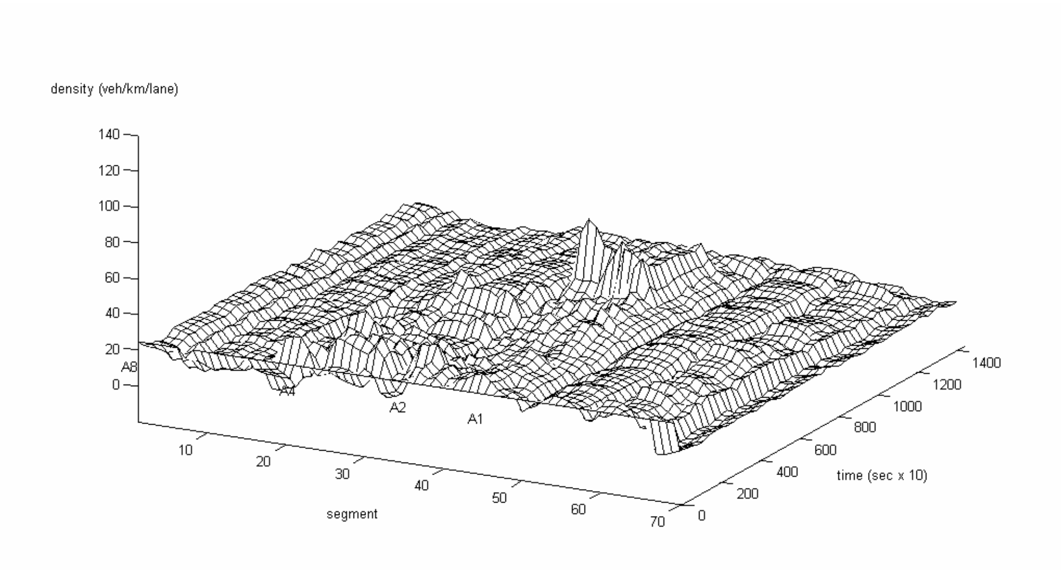

Figure 6-22: ALINEA scenario 10 density profile.

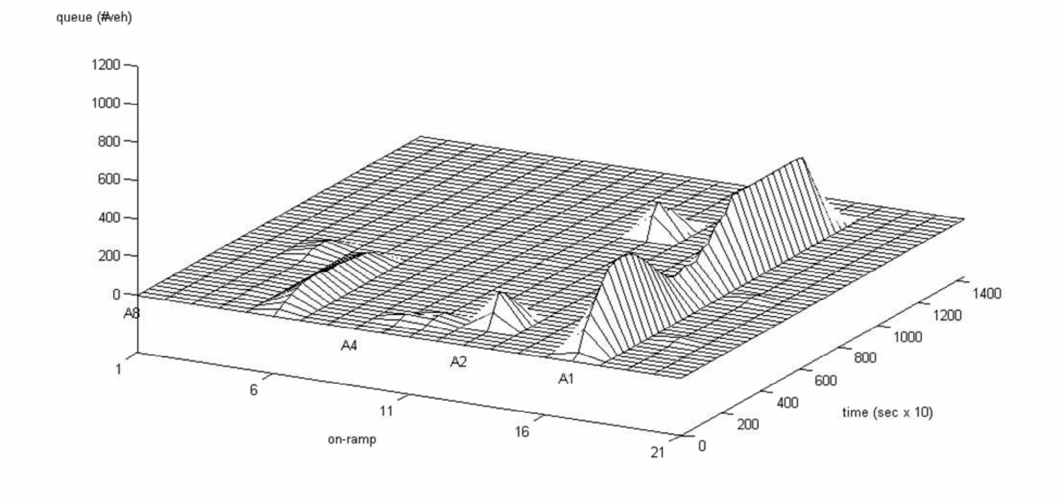

Figure 6-23: ALINEA scenario 10 queue profile.

6.4.2 Equity

The results presented so far make it clear that it is necessary to hold back vehicles and store them on the on-ramps to avoid congestion or at least keep it on a lower level. With ramp metering TTS is reduced and the duration of congestion is smaller. The cost for this amelioration of the traffic conditions is the queues that form on the on-ramps. The formation of queues is acceptable if the result is better conditions for the network and the drivers. These results however should benefit all the users of the network. Thus if a portion of the drivers experiences worse conditions than the rest of the drivers or worse than the no-control case in order to achieve the better conditions then the control strategy is not fair towards them.

The fairness of the control strategy is called equity. A thorough study on how efficiency relates to equity was performed in Kotsialos and Papageorgiou (2001a). In this study equity is measured by the average time $\overline{t_o}$ spent by a vehicle in the ramp queue plus travelling 6.5 km downstream on the motorway and is calculated according to (6.1). In Figure 6-24 the equity is shown for the no-control case and ALINEA application for scenarios 1 and 4. In terms of equity, scenario 4 seems to be the best. In scenario 1 travel times are low for every on-ramp but for A1 where a large peak occurs. In the no-control case, travel times are bigger downstream of A2, at the west part of A10, due to the congestion created there. This graph shows that the most efficient scenario (scenario 1) is worse when it comes to equity to less efficient scenarios which confirms the statement that efficiency and equity are two partially competing properties of a control strategy (Kotsialos and Papageorgiou 2004b).

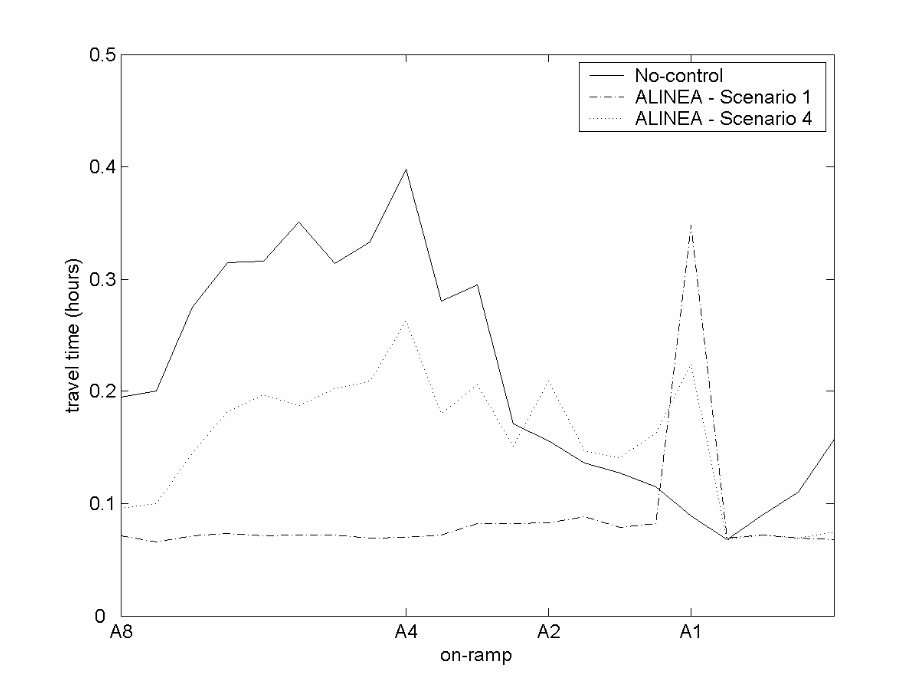

Figure 6-24: Equity graph for no-control case, ALINEA scenario 1 and ALINEA scenario 4.

In the following equation (6.1), for each on-ramp o, the average travel time $\overline{t_o}$ is computed, with ω_1 being the link index number of the link downstream of

o and ω_2 the link index number for whose segment $\xi \le N_{\omega_2}$ the considered mainstream section of 6.5 km ends.

$$\bar{t}_o = \frac{1}{K}\sum_{k=0}^{K-1}\left[\frac{w_o(k)}{q_o(k)} + \sum_{i=\omega_1}^{\omega_2}\sum_{j=1}^{\xi}\frac{L_i}{v_{i,j}(k)}\right] \tag{6.1}$$

6.5 Application of AMOC

As mentioned before (section 4.3), AMOC is of an open-loop nature. This means that the results obtained are under the assumption of a perfect model and perfect information with respect to the future disturbances for the entire simulation horizon. It is obvious that because of these assumptions the results of AMOC would not be observed in a real-world application because the model, the measurements and the predictions of the disturbances are not perfect. Nevertheless the solution of AMOC is what we would get with ideal conditions and therefore it is an upper bound for the efficiency that can be achieved by any control strategy. The results of AMOC and the amelioration of the traffic conditions compared to the no-control case are depicted for all scenarios in Table 6-3. These results can act as a goal and as a measurement of efficiency for any other control strategy, including the hierarchical control strategy presented in section 4.3.

Table 6-3: Results of the application of AMOC and improvement compared to the no-control case.

Scenario	**AMOC TTS (veh*h)**	**Improvement to the no-control case in %**
1 (∞/∞)	7088	50,0%
2 (30/-)	11005	22,3%
3 (30/100)	7574	46,5%
4 (30/200)	7073	50,1%
5 (30/300)	7066	50,1%
6 (30/400)	7072	50,1%
7 (-/100)	8716	38,5%
8 (-/200)	7720	45,5%
9 (-/300)	7231	49,0%
10 (-/400)	7187	49,3%

The improvement that AMOC manages to achieve compared to the no-control case ranges from around 20% in the worst case to 50% in the best case. As was expected scenario 2 has the worst performance. Its TTS is 11005 veh*h, an improvement of 22%. The density and queue profiles for scenario 2 are depicted in Figure 6-25 and Figure 6-26 respectively.

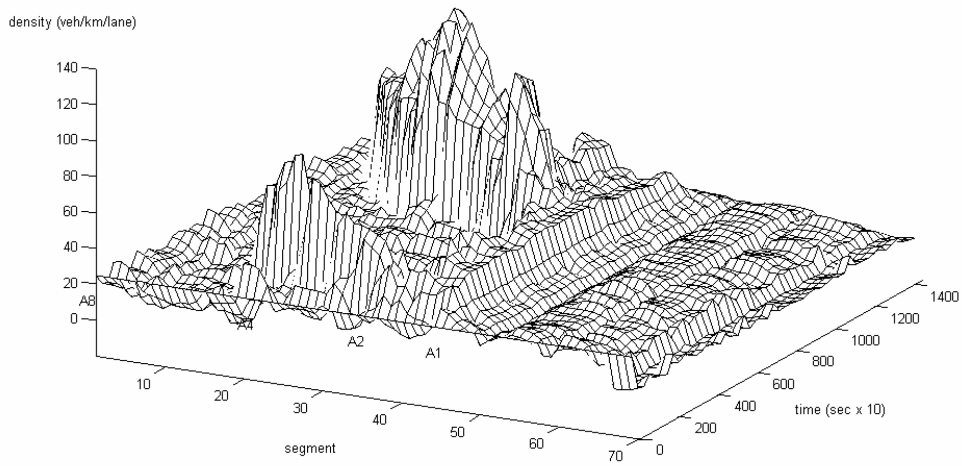

Figure 6-25: AMOC scenario 2 density profile.

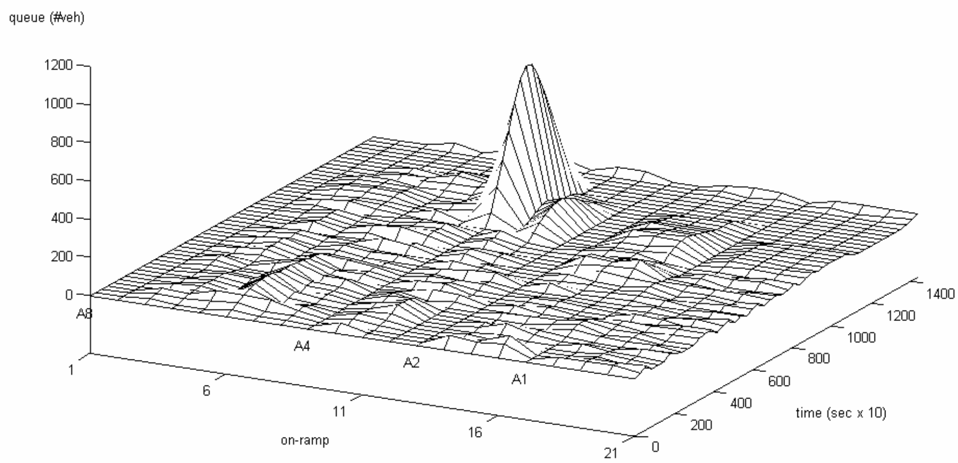

Figure 6-26: AMOC scenario 2 queue profile.

On the other hand, scenario 1 is expected to achieve the best results. By studying Table 6-3 it seems this is not the case as scenarios 4, 5 and 6 have better values. In reality the difference of the results of these 4 scenarios (1, 4, 5 and 6) is minimal and can be attributed to numerical instabilities when solving the optimal control problem. The results of these scenarios can actually be considered equal as the biggest difference is between scenario 1 and 5 and is only 22 veh*h which is an insignificant value. As a conclusion that can be drawn from these results is that with scenario 4 that allows for up to 30 vehicles to queue up on the urban on-ramps and 200 on the mtm on-ramps, enough space is allocated to cope with the congestion and it seems there is no need for bigger admissible queues. In the next figures (Figure 6-27 to Figure 6-34) the density profiles for scenarios 1, 4, 5 and 6 are shown.

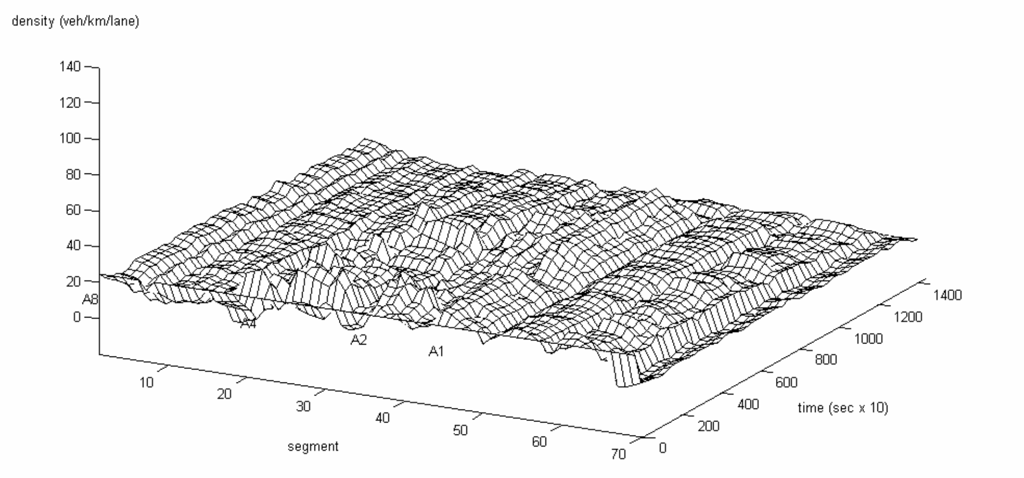

Figure 6-27: AMOC scenario 1 density profile.

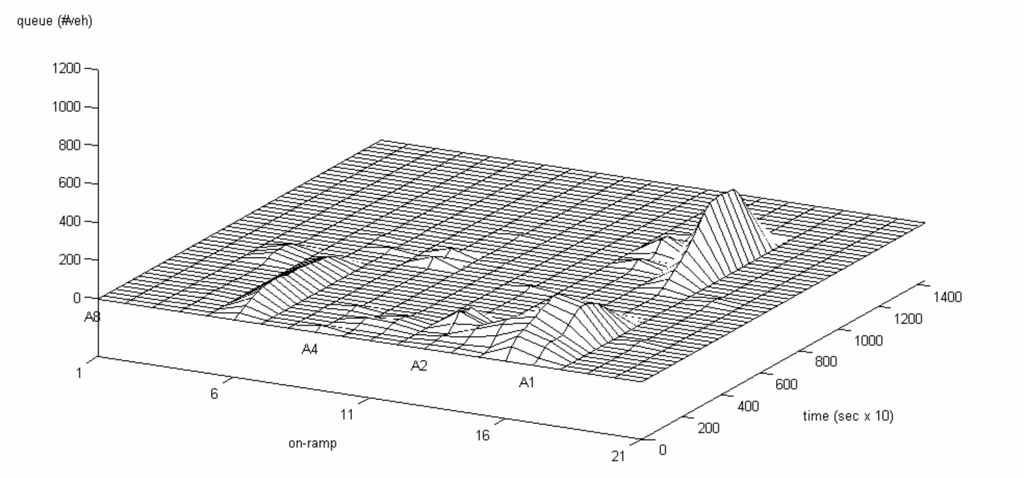

Figure 6-28: AMOC scenario 1 queue profile.

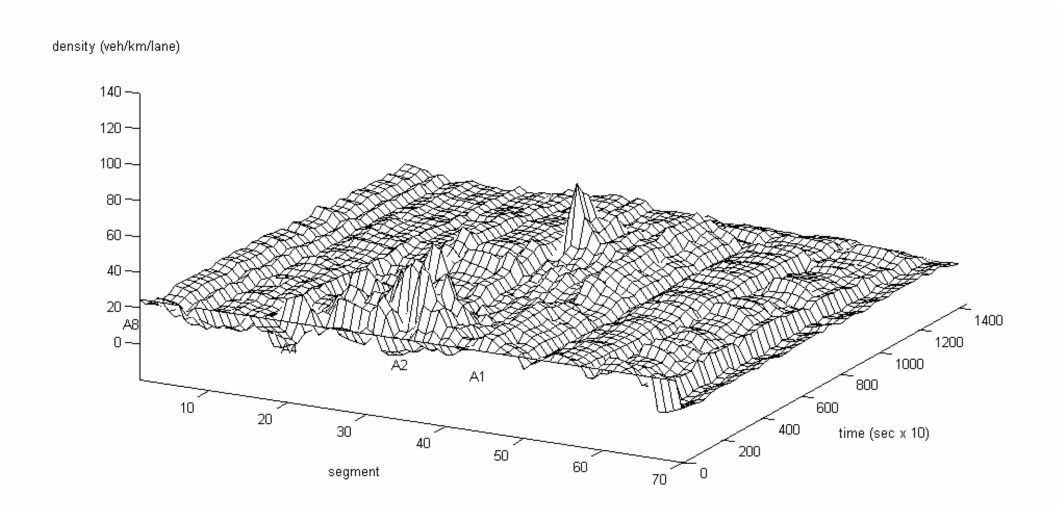

Figure 6-29: AMOC scenario 4 density profile.

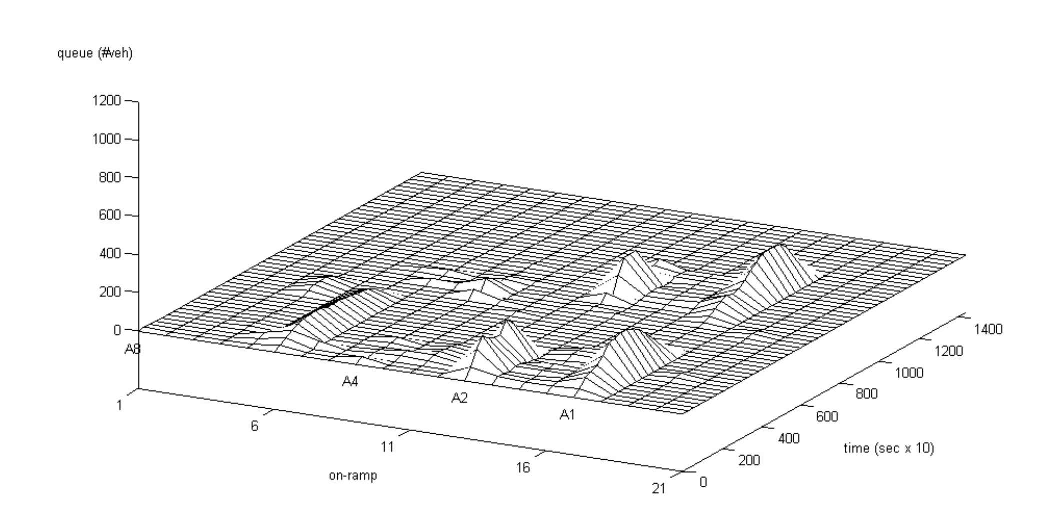

Figure 6-30: AMOC scenario 4 queue profile.

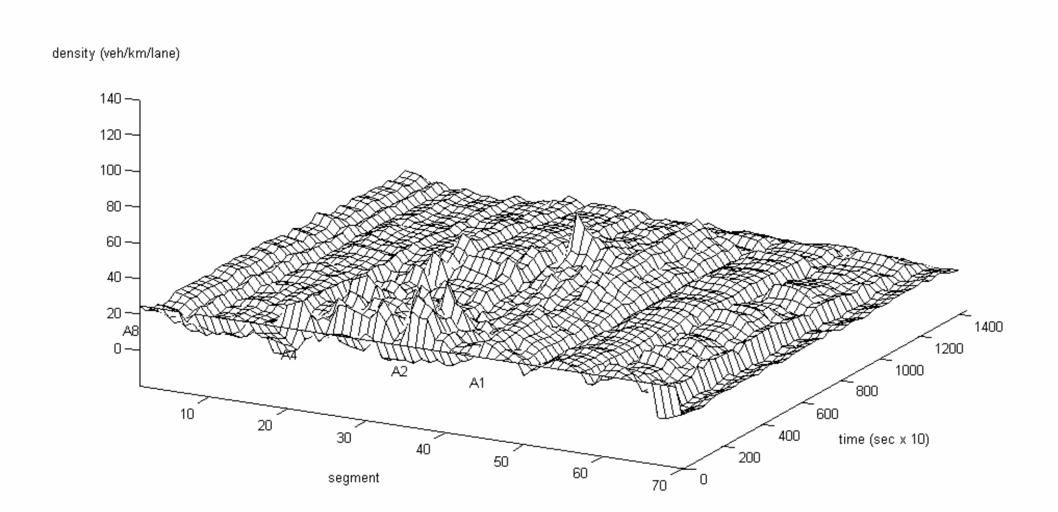

Figure 6-31: AMOC scenario 5 density profile.

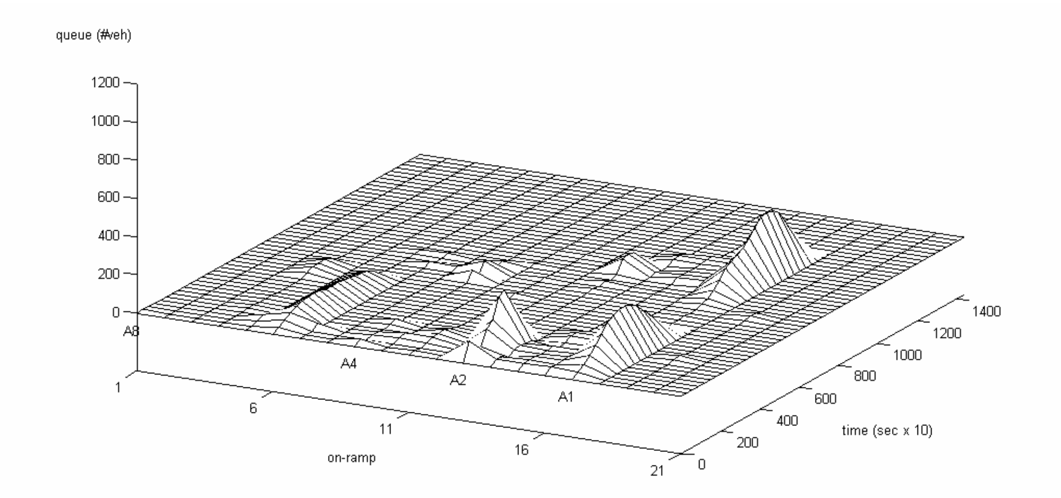

Figure 6-32: AMOC scenario 5 queue profile.

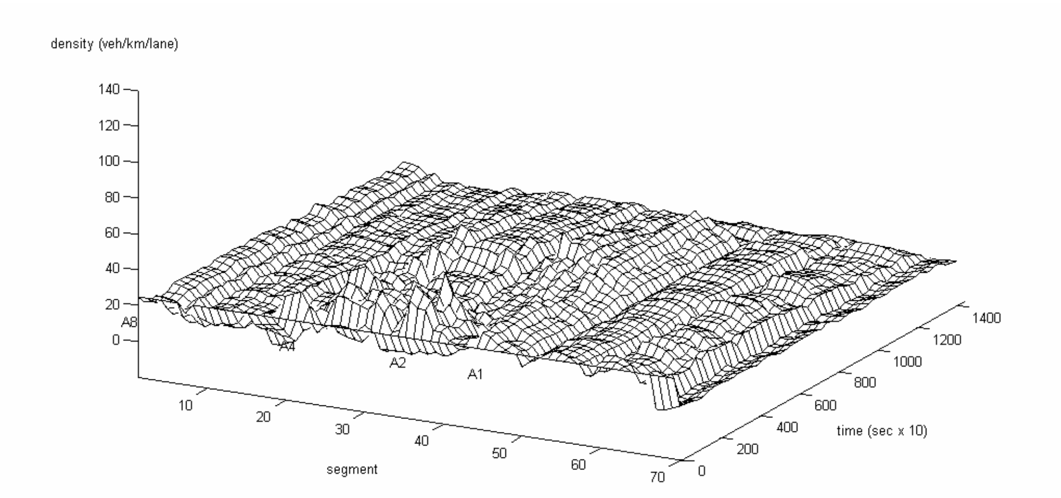

Figure 6-33: AMOC scenario 6 density profile.

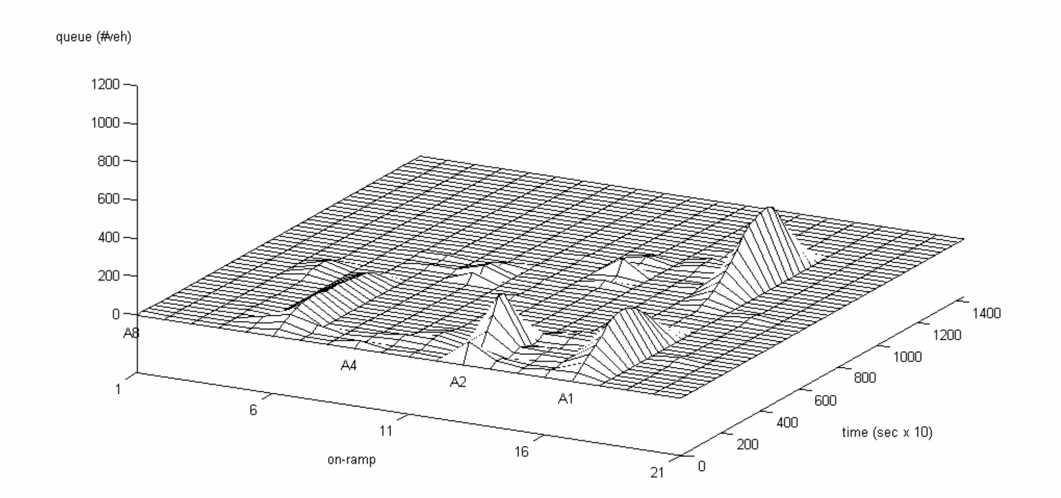

Figure 6-34: AMOC scenario 6 queue profile.

The scenarios 3 and 7 improve the TTS by 46% and 38% respectively. These scenarios both have an admissible ramp queue of 100 vehicles for mtm on-ramps but in scenario 3 urban on-ramps have also an admissible ramp queue of 30 vehicles whereby in scenario 7 they are not controlled. The results of these scenarios are good but not as good as scenario 4 for example. This is an indication that 100 vehicles admissible ramp queue for the mtm on-ramps is not enough and more space is needed. This is made more clear if scenario 3 is compared with scenario 7. Scenario 3 has extra space available by controlling the urban on-ramps opposed to scenario 7 where this is not the case. The better results of scenario 3 emphasize the importance of the extra space. The density and queue profiles for the two scenarios can be seen in Figure 6-35 to Figure 6-38.

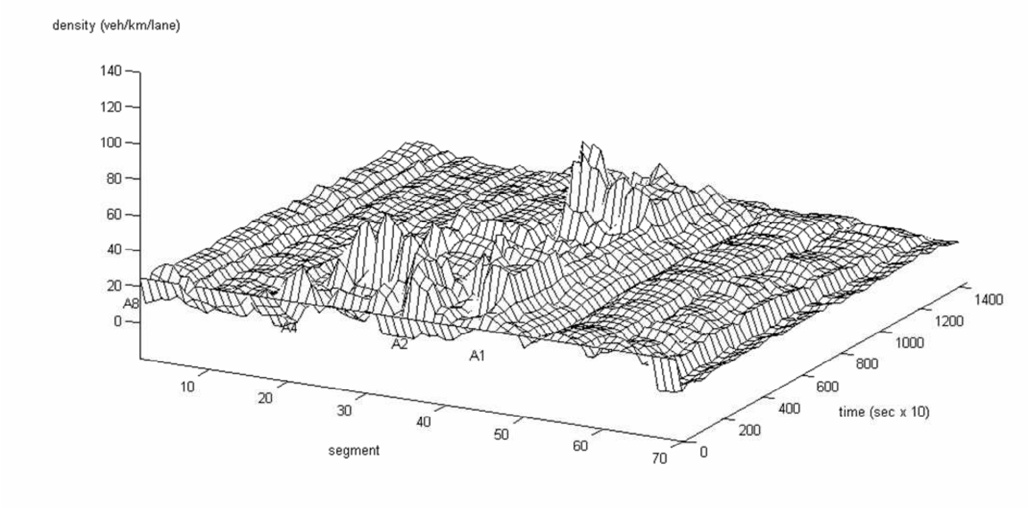

Figure 6-35: AMOC scenario 3 density profile.

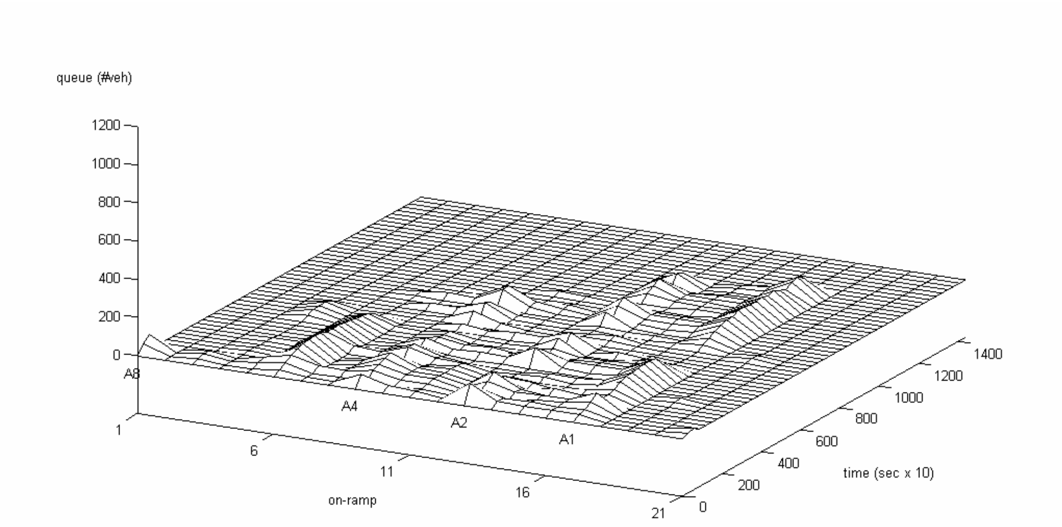

Figure 6-36: AMOC scenario 3 queue profile.

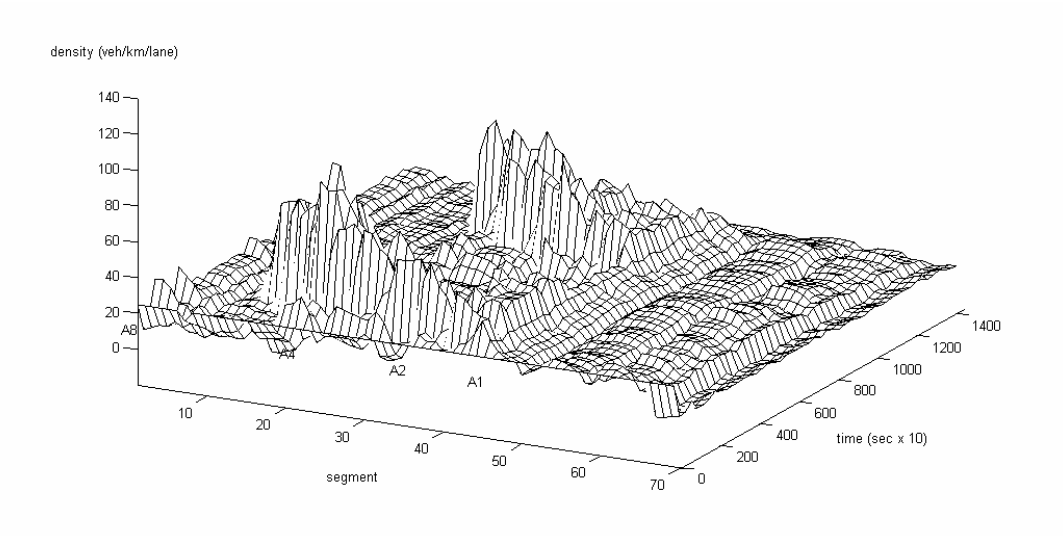

Figure 6-37: AMOC scenario 7 density profile.

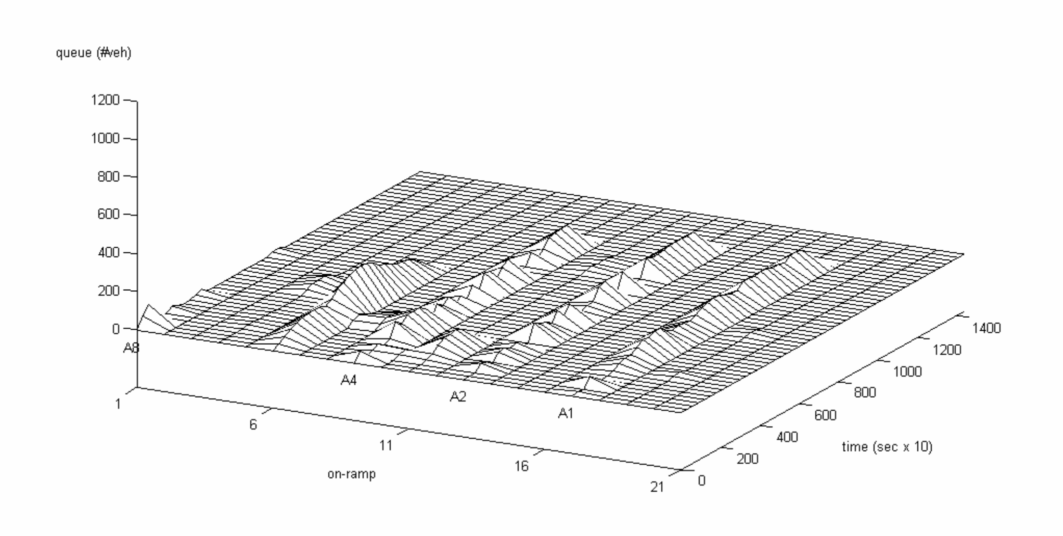

Figure 6-38: AMOC scenario 7 queue profile.

The rest of the scenarios are 8, 9 and 10. In these scenarios only the mtm ramps are controlled with an admissible queue of 200, 300 and 400 vehicles respectively. The efficiency of these scenarios is worse than the corresponding scenarios that implement also ramp metering on the urban on-ramps. Especially if scenarios 4 and 8 are compared the difference is quite significant. This means that although the admissible queue on urban on-ramps is small it helps solve the congestion problem. When the admissible queue on the mtm ramps rises over 200 the difference between the scenarios that control all the ramps compared to the scenarios where only the mtm ramps are controlled fades away. In Figure 6-39 to Figure 6-44 the density and queue profiles for the remaining scenarios 8, 9 and 10 are shown.

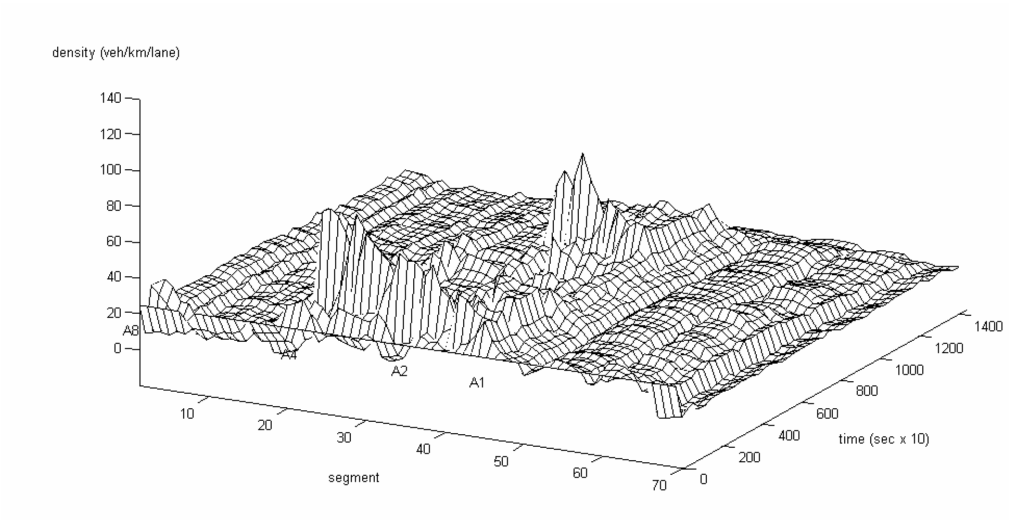

Figure 6-39: AMOC scenario 8 density profile.

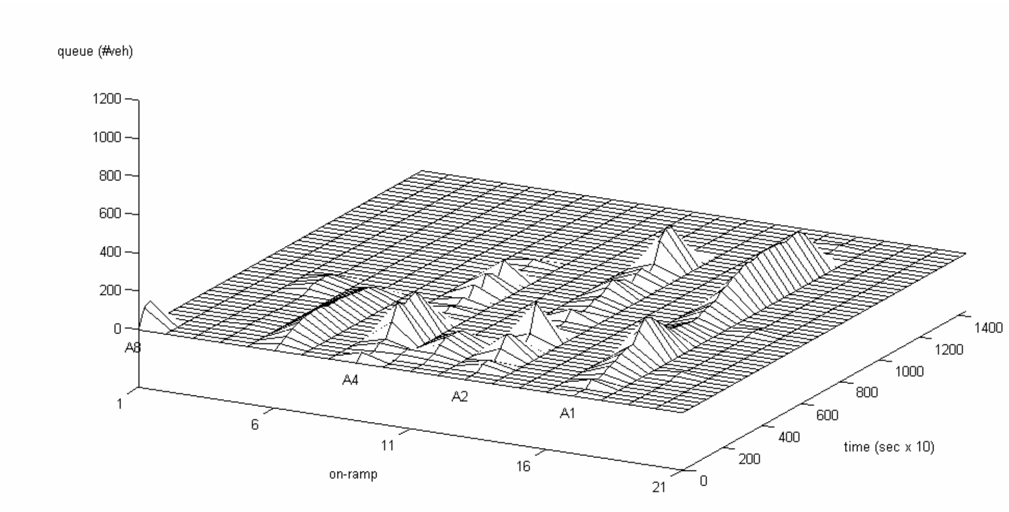

Figure 6-40: AMOC scenario 8 queue profile.

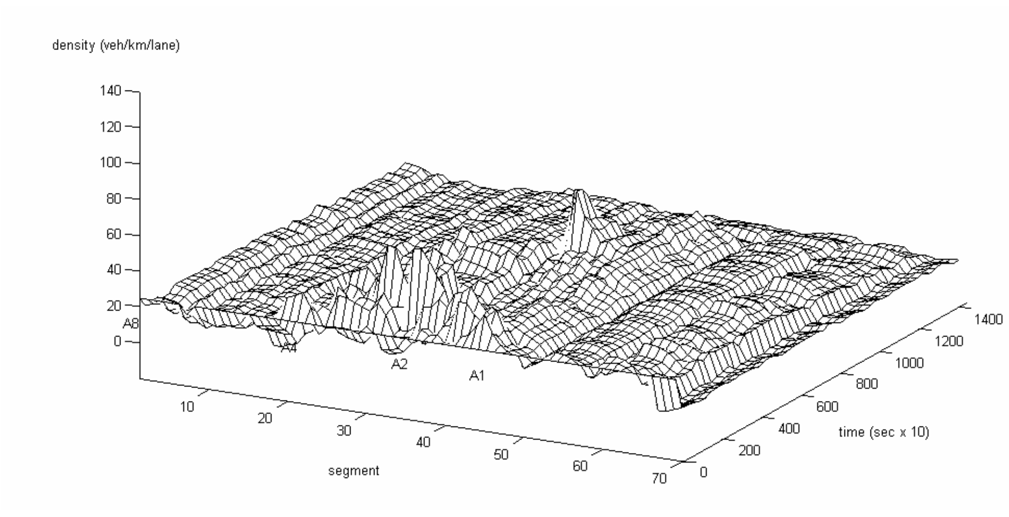

Figure 6-41: AMOC scenario 9 density profile.

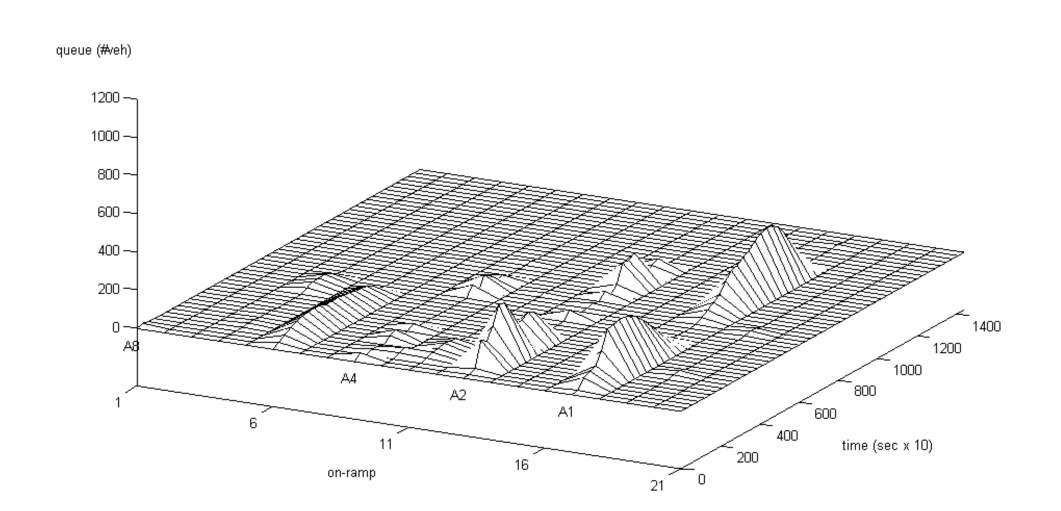

Figure 6-42: AMOC scenario 9 queue profile.

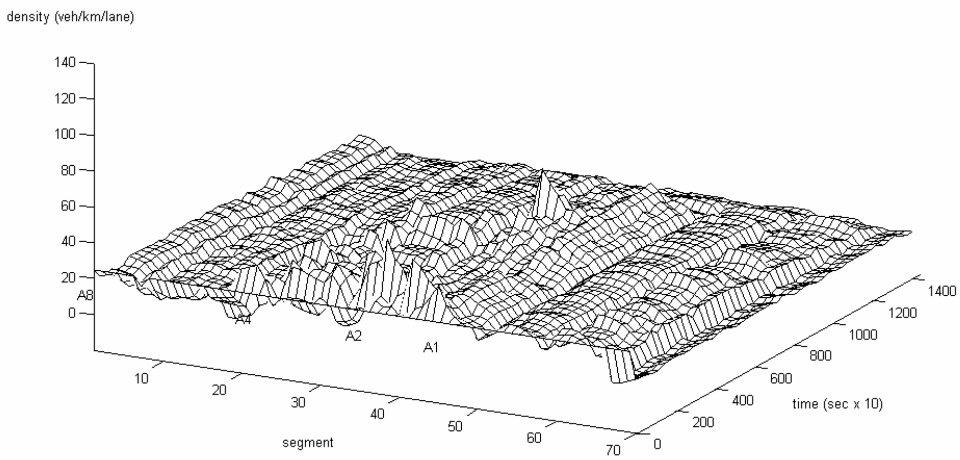

Figure 6-43: AMOC scenario 10 density profile.

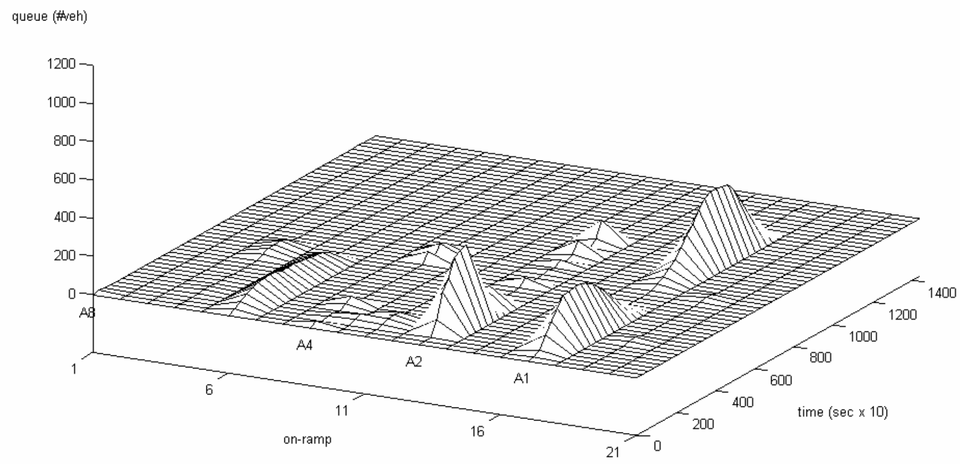

Figure 6-44: AMOC scenario 10 queue profile.

As said before, these values are of course an "upper bound" for the efficiency of the hierarchical control strategy. It can be observed that the formed queues at the mtm on-ramps are within the prescribed bounds of each scenario in most cases. In particular, in scenario 4 AMOC is able to anticipate the creation of the congestion and it counters its cause by creating queues to the extent, location and duration necessary along with the respect of the imposed queue constraints. Its anticipatory behaviour, as opposed to the reactive nature of ALINEA, deals with the causes of the problem before their consequences are manifested. Remarkably, when, e.g., the A4 ramp is metered, then the created ramp queue is much shorter than when no metering is applied (as in no-control or in scenario 2).

In Figure 6-45 TTS values are plotted for different admissible ramp queues for the mtm on-ramps. When urban on-ramps are not controlled (no-control case and scenarios 7 to 10) TTS values are higher compared to those calculated when urban on-ramps are controlled, with an admissible ramp queue equal to 30 veh. Again, both trajectories converge towards the (dotted) TTS value that corresponds to the value achieved by AMOC open-loop strategy if the storage capacity of mtm ramps were infinite (scenario 1).

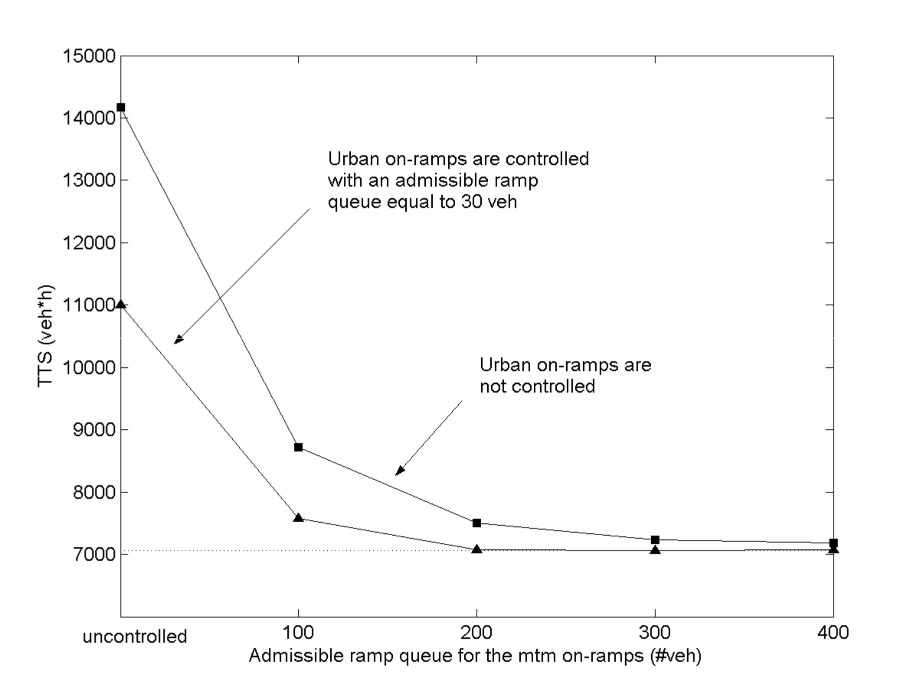

Figure 6-45: TTS values when AMOC is applied for the different scenarios.

6.6 Application of Hierarchical Control

As already mentioned before, because the assumption of exact measurements and perfect knowledge of future disturbances cannot hold in practice the results obtained by AMOC's open-loop solution are not realistic. To cope with this problem the hierarchical control structure with a rolling horizon technique has been proposed.

To implement the rolling horizon technique, the values for K_P and K_A have to be defined. The choice of these values influences both the quality and speed of the solution as mentioned in section 4.3.4. In Kotsialos and Papageorgiou (2004d) a study was performed for different values for K_P and K_A coming to a conclusion that the most efficient application horizon is 10 minutes ($K_A = 60$) with an optimization horizon of 1 hour ($K_P = 360$). These are the values that were used also in this study of the hierarchical control. The assumption is made that when AMOC is applied every 10 minutes the system state is known exactly. Also it is assumed that a fairly good predictor is available for the predictions of the on-ramps' demand and the off-ramps' turning rates so that the smoothed real trajectories are used as the predicted ones for the simulation. In Figure 6-46 and Figure 6-47 the actual and predicted demand for two different on-ramps are shown as an example. Likewise, in Figure 6-48 and Figure 6-49 two examples of actual and predicted turning rates for two off-ramps are depicted.

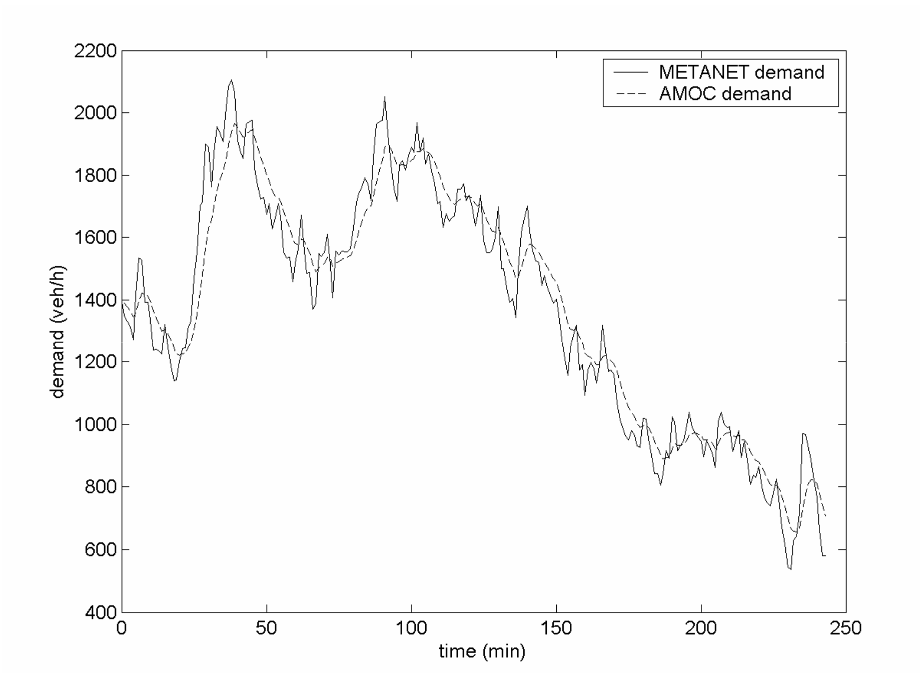

Figure 6-46: Real and predicted demand at the A1 mtm on-ramp.

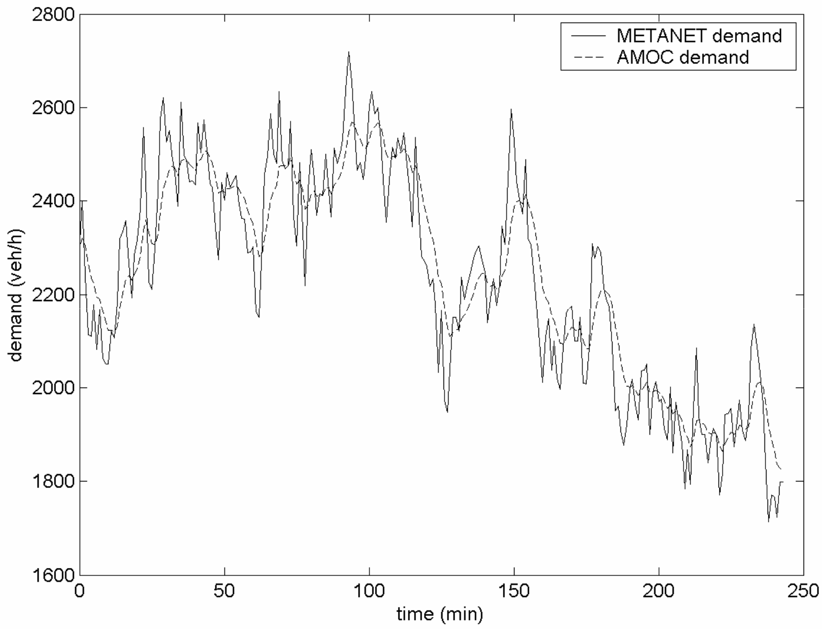

Figure 6-47: Real and predicted demand at the A8 mtm on-ramp.

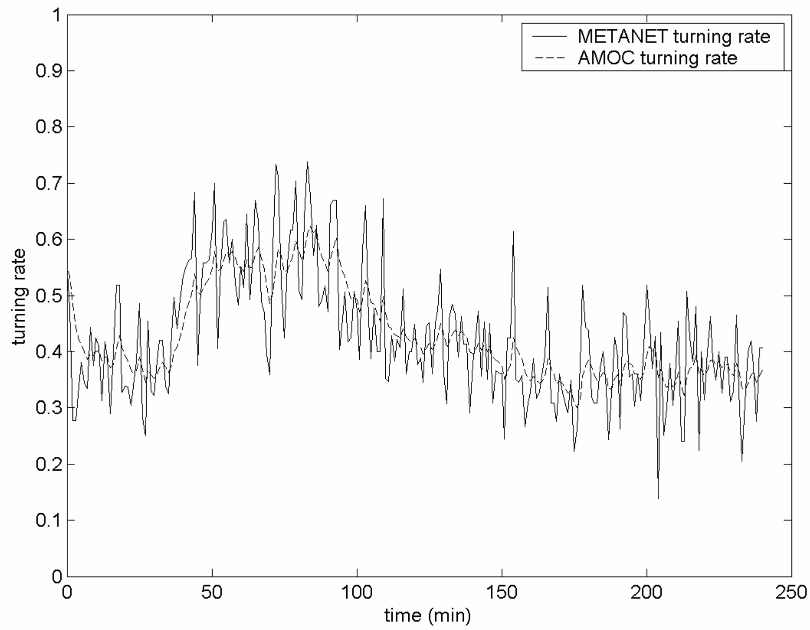

Figure 6-48: Real and predicted turning rate at the A2 off-ramp.

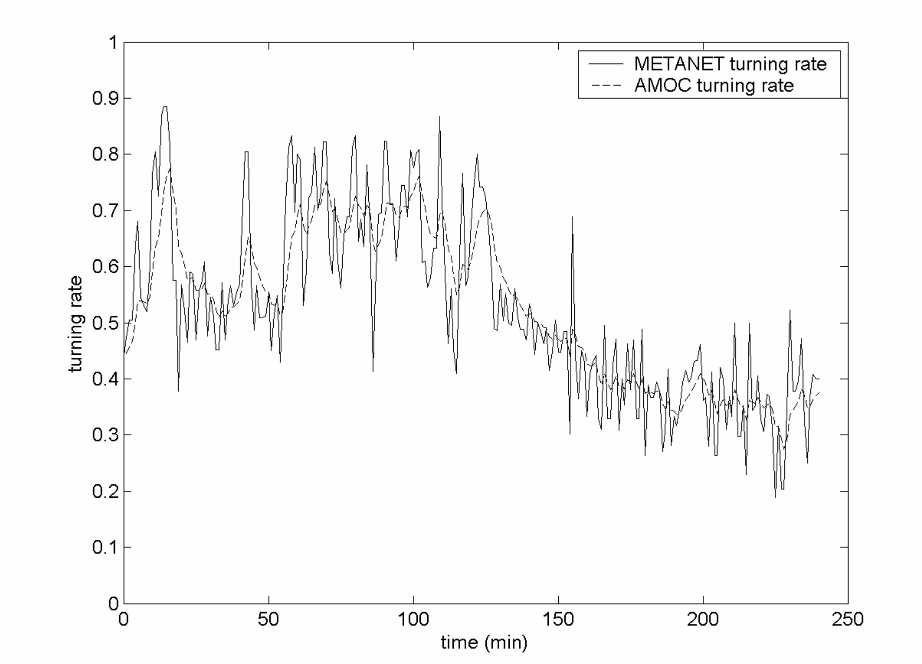

Figure 6-49: Real and predicted turning rate at the A4 off-ramp.

In section 4.3.3, where the Direct Control Layer of the hierarchical control structure is described, it is mentioned that there are two different methods available to apply the optimal trajectories provided by AMOC in the previous layer. The optimal trajectories can either be applied directly to the traffic flow process or passed on to the local controllers, in this case ALINEA or FL-ALINEA, as set points. If scenario 4 is examined, both methods have similar results. In the first case the TTS is 7422 veh*h, an improvement of 47,6% compared to the no-control case and just 4,9% worsening compared to the open-loop results. In the second case the TTS is 7399 veh*h, practically the same as in the previous case with 47,8% improvement to the no-control-case and 4,6% worsening to the open-loop control. The results are summarized in Table 6-4. The density and queue profiles for both cases can be seen in Figure 6-50 to Figure 6-53.

Table 6-4: Results for different methods in the Direct Control Layer for scenario 4.

Direct Control Layer	TTS (veh*h)	Improvement to the no-control case in %	Worsening compared to open-loop control in %
Direct Application of flows	7422	47.6%	4.9%
Use of ALINEA	7399	47.8%	4.6%

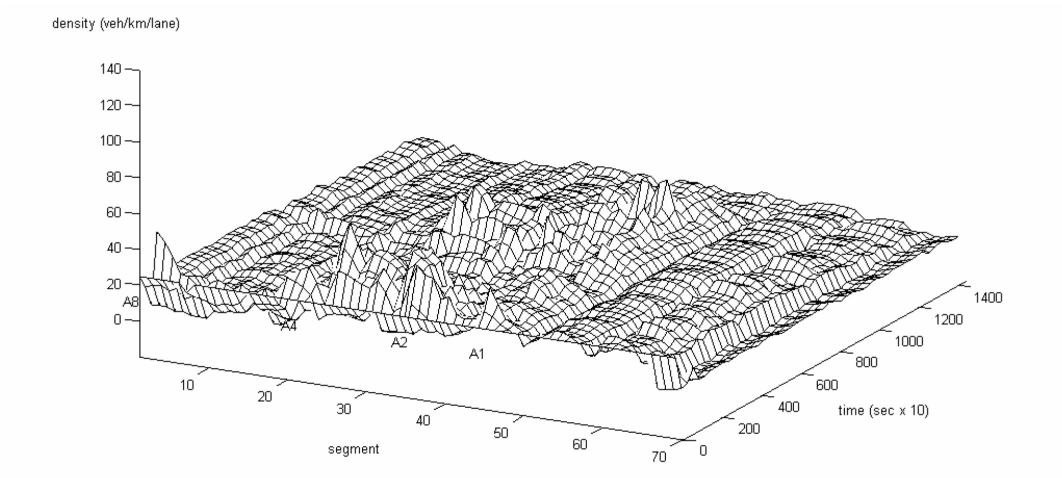

Figure 6-50: Hierarchical Control with direct application of optimal flows density profile for scenario 4.

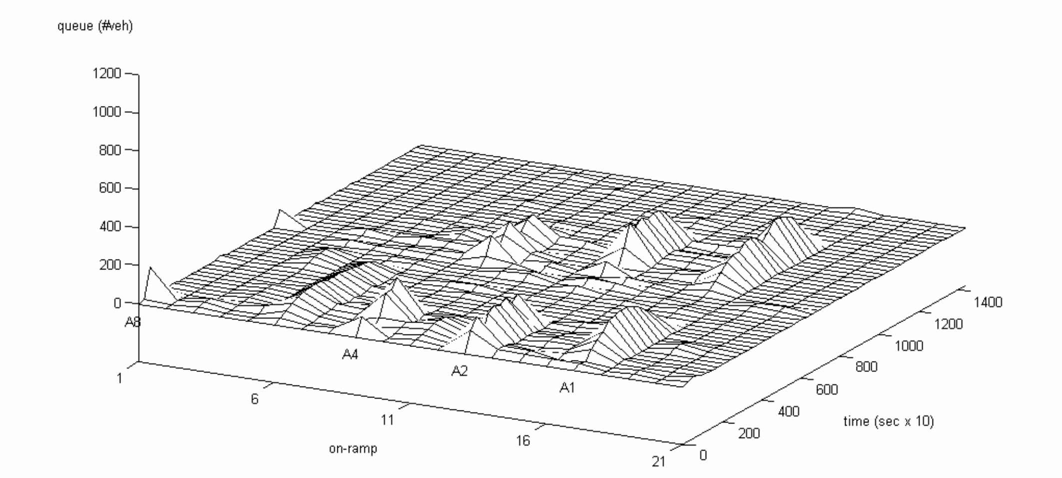

Figure 6-51: Hierarchical Control with direct application of optimal flows queue profile for scenario 4.

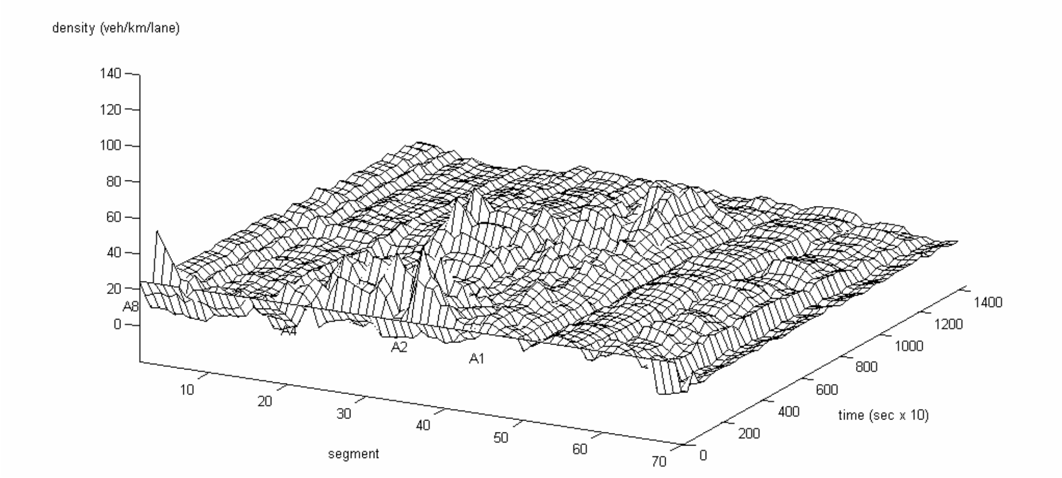

Figure 6-52: Hierarchical Control with optimal flows used as set points for ALINEA. Density profile for scenario 4.

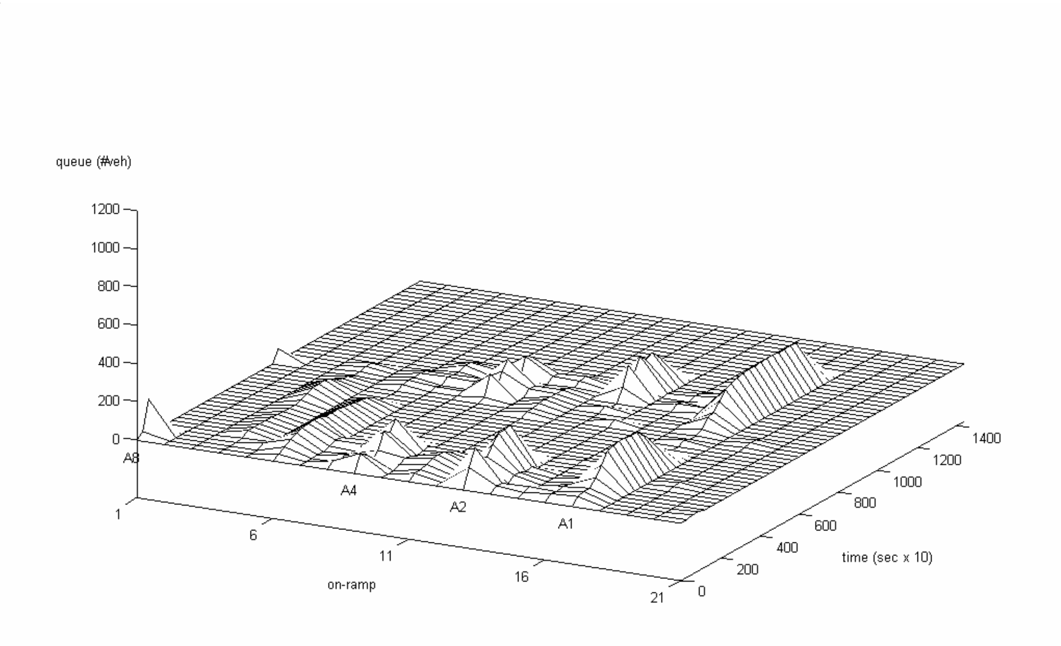

Figure 6-53: Hierarchical Control with optimal flows used as set points for ALINEA. Queue profile for scenario 4.

It seems that there is not any significant difference between the two cases. This is due to the use of the smoothed real trajectories of the actual demand as a prediction, which is a fairly good prediction. If the assumption that a good predictor is available does not hold, the results differentiate. When uniform under- or overestimated smoothed trajectories are used as the predicted ones, the superiority of the second case where the ALINEA and the FL-ALINEA strategies are employed in the Direct Control Layer becomes obvious. The results are presented in Table 6-5. A graphical representation is shown in Figure 6-54. In the same plot there is a line representing the TTS obtained by ALINEA for the same scenario. Of course this TTS value does not depend on the error of the demand prediction as the reactive nature of ALINEA needs no prediction at all.

Table 6-5: TTS (veh*h) values for demand prediction under- or overestimation for different methods in the Direct Control Layer for scenario 4.

Direct Control Layer	10% demand prediction under-estimation	5% demand prediction under-estimation	Smoothed demand	5% demand prediction over-estimation	10% demand prediction over-estimation
Direct Application of flows	8397	7584	7422	8591	8920
Use of ALINEA	7502	7552	7399	7613	7625

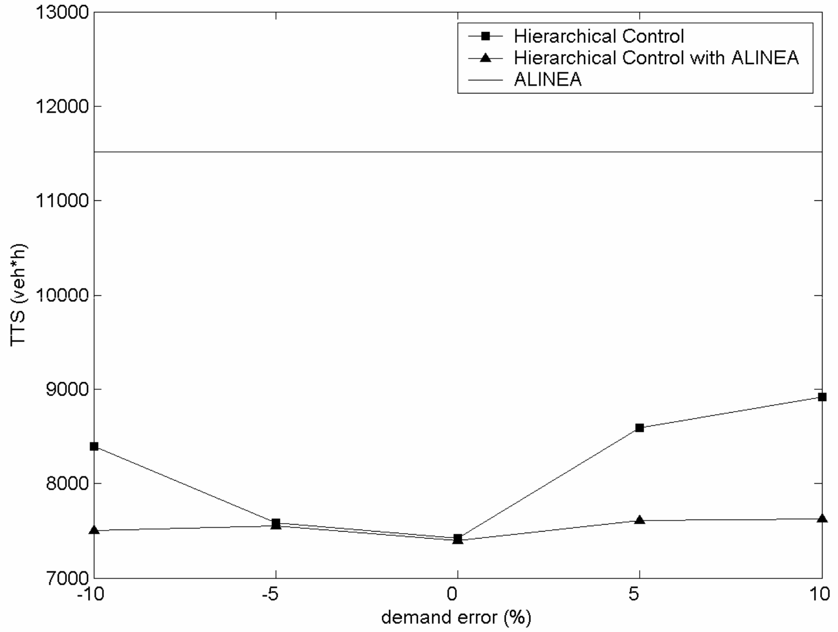

Figure 6-54: TTS values for demand prediction under- or overestimation for different methods in the Direct Control Layer for scenario 4.

The results presented make clear that the Hierarchical Control structure with ALINEA employed in the Direct Control Layer is better suited to reject errors introduced into the predictions. The optimal solution of AMOC consists of optimal ramp metering rates translated to admissible flows for the on-ramps. AMOC calculates these metering rates in order to keep the traffic states of the mainstream at certain levels. If the demand that arrives at every on-ramp is not as predicted the metering rates computed by AMOC cease to be optimal in contrast to the traffic states that are still optimal. The control structure with ALINEA aims at achieving these states by calculating its own rates reacting to the current situation rather than applying the rates without regard to the situation.

The hierarchical control structure with ALINEA employed in the Direct Control Layer performs better and for this reason all further studies are carried out following this method. The results of the TTS values obtained for all scenarios are summarised in Table 6-6. It becomes obvious that it is not possible to have results similar to the open loop solution if the mtm on-ramps are not controlled ot if the admissible ramp queues are lower than 200 veh*h. This is clear because the TTS for scenario 4 is just 4,61% worse than the corresponding open-loop solution and scenario 8 is even 2,56% better than the corresponding open-loop solution[1], while scenarios 3 and 7 are 55,93% and 47,54% worse than the open-loop solution respectively. The improvement to the no-control case is 47,78% and 46,91% for scenarios 4 and 8 respectively while only 16,64% and 9,23% for scenarios 3 and 7. It becomes also apparent that even with infinite admissible queues the amelioration achieved is on the same level as with an admissible ramp queue of 200 veh*h for the mtm ramps. In Figure 6-55 the TTS values are plotted for different admissible ramps queues for the mtm on-ramps. When urban on-ramps are not controlled (scenarios 1, 7, 8, 9 and 10), TTS values are higher compared to those calculated when urban on-ramps are controlled with an admissible ramp queue equal to 30 veh. This is true only for low values of the admissible queue for the mtm on-ramps. For bigger values of the admissible queue for the mtm on-ramps the TTS is almost identical. The trajectories converge to each other for an admissible queue for the mtm on-ramps equal to 200 veh (scenarios 4 and 8) and almost reach the (dotted) TTS value that would have been achieved by the hierarchical control strategy if the storage capacity of mtm ramps were infinite (scenario 1).

Table 6-6: Results of the application of the hierarchical control structure, improvement compared to the no-control case and difference to the open-loop solution.

Scenario	Hierarchical Control with ALINEA int the Direct Control Layer TTS (veh*h)	Improvement to the no-control case in %	Worsening to the open-loop results in %
1 (∞/∞)	7396	47,8%	4,3%
2 (30/-)	13496	4,7%	22,6%
3 (30/100)	11810	16,6%	55,9%
4 (30/200)	7399	47,8%	4,6%
5 (30/300)	7442	47,5%	5,3%
6 (30/400)	7414	47,7%	4,8%
7 (-/100)	12860	9,2%	47,5%
8 (-/200)	7522	46,9%	-2,6%
9 (-/300)	7357	48,1%	1,7%
10 (-/400)	7430	47,6%	3,4%

[1] this is due to numerical instabilities when solving the optimal control problem as explained in a similar situation in section 6.5

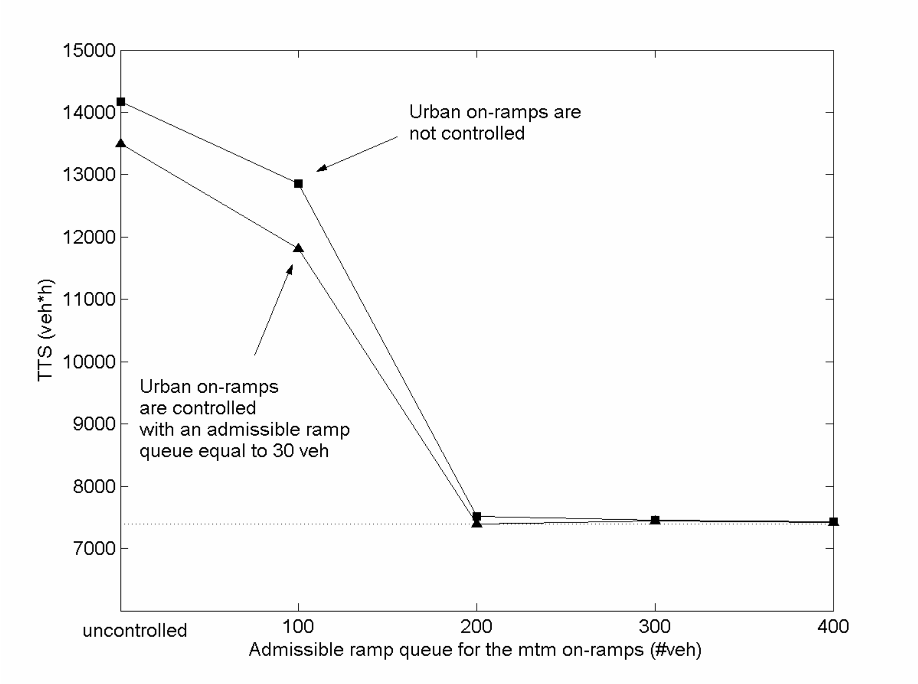

Figure 6-55: TTS values when Hierarchical Control is applied for the different scenarios.

If the results of scenario 4 with the hierarchical control strategy are compared with the results of ALINEA the differences of both approaches are becoming clear. The density profile in the first case (Figure 6-52) opposed to ALINEA (Figure 6-10) has no pronounced peaks. The queues are built early in the simulation time in anticipation of the future congestion, contrary to the reactive behaviour of ALINEA where queues are built in the second half of the simulation horizon as a reaction to the congestion that has formed. In the case of the hierarchical control, queues are built in such a manner that the maximum queue constraints are taken into consideration and not violated and yet the strategy achieves this without serious degradation of the strategy's efficiency. This becomes clear when Figure 6-11 is compared to Figure 6-53.

To have a complete graphical representation of the results, in the next figures (Figure 6-56 to Figure 6-73) the density and queue profiles of scenarios 1 to 3 and 5 to 10 are presented.

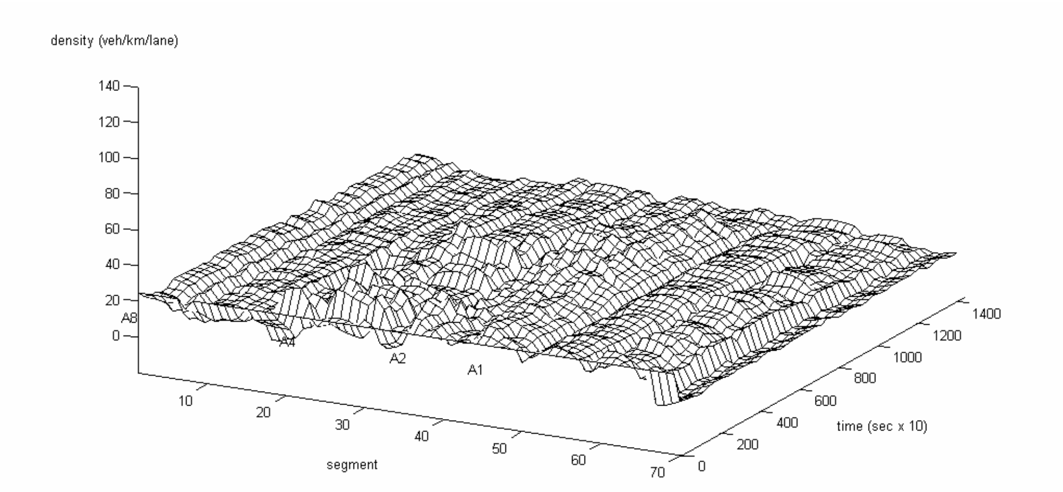

Figure 6-56: AMOC Hierarchical Control scenario 1 density profile.

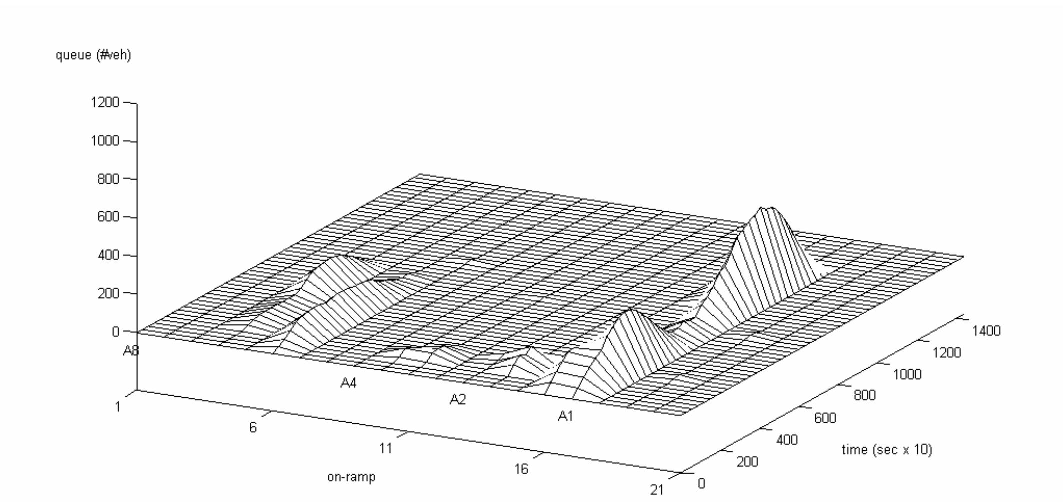

Figure 6-57: AMOC Hierarchical Control scenario 1 queue profile.

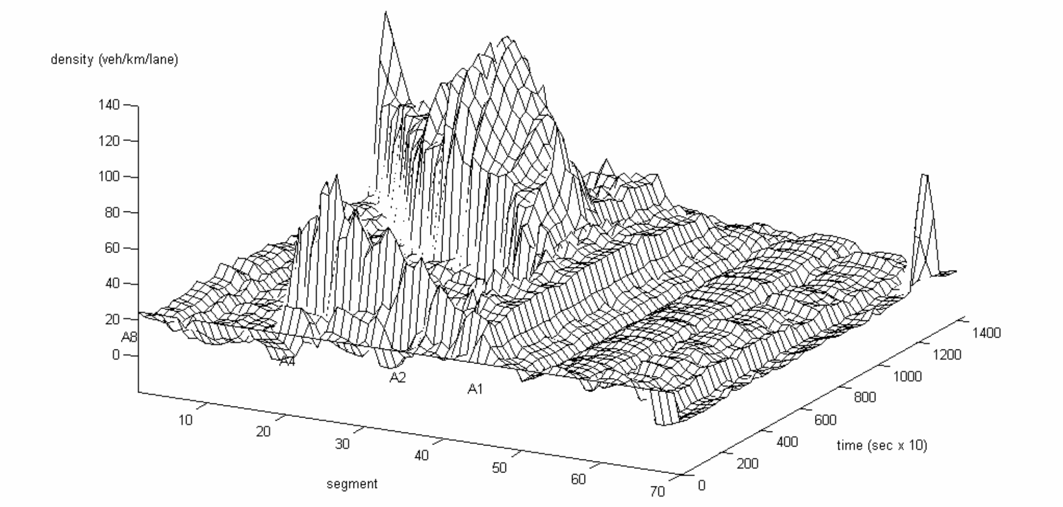

Figure 6-58: AMOC Hierarchical Control scenario 2 density profile.

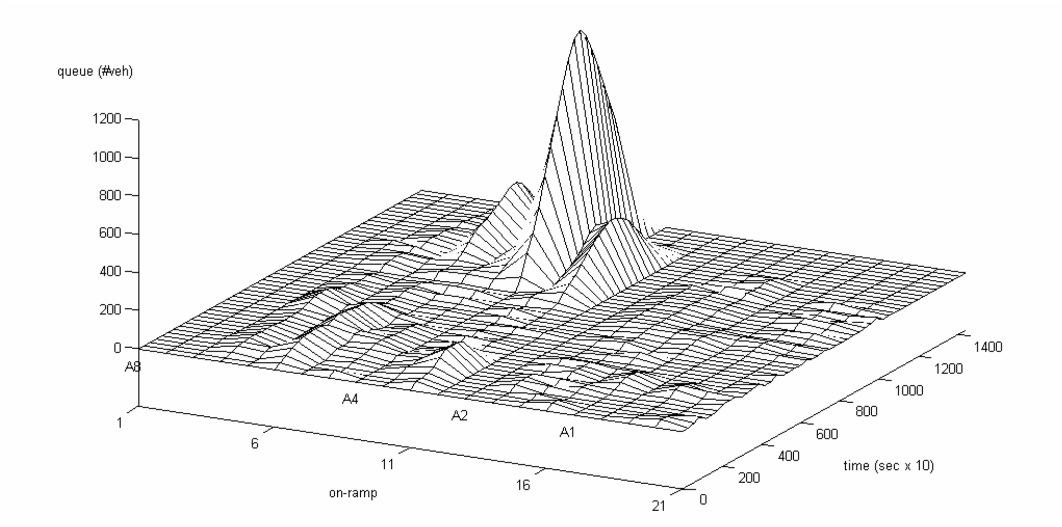

Figure 6-59: AMOC Hierarchical Control scenario 2 queue profile.

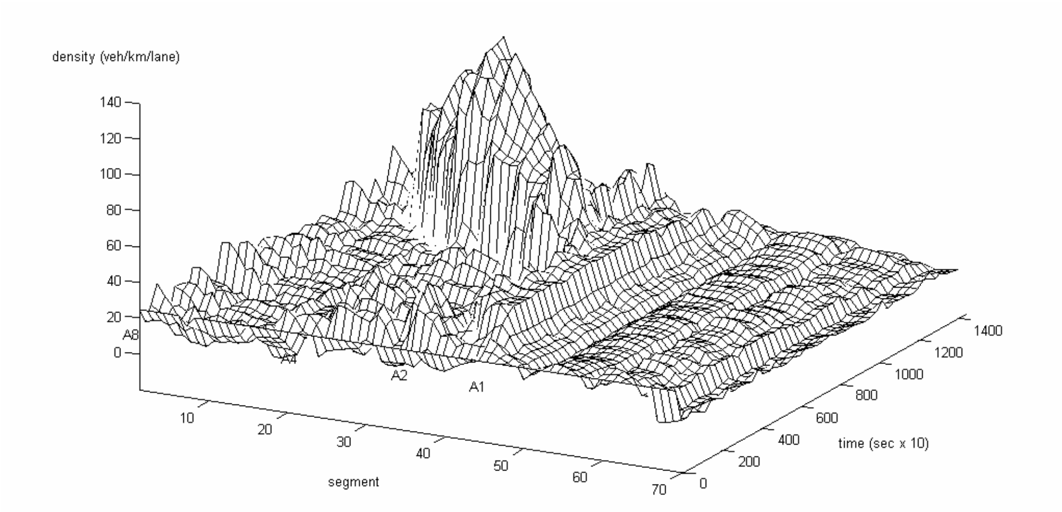

Figure 6-60: AMOC Hierarchical Control scenario 3 density profile.

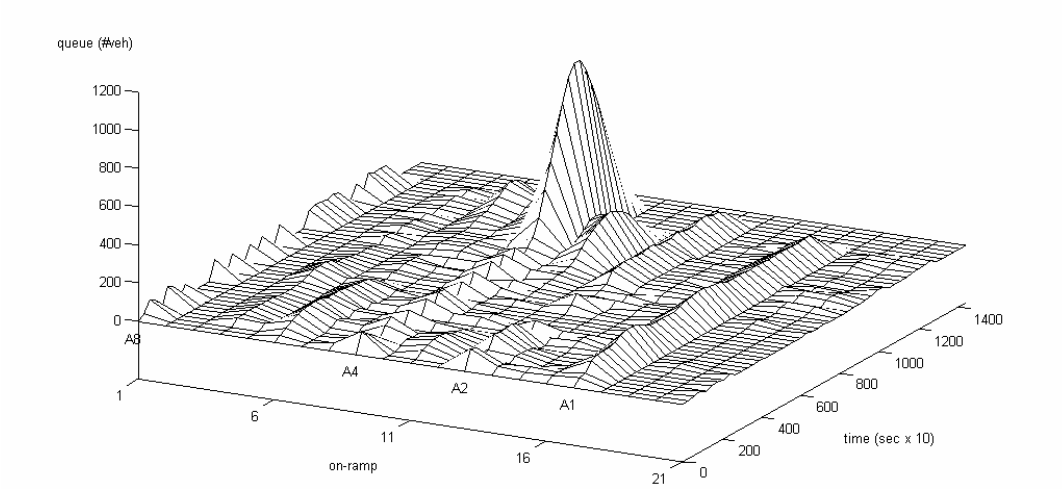

Figure 6-61: AMOC Hierarchical Control scenario 3 queue profile.

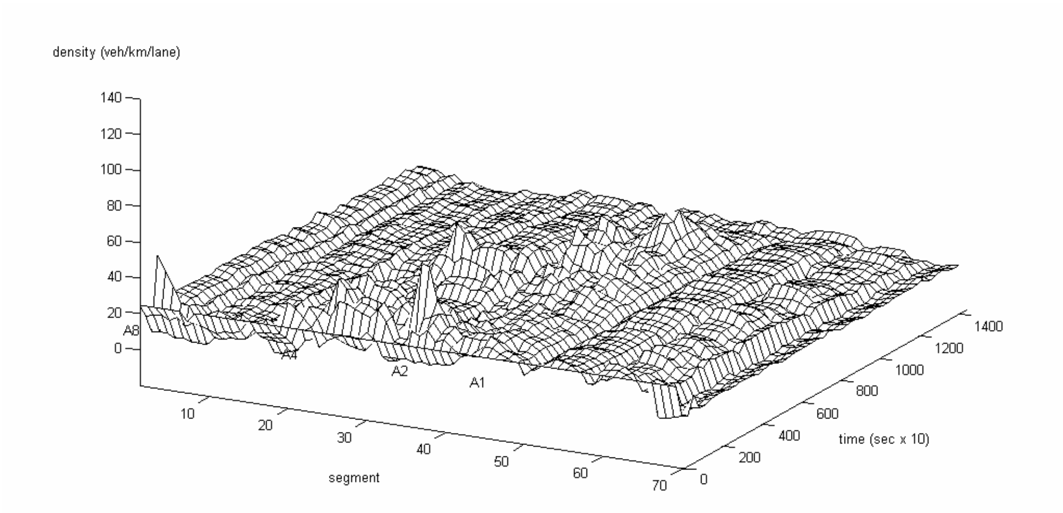

Figure 6-62: AMOC Hierarchical Control scenario 5 density profile.

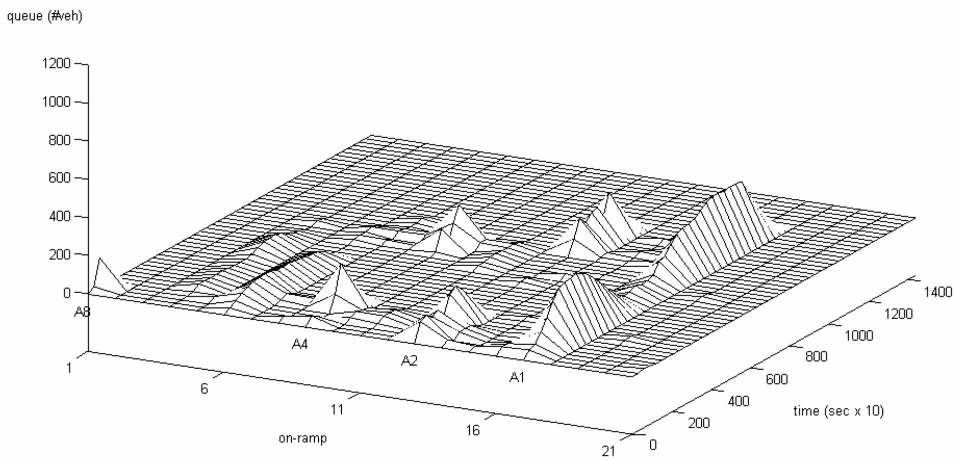

Figure 6-63: AMOC Hierarchical Control scenario 5 queue profile.

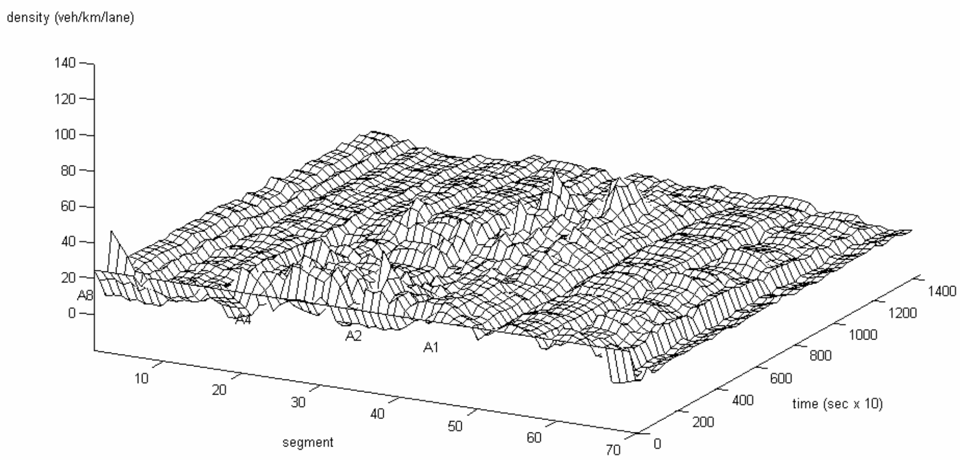

Figure 6-64: AMOC Hierarchical Control scenario 6 density profile.

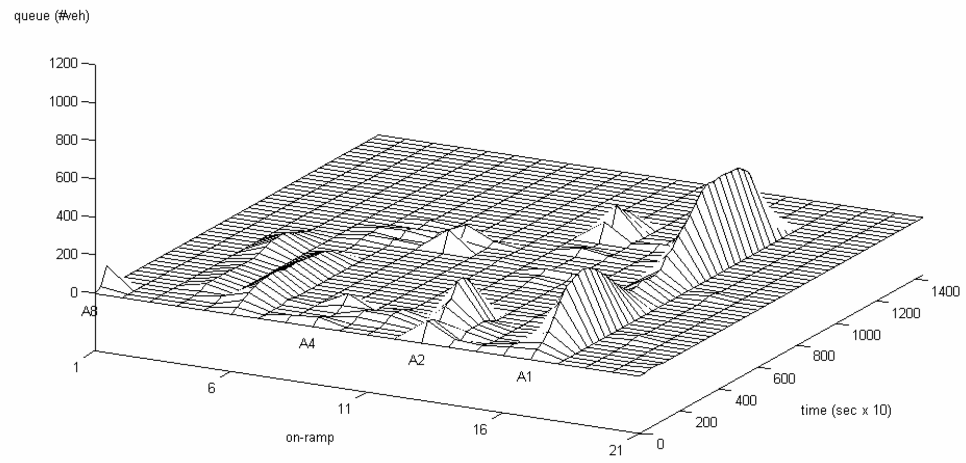

Figure 6-65: AMOC Hierarchical Control scenario 6 queue profile.

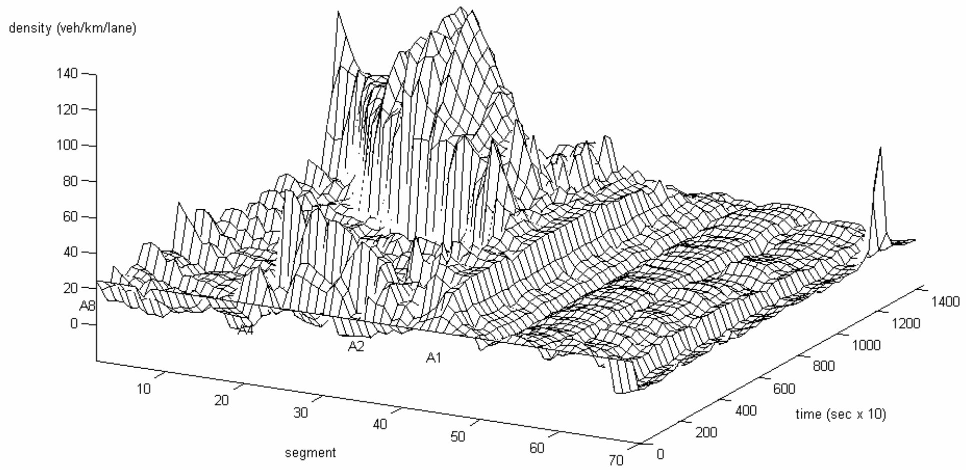

Figure 6-66: AMOC Hierarchical Control scenario 7 density profile.

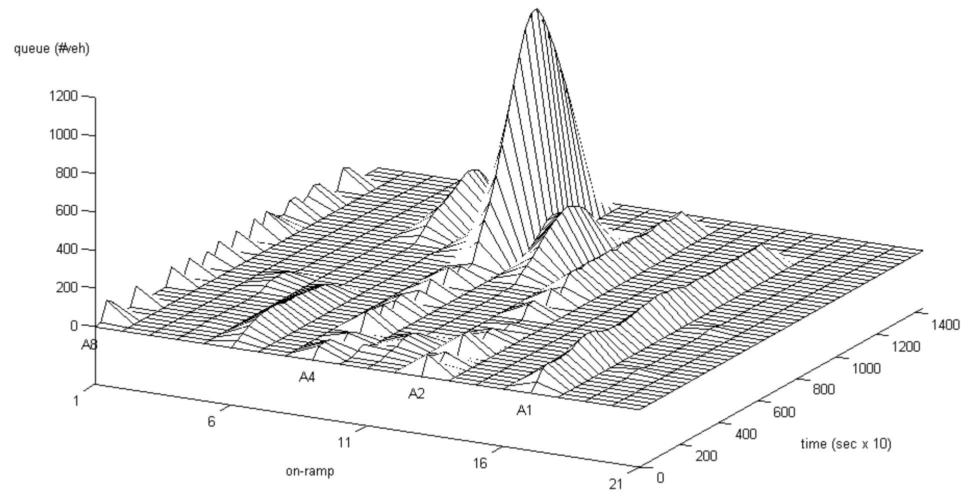

Figure 6-67: AMOC Hierarchical Control scenario 7 queue profile.

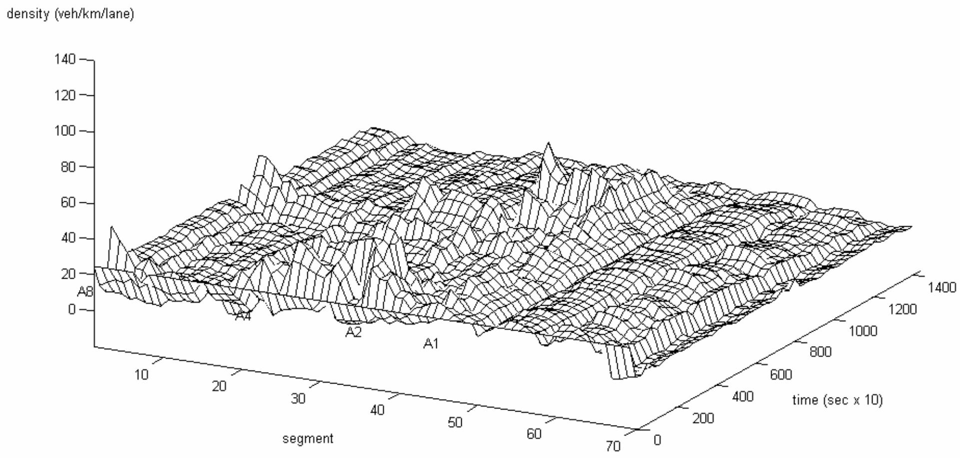

Figure 6-68: AMOC Hierarchical Control scenario 8 density profile.

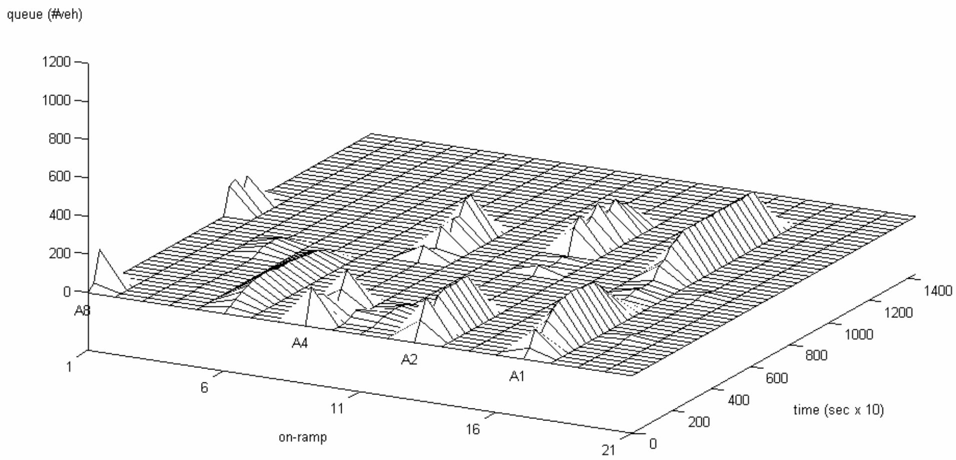

Figure 6-69: AMOC Hierarchical Control scenario 8 queue profile.

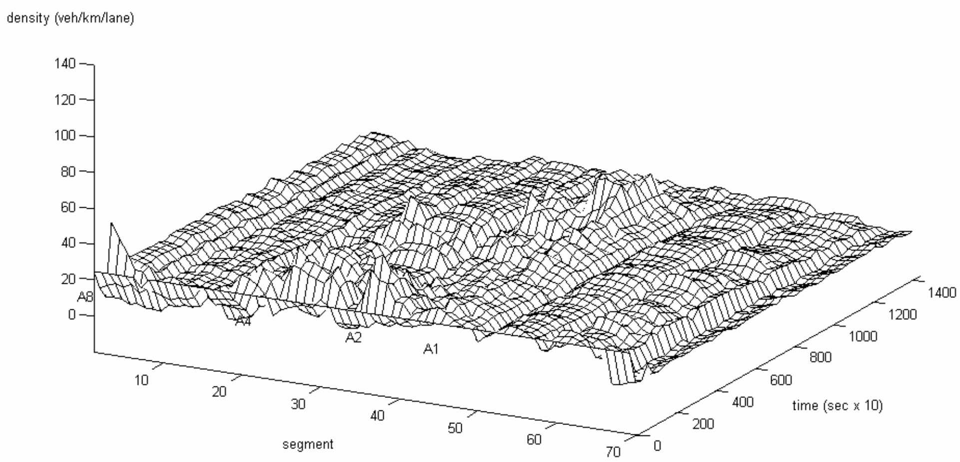

Figure 6-70: AMOC Hierarchical Control scenario 9 density profile.

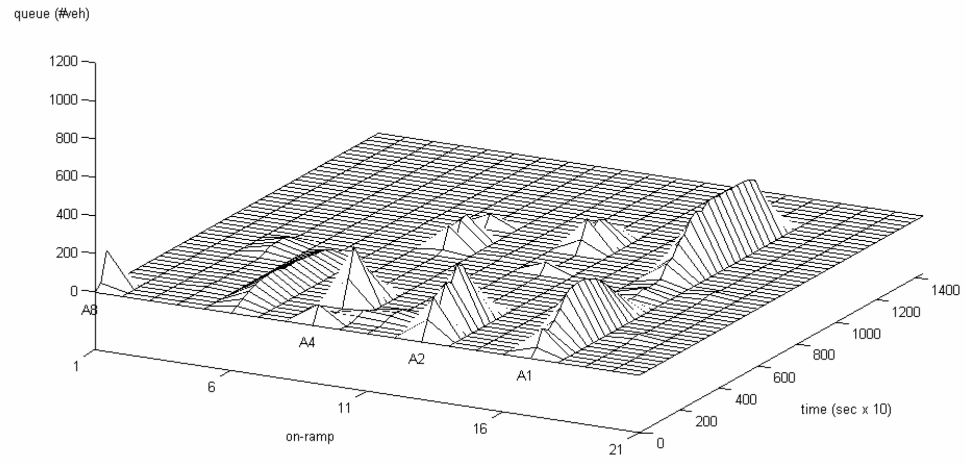

Figure 6-71: AMOC Hierarchical Control scenario 9 queue profile.

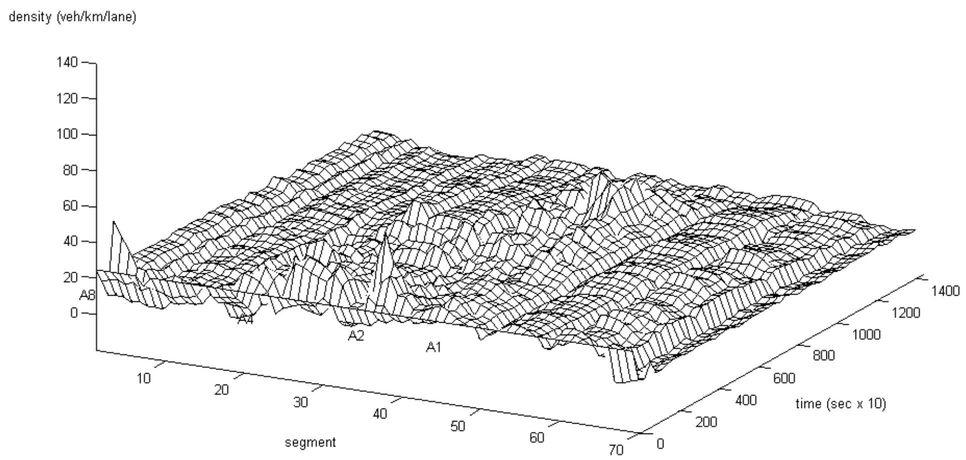

Figure 6-72: AMOC Hierarchical Control scenario 10 density profile.

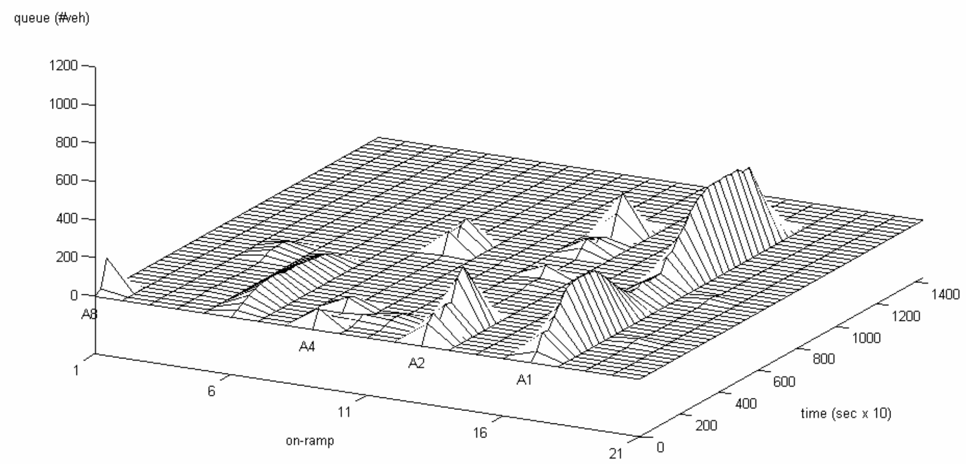

Figure 6-73: AMOC Hierarchical Control scenario 10 queue profile.

In terms of equity, studied through the average time spent by a vehicle in the ramp queue plus travelling 6.5 km downstream on the motorway, the hierarchical control structure behaves quite well. The equity results for scenarios 3, 4, 6 compared to the no-control case are shown in Figure 6-74. The hierarchical control manages to keep travel times significantly lower than for the no-control case. The efficiency is practically the same for scenarios 4 and 6, as it is clear from Table 6-6 and Figure 6-55, however the distribution of delays between the two mtm on-ramps of A1 and A2 is performed in a slightly more balanced and therefore more equal way for scenario 4.

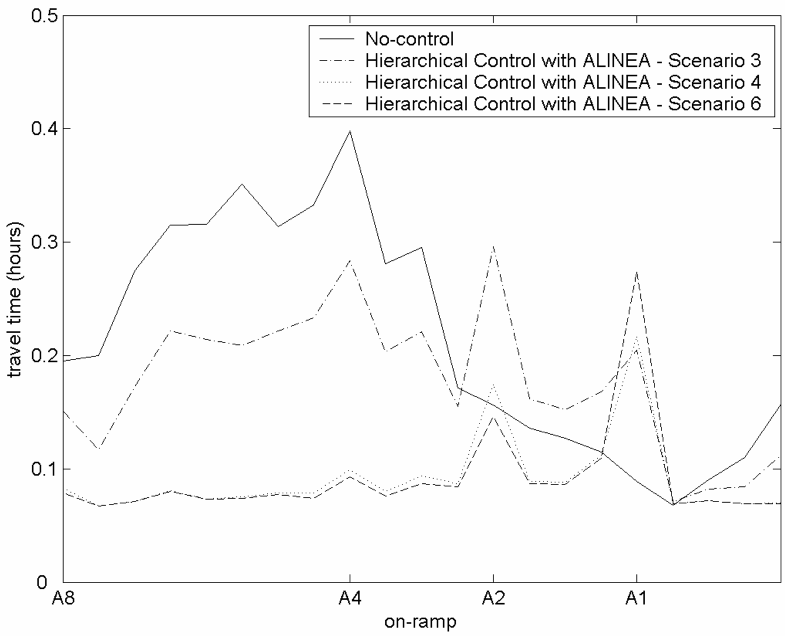

Figure 6-74: Equity graph for no-control case and hierarchical control scenario 3, 4 and 6.

6.7 Comparison of the examined strategies

6.7.1 Efficiency

In this study ALINEA as a standalone strategy, AMOC and Hierarchical Control were tested and compared to the no-control case. The test was performed by use of the METANET simulator for the counter-clockwise direction of the Amsterdam ring-road.

Various scenarios were considered which included ramp metering of urban and/or mtm on-ramps with different admissible queues. In Figure 6-75 it is shown how ALINEA and Hierarchical Control behave for the different admissible queues on the mtm ramps and how they compare to the open-loop solution of AMOC. In this case the results shown are with urban on-ramps controlled (scenarios 2 to 6). It can be observed that when mtm on-ramps are not controlled then ALINEA and the hierarchical control strategy perform equally well. However, ALINEA is outperformed by the hierarchical control strategy when mtm on-ramps are controlled. Additionally, when the admissible ramp queue for the mtm on-ramps is equal to 200 veh, then the hierarchical control strategy virtually reaches the efficiency of the optimal open-loop solution. Efficiency remains the same for even larger values. For the case where urban on-ramps are not controlled the results are shown in Figure 6-76. The situation is similar as before, when the admissible ramp queue for the mtm on-ramps is equal to 200 veh, then the hierarchical control strategy virtually reaches the efficiency of the optimal open-loop solution.

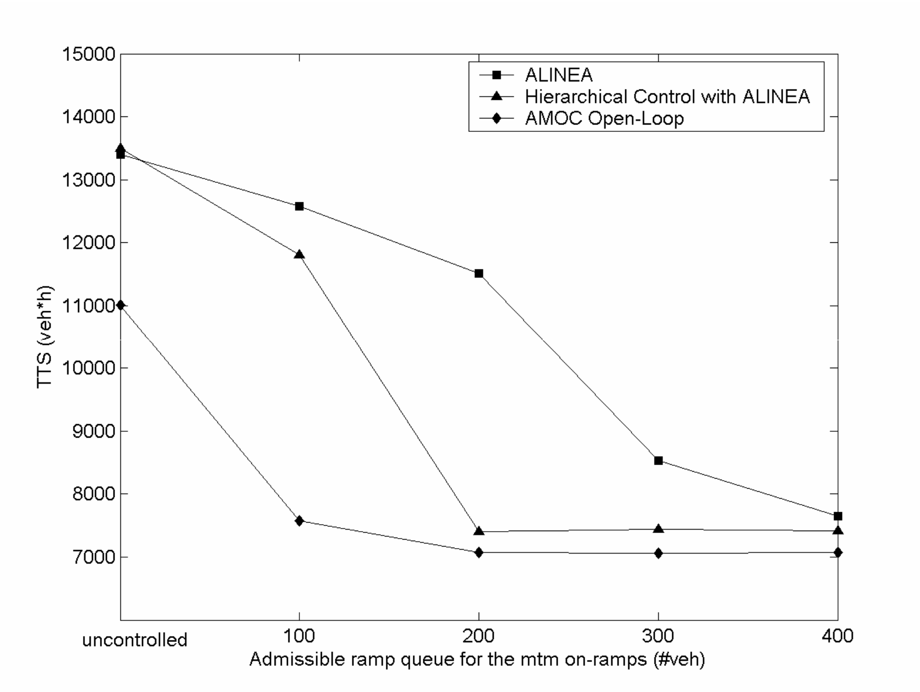

Figure 6-75: TTS values when urban on-ramps are controlled for different admissible ramp queues for the mtm on-ramps.

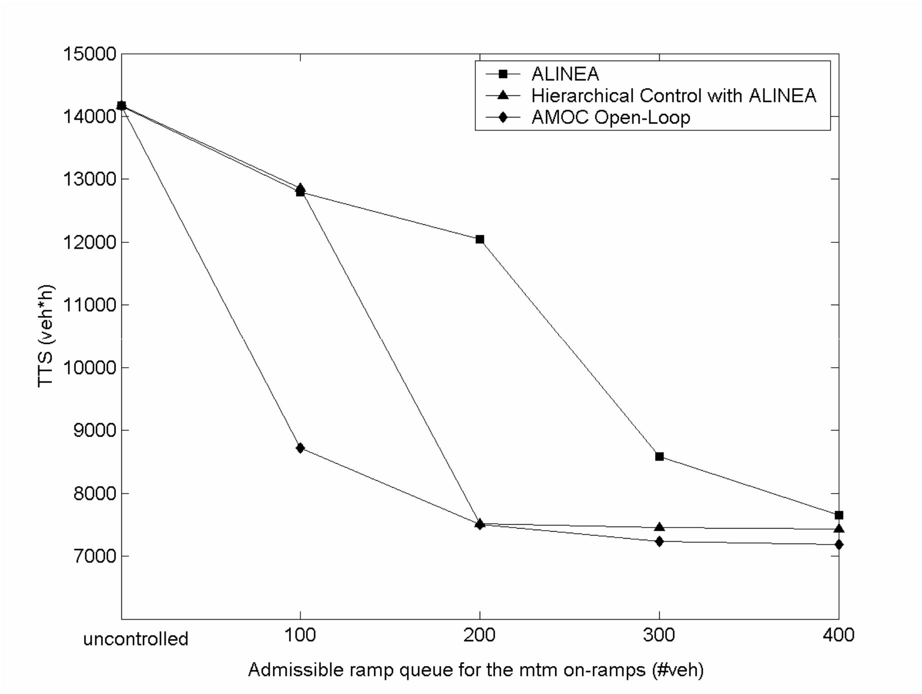

Figure 6-76: : TTS values when urban on-ramps are not controlled for different admissible ramp queues for the mtm on-ramps.

6.7.2 Equity

Equity is a very important aspect of every control strategy. However well any control strategy performs, if the amelioration of the traffic conditions is achieved on the expense of a group of vehicles, then the strategy is not very successful. The infrastructure is a social commodity and everyone should be able to use it and have the same benefits (or disbenefits) as everyone else.

As first mentioned in section 6.4.2, equity is studied through the average time $\overline{t_o}$ spent by a vehicle in the ramp queue plus travelling 6.5 km downstream on the motorway and is calculated by equation (6.1). In Figure 6-77 the equity diagrams are presented for the no-control case, ALINEA and the hierarchical control both for scenario 4. Scenario 4 was chosen because, as mentioned before, it is a scenario that the authorities could implement almost with no change at the present infrastructure and has results that are almost the same with scenarios which employ longer admissible queues on the mtm on-ramps. It is apparent that for the hierarchical control the travel times are significantly lower than for the no-control case or ALINEA strategy. The high peaks are either reduced (as the one at A2) or even not present anymore (as at A4). Clearly, the hierarchical controller's distribution of delays is performed in a more balanced way, which is more equitable for the drivers entering the mainstream at different ramps.

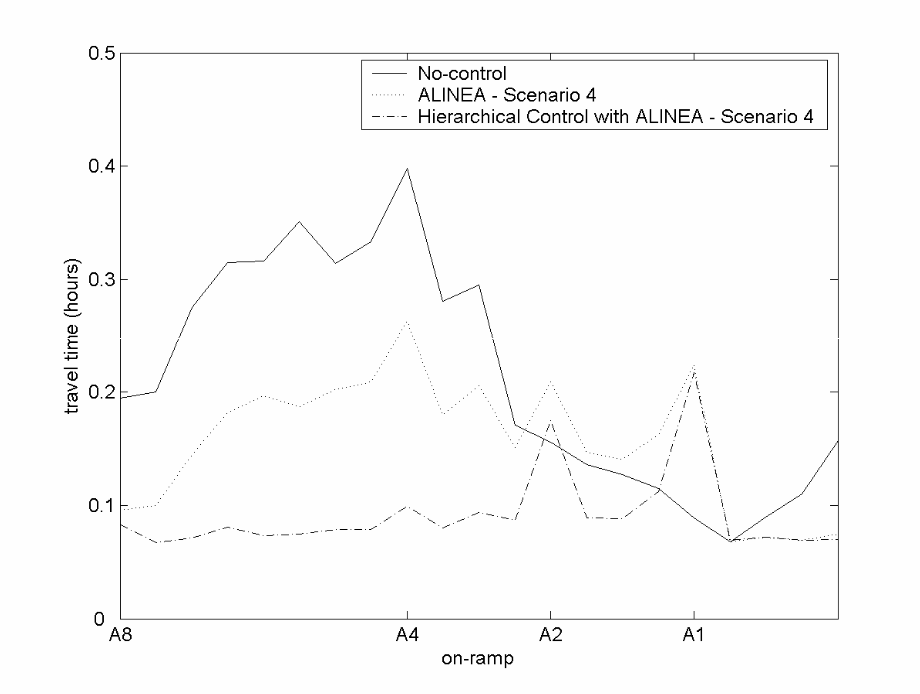

Figure 6-77: Equity graph for no-control case, ALINEA and Hierarchical Control both for scenario 4.

7 Conclusions and Recommendations

7.1 Conclusions

In this study the results of the application of local feedback control (ALINEA), optimal open-loop control (AMOC) and rolling horizon hierarchical coordinated optimal control (Hierarchical Control) to the counter-clockwise direction of the Amsterdam ring-road have been presented and compared to the no-control case. The strategies were implemented for several scenarios and the results were investigated for their efficiency as well as for their equity.

Uncoordinated local feedback control with ALINEA was quite successful in reducing the TTS and resolving congestion up to a certain degree which in most cases depends on the imposed queue-length restrictions. However, the main problem, the large queues on A4, is unavoidable in the realistically restricted cases.

Optimal open-loop control with AMOC has great results but is representing an ideal situation where the traffic state is known exactly at the initial point and the predictions of the disturbances are 100% accurate which is not always the case in real world applications. However AMOC's open loop solution can act as an upper boundary for the achievable efficiency of any control strategy.

As expected, the hierarchical control with AMOC in the optimization layer and ALINEA in the direct control layer outperforms the uncoordinated local ramp metering approach. The results are very promising and in the worst case they are at least as good as a standalone ALINEA and in the best case they are almost as good as the open loop solution. The only downside of this approach is the computation time needed, but there exist certain methodologies to address this problem. With computer power increasing constantly this problem becomes less significant.

This study made apparent the need to introduce ramp metering on the mtm on-ramps. In the network studied and for the specific disturbance profiles used, the introduction of ramp metering at the urban on-ramps reduced some local traffic problems. However, a significant amelioration of the global traffic conditions in the network calls for comprehensive control of the mtm on-ramps in the aim of optimal utilization of the available infrastructure. By building queues that do not exceed 200 veh on the mtm on-ramps, hierarchical control leads to a 47,8% improvement over the no-control case. The available storage capacity in mtm intersections is sufficient to effectively and ultimately combat motorway congestion for the network studied. Authorities often hesitate to introduce ramp metering on mtm ramps but it is important to mention that without control of the mtm ramps much bigger queues are built on them anyway. This means that the introduction of ramp metering on mtm on-ramps actually manages to reduce both the congestion and the length of the queues that are built.

By observing ALINEA and both open loop AMOC and Hierarchical Control, some remarks were made. Local control with ALINEA as was employed with set-values equal to the respective critical densities can be used at each ramp as a stand-alone strategy without any kind of coordination. ALINEA maintains the downstream traffic density around the set-point. Whenever traffic demand received by an on-ramp exceeds the outflow calculated by the regulator, a queue is formed at the on-ramp that may also be controlled by a maximum queue constraint. When the queue reaches its maximum admissible value, motorway congestion is created that travels upstream and activates local ramp metering at the next upstream on-ramp as well and so forth, leading to a spreading of ramp queues in reaction to the congestion that has formed. Thus, independent (uncoordinated) application of ALINEA at each ramp (with limited storage space) may ameliorate the traffic conditions (compared to no control) but cannot eliminate the congestion forming queues at the on-ramps.

7.2 Recommendations

The results obtained by this study have lead to certain realizations and in turn to suggestions for the future.

At first the point must be made that depending on the network and its traffic conditions authorities have to take an important decision to implement ramp metering on urban on-ramps and probably on mtm on-ramps as well. Authorities are reluctant to use ramp metering on mtm on-ramps because it usually is against the initial purpose of motorways to allow for free and without restrictions flow of vehicles. Also, the users of motorways often do not like to have restriction imposed on them. But the increased demand leads to degradation of the infrastructure through congestions and long queue build-up which abolishes the initial purpose of the motorways anyway. Thus the implementation of ramp metering, even on mtm ramps, actually is a step towards the initial purpose of motorways. The public is certain to accept this kind of measures if the improvement of the traffic conditions becomes apparent. Equity of the strategy is another way to persuade the public to accept new measures. If the delays and the deficiencies are the same for all, it will be easier to accept the imposed regulations.

In the hierarchical control case the queues are built early in the simulation time in anticipation of the future congestion due to AMOC's predictive control nature and they are kept below the maximum admissible value in most cases. However, the achievement of good results through the application of hierarchical control requires accurate model, state estimates and disturbances prediction. The efficiency of AMOC (and hence of the hierarchical control strategy) deteriorates moderately but increasingly with increasing disturbance prediction errors or in case of model-versus-reality mismatch. Moreover, AMOC (and hence the hierarchical control strategy as a whole) is a rather complex code incorporating a full macroscopic mathematical model of the traffic flow process as well as a numerical solution algorithm for the addressed optimal control problem. Code complexity, relatively intensive computations and the "black box" character of the optimization procedure may be perceived as obstacles for ready and broad application of the method.

In view of this discussion, it would be desireful to have a ramp metering strategy that possesses the following features:

- It should coordinate local ramp metering actions in a suitable way so as to avoid the pitfalls of uncoordinated ALINEA application.
- It should be simple and transparent, e.g. rule-based.
- It should be reactive so that no external disturbance prediction is needed.
- It should approach the efficiency of sophisticated optimal control.
- It should be generic (i.e. directly applicable to any motorway network) without a need for cumbersome parameter calibration.

A control strategy possessing all mentioned features is under development; the strategy was given the name HERO (HEuristic Ramp metering co-Ordination) and future studies will further develop and test this strategy.

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