TØI report 1358/2014

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Evaluation of methods for calculating traffic assignment and travel times in congested urban areas with strategic transport models

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Summary:

The report evaluates methods for traffic assignment modelling (static macroscopic, dynamic macroscopic and dynamic micro/mesocopic) within strategic transport model systems. Our evaluation of traffic assignment models found that dynamic meso/micro models are most appropriate for all (considered) application purposes in congested urban areas. The biggest advantages are connected to the realistic modelling of congestion and the richness in analysis (allowing to aggregate results in any desirable way). Those models have some practical challenges/disadvantages. They require more detailed input data, are more demanding with respect to implementation, calibration and usage and set high requirements (expert knowledge) on the users. The stochasticity of dynamic meso/micro models imply that distributions of predictions from several model runs should be compared.

Language of report: English

Tittel: Vurdering av metoder for å beregne trafikkavvikling og reisetider i byområder med købelastning i strategiske transportmodeller

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Sammendrag:

Rapporten vurderer metoder for trafikkavviklingsmodeller (statisk makroskopisk, dynamisk makroskopisk og dynamisk mikro/mesoskopisk) i strategiske transportmodeller. Vår evaluering av metoder for trafikkavvikling beskriver dynamiske meso- eller mikromodeller som mest egnet for alle (vurderte) analysehensikter i købelastede byområder. De største fordelene er knyttet til en realistisk modellering av kø og bredden i analysemuligheter (muligheten til å aggregere resultater på alle ønskelige måter). Disse modellene har imidlertid noen utfordringer/ulemper i praksis. De krever mer detaljerte inndata, er mer krevende med hensyn på implementering, kalibrering og bruk og stiller høyere krav (ekspertkunnskap) på brukersiden. Pga. stokastikken i dynamiske meso/mikro-modeller bør fordelinger av prediksjoner fra flere modellkjøringer sammenlignes.

This report is available only in electronic version.

Rapporten utgis kun i elektronisk utgave.

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Preface

The increasing need to capture dynamic effects of congestion for strategic transport planning purposes motivates this report. Traditional strategic transport models have several weaknesses in this respect due to their static (and aggregated) nature. Dynamic and dissagregated methods, applicable for strategic transport planning, are emerging but are not yet widely used in practical applications.

The report evaluates methodological approaches to traffic assignment models based on 1) planned application context of the model system 2) properties of the available (or to-be-developed) travel demand model 3) further model capabilities and practical features.

The report is written by Stefan Flügel, Institute of Transport Economics (TØI), Gunnar Flötteröd (KTH Royal Institute of Technology), Chi Kwan Kwong (TØI) and Christian Steinsland (TØI). Stefan Flügel has been Project Manager. Anne Madslien was responsible for quality assurance.

The project was commissioned by the Norwegian Road Administration (SVV) and is part of the larger research program ("Bedre By"). Contact person at SVV was Guro Berge. We also thank Henrik Vold, Oskar Andreas Kleven and Børge Bang for important comments on the draft report.

Oslo, October 2014
Institute of Transport Economics

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Contents

Summary:

Evaluation of methods for calculating traffic assignment and travel times in congested urban areas with strategic transport models

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Transport processes, i.e. movements of persons and goods in space and time, are by nature dynamic. Decisions on the demand side are made in a dynamic context of reaching and scheduling activities at desirable starting times. The network performance (representing the short-term supply side) depends on traffic flow propagations resulting from dynamic interactions of many vehicles and the given infrastructures. Travel times experienced by travellers in urban areas can vary significantly over the day due to congestion patterns which are both depending on human behaviour (in particular mode, departure time and route choice) and complex physical processes in the network.

Our evaluation of traffic assignment models found that dynamic meso/micro models are most appropriate for all application purposes in congested urban areas. The biggest advantages are connected to the realistic modelling of congestion and the richness in analysis (allowing to aggregate results in any desirable way). Those models have some practical challenges/disadvantages. They require more detailed input data, are more demanding with respect to implementation, calibration and usage and set high requirements (expert knowledge) on the users.

The Institute of Transport Economics (TØI) and Associate Professor Gunnar Flötteröd from KTH's Department for Transport Science had been commissioned by the Norwegian Road Administration to

- Review and compare different methods for calculating traffic assignment and travel times in congested urban areas with strategic transport models
- Discuss how static [travel demand] and dynamic [traffic assignment] models can be combined and to evaluate the advantages and disadvantages of such approaches

Table S1 and S2 summaries the results of the evaluation (the evaluation for "travel demand management" and "equity analysis" rests on the assumption that they are coupled with corresponding disaggregated travel demand models).

Table S1: Evaluation of network assignment packages for application purposes

	Static macro	**Dynamic macro**	**Dyn. meso/micro**
Congestion mitigation	Inadequate (S)	Adequate	Adequate
ITS	Inadequate (S,A)	Inferior (A)	Adequate*
Travel demand management	Inferior (A)	Acceptable	Adequate
Equity analysis	Inadequate (A)	Inferior (A)	Adequate
Standard Cost-benefit analysis	Adequate if congestion low	Adequate	Adequate**

Reasons (S): Static, (A): Aggregated; *micro-level might be necessary **if distributions of predictions are compared

Table S2: Evaluation of network assignment packages on general model capabilities and practical features

	Static macro	**Dynamic macro**	**Dyn. meso/micro**
Robust and accountable	Yes but potential biased (S)	Sensitive	Stochastic*
Richness in analysis	Limited (S,A)	Moderate (A)	High
Computation times	Fast**	Slow	Slow***
Implementation, calibration, use & maintenance	Simple (S,A)	Moderate (A)	Involved
Flexibility and extendibility	Low	Moderate	High

Reasons (S): Static, (A): Aggregated; *single model runs not robust **slow if number of segments high ***micro-level may be too slow for large scenarios

Static assignment models are inadequate to calculate traffic flows and travel time in congested urban areas. Assuming instantaneous network flows, these models are not capable of accounting for spatiotemporal dynamics of traffic flow. Most static assignment models are based on volume-delay-functions (VDF) which predict travel time delays as an increasing function from traffic flow but independent of the traffic density (level of congestion). This makes travel times estimates in congested traffic conditions unreliably. The same applies to estimates of traffic flow, which come with the additional danger that the model may predict traffic flow beyond capacity, i.e. traffic assignment that is physically not possible. Another shortcoming of these models, especially severe in the context of urban areas, is that these models cannot capture congestion spill-backs. This makes the calculation of travel time and prediction of route choice for links upstream of bottlenecks biased.

For a strategic transport model, i.e. a model systems that couples a travel demand model with a traffic assignment (or traffic flow) model component, an obvious question relates therefore to if and how the static assignment component can be replaced with a dynamic one. Dynamic traffic assignment (DTA) models come in various resolutions and instances, reaching from (aggregated) macroscopic models to (fully disaggregated) micro-simulation models. The adequateness of possible couplings is strongly related to the data structures of the model components. A static/macroscopic travel demand model, as the Norwegian TraMod_by, produces OD-matrices which is a fit to static/macroscopic assignment models that produce inter-zonal travel cost matrices (as Emme or Cube Voyager). Data structures are not directly compatible, when coupling a static/macroscopic travel demand model with a dynamic meso/microscopic assignment model (e.g. coupling TraMod_by with Aimsun meso),. To achieve a technical coupling, methods to disaggregate demand (by exogenous data) are required and for the iterative process, the detailed measures of network performance must be aggregated again before they can feedback to the travel demand model. This will always come with information losses.

For strategic transport models, the questions about appropriate traffic assignment models is therefore inevitably connected to the question about appropriate travel demand models. The best fit to a dynamic meso/microscopic assignment model is a demand model that can fully utilize the dynamic and detailed network performance measure that it produces. The best travel demand models are therefore also dynamic and disaggregated. Activity-based demand models (ABDM) based on all-day trip (activity) lists come in mind. These models have a strong behavioural foundation and can be built on a synthetic population enabling a high degree of traveller's heterogeneity.

Our evaluation of traffic assignment models found that dynamic meso/micro models are most appropriate for all application purposes in congested urban areas. The biggest advantages are connected to the realistic modelling of congestion and the richness in analysis (allowing to aggregate results in any desirable way). Those models have some practical challenges/disadvantages. They require more detailed input data, are more demanding with respect to implementation, calibration and usage and set high requirements (expert knowledge) on the users.

The stochasticity of dynamic meso/micro models is argued to be conceptually favourable but it can involve some challenges in practical applications. In particular, stochasticity affects the prediction from a single model run such that distributions of predictions (rather than fixed point predictions) should be compared. This might be time-consuming in particular for cost-benefit analysis where many alternatives/scenarios need to be compared to each other.

MATSim, which has in Norway been prototypically implemented for the region of Trondheim, is a model system that can be used for dynamic and detailed traffic flow and (short-term) travel demand modelling (i.e. changes in mode-, departure time and route choice but not in destination choice and trip frequency). Its integrated approach avoids information losses and guarantees a one-to-one mapping of decision makers and vehicles. As the standard model in MATSim does not include trip generation and destination choice, it should be coupled with full-fletched ABDM or land use models such to make it applicable for long-term strategic transport modelling purposes.

As dynamic and meso/microscopic transport model systems are feasible and favourable, the choice of which type of strategic transport model to apply amounts to how much simplification one is willing to accept. Even if most (current) application purposes seemingly allow for simplifications (as arguable in ("standard") cost-benefit-analysis that only are meant to provide rough estimates of aggregated measures), pragmatic decisions for simple models put bounds on possible future developments. This is because it is virtually impossible to make a static model dynamic and ad-hoc modifications are likely to be insufficient to truly account for the dynamic nature of transportation processes.

All strategic transport model systems are very complicated and the knowhow of the users are essential for successful modelling and result interpretation. For a possible transition in Norway to more advanced models it is therefore inevitable to educate (potential) users in the theory and practice of these new methods; international collaborations are an effective mean towards this goal.

Sammendrag:

Vurdering av metoder for å beregne trafikkavvikling og reisetider i byområder med købelastning i strategiske transportmodeller

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Author(s): Stefan Flügel (TØI), Gunnar Flötteröd (KTH),Chi Kwan Kwong (TØI), Christian Steinsland (TØI)
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Transportprosesser, dvs. bevegelser av personer og gods i rom og tid, er i sin natur dynamiske. Valgene på etterspørselssiden gjøres i en dynamisk sammenheng ved å planlegge og utføre dagens aktiviteter til ønskelige klokkeslett. Nettverksforholdene (som representerer den kortsiktige tilbudssiden) avhenger av trafikkflyten som oppstår som følge av dynamiske interaksjoner av mange biler og den gitte infrastrukturen. Reisetidene i urbane områder kan variere betydelig over dagen grunnet kø som er avhengig av både menneskelig adferd (spesielt valg av transportmiddel, avreisetidspunkter og rute) og komplekse fysiske prosesser i nettverket.

Vår evaluering av metoder for trafikkavvikling beskriver dynamiske meso- eller mikromodeller som mest egnet for alle (vurderte) analysehensikter i købelastede byområder. De største fordelene er knyttet til en realistisk modellering av kø og bredden i analysemuligheter (muligheten til å aggregere resultater på alle ønskelige måter). Disse modellene har imidlertid noen utfordringer/ulemper i praksis. De krever mer detaljerte inndata, er mer krevende med hensyn på implementering, kalibrering og bruk og stiller høyere krav (ekspertkunnskap) på brukersiden.

Bakgrunn

Transportøkonomisk Institutt (TØI) og Gunnar Flötteröd fra KTH har på oppdrag fra Statens Vegvesen gjennomført prosjektet: «Vurdering av metoder for å beregne trafikkavvikling og reisetider i byområder med købelastning i strategiske transportmodeller». Prosjektet hadde til oppgave å

- Kartlegge metoder for å beregne trafikkavvikling og reisetider i byområder med købelastning i strategiske transportmodeller.
- Vurdere hvordan statiske og dynamiske modeller for å beregne trafikkavvikling og reisetider i byområder kan kombineres, og vurdere fordelene og ulempene ved en slik tilnærming.

Rapporten motiveres av at den statiske trafikkavviklingsmodellen i de norske regionale persontransportmodellene (RTM) ikke kan fange opp dynamisk kødanning, noe som kan føre til unøyaktige beregninger av reisetider og trafikkavvikling i købelastede byområder.

Strategiske transportmodeller

I tråd med prosjektets tittel beskriver og diskuterer vi metoder som er relevante for strategisk transportmodellering. Skillet mot taktiske og operative modeller er i form av planleggings- og managementperspektiv i bruk av modellene.

Strategiske transportmodeller har størst omfang, og disse brukes ofte for å analysere langsiktige konsekvenser i transportsystemet til en hel region eller nasjon. Et vesentlig element i disse modellene er at etterspørselssiden beregnes/predikeres i modellen (etterspørselen er endogen). Adferdselementer som tas med ved modellering av etterspørselen er reisefrekvens, destinasjonsvalg, reisemiddelvalg, valg av avreisetidspunkt (kun modellert i dynamiske modeller) og rutevalg.

I taktiske transportmodeller er etterspørselen delvis endogen (total antall reiser er ofte forhåndsbestemt) og disse modeller brukes gjerne for mer kortsiktige prognoser. I en operasjonell transportmodell er etterspørselen gitt (bortsett fra rutevalg i noen tilfelle), og disse modeller brukes for kortsiktig og detaljert trafikkavviklingsanalyse, vanligvis helt nede på vegstreknings- eller kryssnivå.

De fundamentale byggesteinene i en strategisk (eller taktisk) transportmodell er (i) en adferdsmodell for reiseetterspørsel, og (ii) en fysisk modell for nettverksstrømmer (trafikkflyt).

I klassiske transportmodeller er rutevalg en del av transportavviklingsmodellen (nettverksmodellen). Transportavviklingsmodellen tar (transportmiddelspesifikke) OD matriser som inndata (dvs. matriser som inneholder antall turer mellom hvert sonepar). og beregner (transportmiddelspesifikke) LoS matriser som utdata (dvs. matriser som inneholder egenskaper ved reisen som kostnad, ombordtid, tilbringertid, ventetid osv. mellom hvert sonepar). Etterspørselsmodellen tar LoS-matrisene som inndata og produserer OD-matriser.

I nyere agent-baserte etterspørselsmodeller (som MATsim) er rutevalg en del av etterspørselsmodellen. Det argumenteres for at det bedre skiller mellom adferds-modellering og fysisk trafikkflytmodellering. I slike modeller tar trafikkavviklingsmodellen, som da mer korrekt kalles for trafikkflytmodell, reisene til enkeltpersoner (agenter) som inndata og det produseres reisetider og kostnader på lenkenivå. Disse aggregeres deretter opp på et reisenivå (turnivå). Denne informasjonen brukes som inndata i en (agent-basert) etterspørselsmodell som igjen produserer reiser (turer) til agentene.

I begge tilfellene blir løsningen av modellsystemet funnet ved å bringe tilbudssiden (nettverket) og etterspørselssiden i en likevekt. Dette oppnås vanligvis ved å iterere mellom etterspørselsmodellen og trafikkavviklingsmodellen. Integreringen av alle modellkomponenter er vesentlig for strategiske transportmodeller, som krever at etterspørselssiden er følsom for forhold og endringer i nettverket.

Modellklassifisering

På generelt vis kan **transportmodeller** klassifiseres etter 1) hvordan de representerer tid (statiske eller dynamiske modeller), 2) modelloppløsningen (makro-, meso- eller mikromodeller), og 3) hvordan de håndterer usikkerhet i prosessene som modelleres (deterministiske eller stokastiske modeller).

Etterspørselsmodeller klassifiseres ytterligere i (a) hvordan de forklarer reisens opphav (soneattraksjons-baserte modeller eller aktivitetsbaserte modeller), (b) hvordan tidsmessig avhengighet mellom enkelte reiser er etablert (reise-basert, tur-basert, eller heldaglige modeller), og (c) hvordan heterogeniteten i reisebefolkningen er tatt hensyn til (segmenteringsmodeller og modeller basert på en syntetisk befolkning).

Trafikkavviklingsmodeller er en kombinasjon av en rutevalgsmodell og en trafikkflytmodell. Rutevalgsmodeller predikerer hvilken rute reisende vil ta gitt de forventete forholdene i nettverket. Trafikkflytmodeller predikerer forholdene i nettverket gitt alle rutevalgene.

I evalueringen av trafikkavviklingsmodeller undersøker vi de tre mest vanlige kombinasjonene

- Statisk, makroskopisk, deterministisk
    - Bilenes bevegelser er i form av aggregerte strømmer (makroskopisk).
    - Antar at den reisende velger ruten med lavest kostnad i modellen (deterministisk rutevalg).
    - Antar momentane nettverksstrømmer og beregner bare forsinkelse i reisetider, men ikke omfanget av og romlig utbredelse av kø. Reisetiden beregnes vanligvis som en stigende funksjon av trafikkmengde, som kan innebærer et trafikkstrømmen estimeres til et nivå som er fysisk umulig (statisk).
- Dynamisk, makroskopisk, deterministisk
    - Tilfører tidsmessig avhengighet i rutevalg og fanger opp den romlige, tidsmessige dynamikken i trafikkflyt; utleder forsinkelse gjennom å modellere kø eksplisitt (dynamisk).
- Dynamisk, mesoskopisk eller mikroskopisk, stokastisk
    - Definerer diskrete rutevalg for den enkelte reisende/kjøretøy (mikroskopisk rutevalg).
    - Antar at reisende velger ruten med lavest subjektiv kostnad. Usikkerheten rundt denne subjektive oppfatningen er representert ved at man åpner for valg av ruter som har høyere kostnad enn laveste kostnad som er definert i modellen (stokastisk rutevalg).
    - Representerer kjøretøy-kjøretøy og kjøretøy-infrastruktur interaksjoner på det enkelte kjøretøynivå (mikroskopisk trafikkflyt) eller aggregerer noen bevegelser innenfor en mikroskopisk modell, men lar den disaggregerte representasjonen av kjøretøyene være intakt (mesoskopisk trafikkflyt).

Kobling av etterspørsel- og trafikkavviklingsmodell

For en velfungerende kobling mellom en etterspørsels- og en trafikkavviklingsmodell er det viktig at dataene som gjensidig produseres og leses inn av hver modelldel, er kompatible med hverandre.

Den klassiske **representasjonen av etterspørselen** er gjennom **OD-matriser** oppdelt i geografiske soner. Hvert element i matrisen representerer antall reiser (per transportmiddel/segment) i en bestemt tidsperiode. Variasjon i etterspørsel over dagen er i så fall gjengitt med separate matriser. En annen type datastruktur er **reiselister** hvor enkeltreisene er oppgitt «etter hverandre», dvs. ikke i en matrisestruktur. I tillegg til opprinnelse/destinasjon (som kan rapporteres basert på et sonesystem eller med eksakte koordinater) føres vanligvis opp informasjon om avreisetidspunkt og forskjellig bakgrunnsinformasjon om reisende og kjøretøy. Denne datastrukturen er altså disaggregert og inneholder vanligvis mer informasjon enn den som er tilgjengelig ved bruk av OD-matriser. Reiselister kan lett aggregeres opp i (tidsavhengige) OD-matriser, men detaljert informasjon som reiselister kan inneholde («eksakte» koordinater, «eksakte» avreisetidspunkt og bakgrunnsvariabler) går vanligvis tapt i en slik aggregering. En skritt videre går **reisesekvenslistene** som presenterer heldaglige reiseplaner. En slik datastruktur kan bare brukes dersom både etterspørselsmodellen og nettverksmodellen er i stand til å håndtere reisesekvenser (mulig i dynamiske agent-baserte metoder som MATSim).

En viktig type inndata til etterspørselsmodellen er informasjon om forholdene i nettverket («nettverksdata»). Slik informasjon produseres i trafikkavviklingsmodellen (nettverksmodellen). Den klassiske representasjonen er i form av **LoS-matriser** oppdelt på et sonenivå. Disse matrisene angir gjennomsnittlige reisetider, kostnader osv. mellom soner i en gitt tidsperiode, ofte oppdelt etter transportmiddel og befolkningssegmenter. Datastrukturen for LoS-matrisene er av samme type som OD-matrisene. Variasjon i nettverksforholdene over dagen er gjengitt med separate matriser, f.eks. egne reisetidsmatriser for hhv lavtrafikk og høytrafikkperiode. Nesten all programvare for trafikkavvikling beregner **nettverksdata internt på lenkenivå**. Det er derfor mulig å rapportere nettverksdata mer disaggregert til etterspørselsmodellen. Hvorvidt dette er hensiktsmessig avhenger av i hvilken grad etterspørselsmodellen kan bruke slike disaggregerte data.

Hvis trafikkmodellen er i stand til å nettutlegge individuelle turer, blir det også mulig å skrive ut reisetider slik de faktisk ble opplevd (i simuleringen) av beslutningstakerne. Dette gjør det også mulig å vedlegge informasjon om de reisendes opplevde «stop-and-go» trafikk.

Tabell S1 gir en oversikt forskjellige koblinger.

Tabell S1: Kobling av modeller med ulik tidsrepresentasjon og oppløsning

		Trafikkavviklingsmodell		
		Statisk makro	**Dynamisk makro**	**Dynamisk meso/mikro**
Etterspørselsmodell	**Statisk makro**	Passe	Kan være tilstrekkelig for å studere dynamikken i nettverket i peak-perioder men dynamiske nettverksdata brukes ikke i etterspørselsmodellen	Kan være tilstrekkelig for å studere dynamikken i nettverket i peak-perioder men dynamiske nettverksdata brukes ikke i etterspørselsmodellen
	Dynamisk makro	Lider av forenklet representasjon av kø	Passe	Passe
	Dynamisk mikro	Lider av forenklet representasjon av kø. Kan lide av grovkornet representasjon av reisendes heterogenitet i nettverket	Kan lide av grovkornet representasjon av reisendes heterogenitet i nettverket	Passe (om etterspørsel er representert i reiselistene)

Kobling mellom en statisk og makroskopisk etterspørselsmodell og en statisk og makroskopisk trafikkavviklingsmodell er uproblematisk og relativt enkelt (den forhåndsbestemte tidsperioden bør samsvare). Det samme gjelder dynamiske makromodeller. Her er (de tidsavhengige) OD-matrisene og LoS-matrisene typisk inndelt i mindre tidsperioder og leses inn som sekvens (ikke separat som i statiske modeller). Kobling mellom en dynamisk mikroskopisk etterspørselsmodell og en dynamisk meso- eller mikroskopisk trafikkavviklingsmodell passer også. Her er det nødvendig at etterspørselen er presentert med reiselistene (som i agentbaserte modeller). I en slik tilnærming kan beslutninger for de reisende direkte knyttes til forventede/opplevde nettverksforhold på individnivå. I alle andre typer koblinger diskutert i tabell S1, vil en slik en-til-en kobling mellom beslutningstakerne på etterspørselssiden og kjøretøyene på nettverkssiden ikke være mulig å gjennomføre.

Når modellenes håndtering av tid og/eller oppløsning ikke er i samsvar, så må det disaggregeres på den ene siden av koblingen og aggregeres på den andre. Pga. den manglende informasjonen fra selve modellen må det disaggregeres med ekstern informasjon som kan inneholde en viss skeivhet. Når det skal aggregeres (over tid og/eller over beslutningstakere), går vanligvis mye av den disaggregerte datainformasjonen tapt.

For eksempel vil en kobling mellom en dynamisk og mikroskopisk etterspørselsmodell og en statisk makroskopisk trafikkavviklingsmodell innebære at etterspørselen (vanligvis i form av reiselister) må aggregeres opp i et sonematrisesystem som gjelder for et bestemt tidsrom. Mye av den detaljerte informasjon vil gå tapt med dette. Hvis den statiske nettverksmodellen kun rapporterer LoS-matriser (på sonenivå og ikke lenkenivå), må denne informasjonen disaggregeres igjen (på enkeltreisende-nivå) før den kan brukes i etterspørselsmodellen. Den mikroskopiske etterspørselsmodellen vil i denne type kobling ofte lide av for grov nettverksinformasjon og svak modellering av kø i en statisk nettverksmodell.

Kobling mellom en statisk og makroskopisk etterspørselsmodell og en dynamisk og meso/mikroskopisk trafikkavviklingsmodell kan være hensiktsmessig hvis man vil studere dynamikken i nettverket i peak-perioder (rush). Etterspørselen må her disaggregeres ved bruk av ekstern datainformasjon (reisedata, trafikktellinger) og/eller basert på antakelser. Trafikkavviklingsmodellen vil da beregne tidsavhengig nettverksinformasjon, f.eks. reisetiden på en gitt lenke på et gitt tidspunkt på dagen. Denne informasjonen må dog aggregeres igjen før den kan bli brukt i beregning av en makroskopisk etterspørselsmodell. Statisk etterspørselsmodellering betyr også at den dynamiske informasjonen som ligger i nettverksdata ikke kan brukes fullt ut.

Vurdering av metoder for å beregne trafikkavvikling i kø-belastete byer

Tabell S2 og S3 sammenfatter evalueringen av typer trafikkavviklingsmodeller for henholdsvis analysehensikter og praktiske kriterier.

Tabell S2. Evaluering av trafikkavviklingsmodeller for forskjellige analysehensikter

	Statisk makro	**Dynamisk makro**	**Dynamisk meso/mikro**
Kø-reduserende tiltak	Utilstrekkelig (S)	Tilstrekkelig	Tilstrekkelig
ITS	Utilstrekkelig (S,A)	Mindreverdig (A)	Tilstrekkelig*
Transportetterspørsels-regulering	Mindreverdig (A)	Akseptabelt	Tilstrekkelig
Vinner/taper analyser	Utilstrekkelig (A)	Mindreverdig (A)	Tilstrekkelig
Vanlig Nytte-kostnads beregning (enhetspriser)	Tilstrekkelig hvis købelastning lav	Tilstrekkelig	Tilstrekkelig **

Årsak: (S)-Statisk, (A)-Aggregert; *mikro-nivå kan være nødvendig, **hvis fordelinger av prediksjoner er sammenlignet

Tabell S3: Evaluering av trafikkavviklingsmodeller for generelle modellegenskaper

	Statisk makro	**Dynamisk makro**	**Dynamisk meso/mikro**
Robust og etterprøvbar	Ja, men muligens skeiv (S)	Følsom	Stokastisk*
Bredde i analysemuligheter	Begrenset (S,A)	Moderat (A)	Høy
Beregningstid	Rask**	Langsom	Langsom***
Implementering, kalibrering, bruk & vedlikehold	Enkelt (S,A)	Moderat (A)	Krevende
Fleksibilitet og mulighet for utvidelse	Lav	Moderat	Høy

Årsak: (S)-Statisk, (A)-Aggregert; *enkelte modellkjøringer ikke robuste, **langsom hvis antall segmenter er høy, ***mikro-nivå kan være for langsomt for store nettverk.

Hvis man vil predikere effekten av et tiltak for å redusere kø (som kapasitetsutbygning), trenger man en modell som fanger opp den romlige og tidsmessige dynamikken i køen. Så godt som alle modeller som kan dette, er også dynamiske. Statiske modeller er vurdert som tilstrekkelig bare hvis omfanget av kø er lavt.

Når man vil predikere effekten av intelligente transportsystemer (sanntidsinformasjon, trafikavhengige fartsgrenser osv.), er det ofte nødvendig at man i tillegg har en detaljert fremstilling av kjøretøytyper, kjøretøyutstyr eller egenskaper til sjåfører/passasjerer. Mange slike tiltak vil også kreve en fremstilling av kjøretøy og infrastruktur som går ned til et nivå med detaljerte kjøretøybevegelser. Derfor krever ITS-analyser en disaggregert (minst meso- om ikke mikroskopisk) representasjon av trafikkflyten.

Transportetterspørselsregulering erkjenner at effektiviteten av tiltak på tilbudssiden (kapasitetsutbygning, ITS) er begrenset. Etterspørselsregulering tar sikte på å påvirke reisevaner på en måte som fører til en generell bedring av ytelsen i transportsystemet. Ofte vil det kreve en tilstrekkelig grad av realisme i adferdsmodelleringen. To viktige aspekter er (i) det faktum at de forskjellige turer utført av en enkelt reisende er forbundet med hverandre på en ganske komplisert måte og (ii) at de forskjellige reisende kan respondere svært ulikt på samme tiltak. Aspekt (i) krever en dynamisk adferdsmodell, og aspekt (ii) krever en disaggregert adferdsmodell. Aktivitetsbasert etterspørselsmodellering (ABDM) oppfyller disse kravene og er derfor regnet som den mest dekkende tilnærmingen i sammenheng med etterspørselsregulerende tiltak. ABDM passer best sammen med en dynamisk og disaggregert trafikkavviklingsmodell i et strategisk modellsystem.

Det samme gjelder vinner/taper-analyser. Når man skal analysere effekten et gitt tiltak har på velferden til individer, er det viktig å representere de heterogene og komplekse sammenhengene mellom sosio-demografi og mobilitet på en tilstrekkelig realistisk måte. Igjen virker en disaggregert adferdsmodell for transportetterspørsel å være best. Hvis adferdsmodellen er basert på en syntetisk befolking (som i de fleste aktivitetsbaserte modeller), har man en stor fordel sammenlignet med segmentbaserte etterspørselsmodeller på matriseform: En syntetisk befolkning krever ingen a prior aggregering. Det betyr at man kan beregne sammendragsstatistikker over vilkårlige undergrupper av etterspørselen etter at modellen har blitt evaluert. Diskusjonen gjelder også nyttekostnadsanalyser som tar hensyn til heterogenitet av brukerne (for eksempel ved å ta med inntektsforskjeller).

Behovet for disaggregerte etterspørselsmodeller er noe lavere for «vanlige» **nyttekostnadsanalyser som bruker enhetspriser** for forbedringer i transport (f.eks. bruker samme tidsverdi for reisetidsbesparelser i et gitt transportmiddel). En makroskopisk modelltilnærming synes tilstrekkelig for dette formålet, så lenge den kan gi nøyaktige aggregerte estimater (f. eks. nettotidsbesparelse). Siden de fleste makroskopiske modeller er statiske, er beregning av reisetider i købelastede områder imidlertid grov og unøyaktig. En annet ulempe med statiske modeller (basert på volume-delayfunksjoner) er at de ikke uten videre kan skille mellom trafikk i kø og i fri fart. Denne informasjonen kan imidlertid være viktig for en samfunnsøkonomisk vurdering fordi reisetidsbesparelser i kø er verdsatt høyere enn besparelsene i fri fart. En dynamisk og meso-/mikroskopisk trafikkavviklingsmodell er naturligvis den beste tilnærmingen for å gi nødvendig informasjon til å skille mellom reisetidsbesparelser i køtrafikk og fri fart.

Spesielt for nyttekostnadsanalyser hvor man direkte sammenligner scenarier, er det viktig at modellresultatene kan ansees som robuste. **Robusthet** er tett knyttet til hvordan usikkerheten (stokastikken) tas med i modellen. Makroskopiske modeller som i all hovedsak er deterministiske, forutsier ingen usikkerhet i de endogene prosesser som beskrives av modellen. Usikkerhet i prediksjoner er i så fall bare uttrykt ved usikkerhet i eksogene inndata (befolkningsvekst, bensinpriser osv.). Meso- eller mikroskopiske modeller er stokastiske. Dette innebærer at enkelte modellkjøringer med identiske inndata fører til forskjellige modellresultater. For scenariosammenligning bør det derfor gjøres flere modellkjøringer og fordeling over prediksjoner skal være utgangspunkt for evaluering. Dette kan være tidskrevende, men anses som den mest korrekte måten å vurdere komplekse systemer på (for hvilke det ikke finnes «perfekte» modeller).

Etterprøvbarhet av modeller er også en viktig egenskap. For å oppfylle denne egenskapen bør modellen være transparent og konseptuelt forståelig. Mikroskopiske simuleringer forsøker å etterligne virkelige prosesser, og fremstår dermed intuitive. På den annen side gjør det relativt store antall finkornede prosesser det vanskelig å intuitivt forstå de detaljerte årsak-virkningsforhold. Den iboende stokastikken ved meso-/mikro-simuleringer krever også noe statistisk skolering for kunne håndtere den tilfredsstillende. Det motsatte utsagnet er sant for makroskopiske simuleringer: Deres typiske matematiske problemformulering er ganske vanskelig å forstå, men når det er forstått kan man avlede relativt klart de underliggende årsak-virkningsmekanismer. Den ofte (men ikke alltid) garantert unike likevektsløsningen av makroskopiske modeller kan anses som en praktisk fordel som letter tolkningen når man sammenligner scenarier. Men samtidig kommer også risikoen for at man ignorerer andre løsninger av systemet som kan være like gyldige. Stokastiske modeller (på korrekt vis) gir mulighet for ulike systemløsninger.

Siden hver aggregering inneholder et informasjonstap og begrenser analysemulighetene, tilbyr mikromodeller den største **bredden i analysemuligheter** og makroskopiske modeller den minste bredden.

Modellens **beregningstid** kan variere betydelig for ulike metoder, og ansees som en viktig faktor i praksis. I utgangspunktet bruker dynamiske metoder lenger tid enn statiske modeller. En sammenligning mellom aggregerte modeller (segmenterte makromodeller som løses i matematiske programmer) og disaggregerte modeller (meso/mikro modeller som løses ved simulering av individer) avhenger sterkt av hvor mye heterogenitet man vil fange opp. En ikke-segmentert makromodell tar ikke lang tid å kjøre gjennom, men beregningstiden stiger (omtrent lineært) med antall segmenter. RTM som kan inneholde flere hundre segmenter, kan derfor ta ganske lang tid. Simuleringsmodeller med en gitt syntetisk populasjon har en konstant beregningstid uavhengig av hvor mange bakgrunnsvariabler man tilordner beslutningstakerne eller kjøretøyene.

Dynamiske modeller er mer krevende enn statiske modeller når det gjelder **implementering, kalibrering og bruk**. De er basert på tidsavhengige inndata og krever kalibrering av parametere som er avhengig av sine dynamiske mekanismer. De krever også en forståelse av disse mekanismene fra brukerne.

Modellens egenskaper **«fleksibilitet og utvidelsesmuligheter»** refererer til muligheten for å oppdatere modellsystemet i tråd med fremtidige behov. Dette er viktig fordi "levetiden" til et strategisk transportmodellsystem kan være flere tiår, noe som gjør spontane investeringer i helt nye modellsystemer vanskelig. Her bør det understrekes at det er svært vanskelig/umulig å snu et statisk modellsystem til et dynamisk modellsystem eller å snu et makroskopisk modellsystem til et meso-/mikroskopisk modellsystem.

Vurdert over alle de omtalte kriterier, så anbefales en meso/mikroskopisk modell for trafikkavvikling gitt at man har tilstrekkelige ressurser med tanke på økonomiske rammer, tid og kapasitet, samt tilfredsstillende tilgang til data. Det er naturligvis også avgjørende å ha fagfolk med tilstrekkelig kunnskap tilgjengelig. Spørsmålet om mikroskopisk versus mesoskopisk handler om hvilke krav som stilles til detaljeringsnivå på nettverket/trafikkflyt og hvilke beregningstider man er villig til å akseptere. For de fleste strategiske planleggingsformål virker mesoskopiske trafikkmodeller å gi tilstrekkelig detaljert informasjon, og disse er i tillegg i stand til å gi akseptable beregningstider selv for svært store scenarier (opp til 10 millioner biler).

Muligheter for Norske modeller

Rapporten beskriver også mulig modellutvikling for noen «norske» modeller. Fire forskjellige steg av ulikt omfang er kort diskutert.

- **Beholde opplegget med statisk avvikling** i RTM (TraMod_by koblet med Cube Voyager) med sikte på å bruke en finere inndeling av tidsperioder. Dette motiveres av at nåværende inndeling i fire perioder muligens ikke gir tilstrekkelig informasjon om reisetidsvariasjon over en dag. En turgenereringsmodell som kan produsere turer på time-nivå med formål å iterere mellom nettverks- og etterspørselsmodell per time kunne tenkes. Imidlertid setter den statiske naturen sterke restriksjoner på hvor presis en slik modell kan bli.

- **Koble TraMod_by med dynamisk avviklingsverktøy (Aimsun Meso).** En slik re-kobling virker teknisk mulig og vil forbedre beregningen av LoS-data (spesielt kjøretidene). Ulike datastrukturer er imidlertid en utfordring og en slik prosedyre vil innebære informasjonstap blant annet fordi den dynamiske nettverksinformasjon ikke kan brukes fullt ut i TraMod_by.

- **Implementering av MATSim standardmodell (som taktisk modell).** TØI har forsøksvis bygget en MATSim modell for Trondheimsregionen. Flere elementer ved modellen bør forbedres og utvides (veikapasitetsvalidering, simulering av kollektivtransport bl. annet). I så fall vil man få en modell for dynamiske analyser på nettverket og kortsiktige etterspørselsendringer. Den kunne bl. annet brukes for å validere reisetider/trafikkavvikling estimert i RTM. Gitt tilgjengelig inndata kan modellen relativt lett implementeres for andre regioner i Norge.

- **Bygge en state-of-the-art strategisk transportmodell.** Som ideelt modelloppsett for strategiske analyser kunne man tenke seg å implementere en aktivitetsbasert etterspørselsmodell basert på en syntetisk befolkning. En slik etterspørselsmodell kan da bli koblet opp mot en dynamisk og meso/mikroskopisk trafikkavviklingsmodell. Den modulære strukturen til MATSim vil kunne brukes som koblingsverktøy også dersom man senere ønsker å implementere en trafikkavviklingsmodell som er enda mer detaljert enn den som brukes i standard MATSim.

De fire mulige aktivitetene som er beskrevet utelukker ikke hverandre og det kan tenkes at man kan jobbe parallelt med disse. Den fjerde aktiviteten vil være et langsiktig forskningsprosjekt, mens de andre aktivitetene burde være mulige å gjennomføre på relativt kort tid gitt at ressurser og fagfolk kan samles.

Oppsummering

Statiske trafikkavviklingsmodeller (nettverksmodeller) er utilstrekkelige for å beregne trafikkstrømmer og reisetid i købelastede byområder. Disse modellene forutsier momentane nettverksstrømmer, og kan dermed ikke fange opp de tidsmessige og romlige dynamikkene av trafikkflyten. De fleste statiske modeller er basert på volum-delayfunksjoner (VDF) som predikerer reisetidsforsinkelser som en stigende funksjon av trafikkmengde, men uavhengig av trafikktettheten (omfanget av køen). Dette gjør estimater av reisetider i køtrafikk unøyaktige. Det samme gjelder estimater for trafikkstrømmer. VDF-baserte modeller kan predikere trafikkstrømmer som overstiger gatenes fysiske kapasitet. En annen svakhet forbundet ved statiske modeller, som er spesielt alvorlig i sammenheng med urbane områder, er at disse modellene ikke kan fange opp tilbakevirkning av flaskehalser til andre gater. Dette gjør beregning av reisetid og prediksjon av veivalg for oppstrømlenker som er berørt av flaskehalser, unøyaktig.

Et opplagt spørsmål til en strategisk transportmodell, altså et modellsystem som kobler en transportetterspørselsmodell med en nettverksmodell/trafikkavviklings-modell, er om og eventuelt hvordan en statisk nettverksmodell kan erstattes med en dynamisk trafikkavviklingsmodell. Dynamiske trafikkavviklingsmodeller finnes i ulike oppløsninger og versjoner; fra (aggregerte) makroskopiske modeller til (fullt disaggregerte) mikrosimuleringsmodeller. Hvilke koblinger som er tilstrekkelige er sterkt knyttet til datastrukturen til ulike modellkomponenter. En statisk/ makroskopisk etterspørselsmodell (f. eks. TraMod_by) produserer OD-matriser som er naturlige komponenter i statiske/makroskopiske nettverksmodeller (f. eks EMME, Cube Voyager) som produserer LoS-matriser på samme sonenivå. Hvis man kobler en statisk/makroskopisk etterspørselsmodell med en dynamisk meso- eller mikroskopisk modell (f.eks. kobling av TraMod_by med Aimsun meso) er datastrukturene ikke direkte kompatible. For å oppnå en slik teknisk kobling trengs det metoder for å disaggregere etterspørselen basert på eksogene data. For å få den iterative prosessen til å gå opp må også de detaljerte beregningene av reisetiden og andre nettverksforhold fra trafikkavviklingsmodellen aggregeres på et sonenivå før de kan brukes i den aggregerte etterspørselsmodellen. Dette vil alltid innebære noe informasjonstap.

For strategiske transportmodeller er derfor spørsmålet om hva som er en aktuell trafikkavviklingsmodell sterkt koblet til spørsmålet om hva som er hensiktsmessige reiseetterspørselsmodeller. Til en dynamisk meso/mikroskopisk trafikkavviklingsmodell passer det best med en etterspørselsmodell som kan utnytte den dynamiske og detaljerte nettverksinformasjonen som produseres. De beste transportetterspørselsmodellene er derfor også dynamiske og disaggregerte. Aktivitetsbaserte etterspørselsmodeller (ABDM) basert på heldags reise/aktivitetsplaner er aktuelle for det formål. Disse modellene har et sterkere fundament i adferdsmodelleringen, og kan bygges på en syntetisk befolkning slik at man i stor grad får fanget opp de reisendes heterogenitet.

Vår evaluering av metoder for trafikkavvikling beskriver dynamiske meso- eller mikromodeller som mest egnet for alle (vurderte) analysehensikter i købelastede byområder. De største fordelene er knytet til en realistisk modellering av kø og bredden i analysemuligheter (muligheten til å aggregere resultater på alle ønskelige måter). Disse modellene har imidlertid noen utfordringer/ulemper i praksis. De krever mer detaljerte inndata, er mer krevende med hensyn på implementering, kalibrering og bruk og stiller høyere krav (ekspertkunnskap) på brukersiden.

Stokastikk i dynamiske meso/mikro-modeller er beskrevet som konseptuelt fordelaktig, men det innebærer også noen utfordringer ved praktiske anvendelser. Stokastikk gjør at hver enkelt modellkjøring kan gi forskjellig resultat. Derfor bør fordelinger av prediksjoner (snarere enn faste punktestimater) sammenlignes. Dette kan være tidkrevende, særlig for analyser hvor mange alternativer/scenarioer skal sammenlignes med hverandre.

Uansett type er alle strategiske transportmodellsystemer svært kompliserte. Det gjør at brukerkompetanse blir en avgjørende faktor. For en (mulig) overgang i Norge til dynamiske modeller er det derfor uunngåelig å måtte utdanne (potensielle) brukere i teori og praksis knyttet til de nye metodene. Internasjonalt samarbeid er en effektiv måte å nå dette målet på.

1 Background

The Institute of Transport Economics (TØI) and Associate Professor Gunnar Flötteröd from KTH's Department for Transport Science had been commissioned by the Norwegian Road Administration to

- Review and compare different methods for calculating traffic assignment and travel times in congested urban areas with strategic transport models
- Discuss how static [travel demand] and dynamic [traffic assignment] models can be combined and to evaluate the advantages and disadvantages of such approaches

1.1 Scope of report

The financial budget of the project does not allow for runs/tests of existing models or implementation of new models. Thus, the working method of the report is limited to literature reviews and comparative analysis of relevant models and methodological approaches.

The report discusses and evaluates general models and methods of demonstrated practical relevance but will not go into details of advantages and disadvantages of specific models and traffic assignment packages. The exception is the RTM model (the main strategic transport model in Norway, Madslien et al. 2005, Rekdal et al 2012) and a prototype of a MATSim model implemented for the Trondheim region (Flügel and Kern, 2014; Bockemühl, 2014). For these two specific models, we will briefly discuss the current state of practice and sketch upon possible improvements and further developments.

As the focus of the report is on traffic assignment model appropriate for strategic transport planning, we do not concentrate on traffic assignment models with exogenous (=predefined) travel demand as "one-shot" micro-simulation models typically applied to operational models. For the same reason, purely sequential coupling (without feedbacks from the traffic assignment model to the travel demand model) is not described in details in this report. In the Norwegian case such a sequential coupling correspondents to the approach where estimated OD-matrices from TraMod_by (the latest version of the demand model in RTM) are used as (exogenous) input data in the dynamic traffic assignment model Aimsun meso (see SINTEF, 2013a for a description). We will briefly elaborate on how Aimsun meso could be (re-)coupled with TraMod_by to yield an integrated model system (section 6.2.).

We explicitly do not cover possible couplings between land use models and travel demand models. The Norwegian Road administration has - parallel to this work - commissioned a project where these kind of couplings will be investigated (Hanson et al 2014). We also will not discuss coupling with car-ownership models, which sometimes are part of transport model systems.

The presentation in this report is mostly framed around private road traffic. We will not cover travel demand models for freight transport (e.g. how the demand for trucks is generated). Different vehicle types (trucks versus small cars) will however be an issue in discussion of appropriate traffic assignment models. We do not explicitly discuss the assignment for public transport (PT) on tracks (metro, train). However, the general discussion about methods is to a large degree transferable to PT on tracks.

1.2 Content and structure of report

The reminder of the report is structured as follows.

Section 2 introduces strategic transport models.

Section 3 classifies different methods to transport models in general (3.1), travel demand models (3.2.) and traffic assignment model (3.3.).

Section 4 discusses data structures relevant for the coupling of demand and assignment models (4.1) and discusses then the adequateness of couplings with different representation of time (4.2), different resolution (4.3) and different representation of uncertainty (4.4). Subsection 4.5 describes the general workings of the RTM model system and MATSim and briefly reports on recent experience of couplings approaches in Sweden.

Section 5 evaluates general types of traffic assignment models (static macro, dynamic macro and dynamic meso/micro) based on possible application purposes (5.1) and general model capabilities and practical features (5.2.). Subsection 5.3 summaries and synthetises the evaluation.

Section 6 sketches upon some possible development regarding the static RTM model (6.1.) a coupling between TraMod_by and Aimsun meso (6.2.) and MATSim in Norway (6.3).

Section 7 concludes.

Figure 1 gives an overview over methods discussed in this report. The numbers in parenthesis indicate the related subsections in the report.

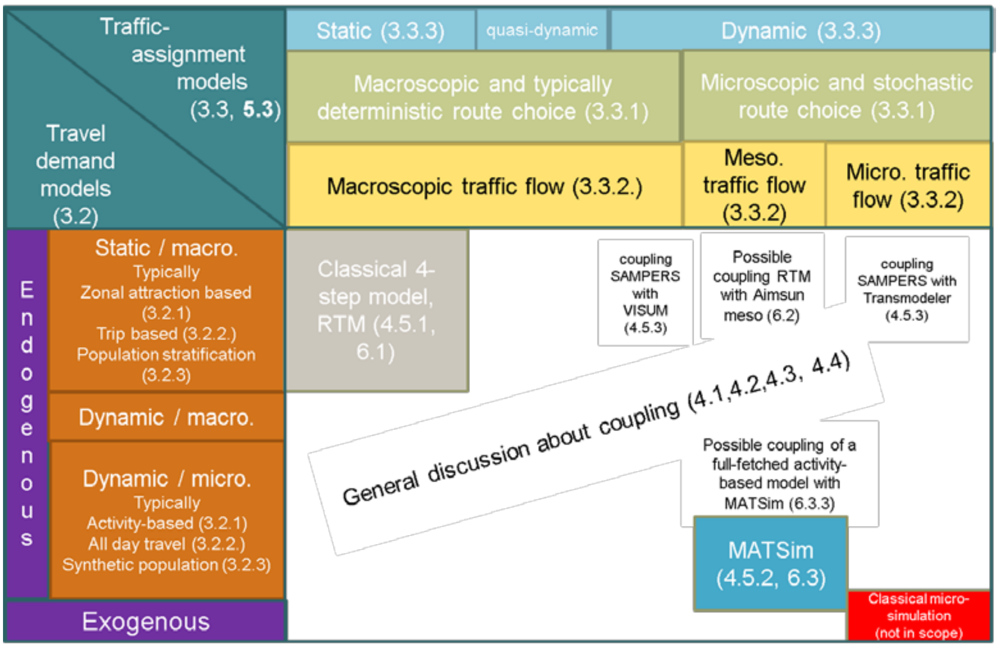

Figure 1: Overview over general methods and main transport models discussed in report

2 Strategic transport models

2.1 Definition and distinction to tactical- and operational models

As title of the report indicates, we describe and discuss methods relevant for strategic transport modelling. The distinction towards tactical and operational models is in terms of the planning-management perspective met by different transport model systems (Ortuzar and Willumsen,2011, page 13).

Strategic transport models have the largest scope and are often concerned with system-wide and long-term impacts. An essential element in these models is that the demand side is an endogenous element of the model, meaning that the demand is not pre-defined but predicted by the model. Choice elements of the demand include trip frequency, destination choice, travel mode choice, departure time choice (in dynamic models) and route choice. It can also include residential choice and location choice of firms but this information may come from a separated land-use model. Strategic transport models are most frequently used for general forecasts and to analyse the impact of bigger transport planning projects (e.g. building new roads, airports or transit connections, major changes in the pricing schemes as city/nation-wide road tolls and so on). Typically, these models are implemented on (at least) a regional level (if not on national or continental level). This is required to be able to model the effect of the complete (or a satisfactory large part of the) demand side. If only a city district is modelled one can, for instance, not take into account patterns in destination choice for traffic that goes through the city district.

Tactical transport models have a more narrow perspective than strategic models, and the planning horizon is normally shorter. The travel demand is only partially endogenous and the total amount of trips is often predefined (models may for example include a travel mode choice element, but no trip frequency and destination choice component). Tactical transport models seem most applicable when analysing optimization of the existing infrastructure (e.g. to decide if an existing lane should be dedicated to public busses, rather than the decision to build an entire new road - which would probably require a strategic transport model).

Operational transport models are used for short-term planning decisions. The travel demand (except route choice in some instances) is held exogenous. Typical applications are the traffic light switching system and other analysis that requires a rather detailed representation of the traffic network.

Working definitions:

Strategic transport model: M*odel with endogenous demand build for longer-term travel forecasts at (at least) a regional level.*

Tactical transport model: *Model with partially endogenous demand build for shorter-term travel forecasts at (at least) a city district level.*

Operational transport model: *Model with exogenous demand build for detailed traffic analysis typically at a level of a road section or crossing.*

It is not always easy to make a clear distinction between tactical and strategic transport models. Some models discussed in this report are on the borderline to tactical transport models. In particular, these are models where the choice of trip frequency and destination choice are not an integrated part of the standard model (as in MATSim).

2.2 Fundamental structure of strategic transport models

Strategic transport models predict travel demand and traffic conditions for certain future scenarios. The specification of scenarios includes socio-demographic projections, changes in land use, parameters having an impact on travel demand (such as economic development or fuel costs) and transport network developments (such as road constructions or public transport schedules).

The vast majority of strategic transport model systems rely on a spatial partitioning of the study region into zones. Two key data structures are defined in terms of a zonal system: Origin/destination (OD) matrices represent the number of trips made between each pair of zones. Travel time matrices (sometimes called "skim matrices") represent the travel time between each pair of zones. Both data structures may be time-dependent.

Besides (total) travel times, components of travel time (in-vehicle time, waiting time, access/egress time) and other travel characteristics such as monetary costs or frequency (number of departures a day) may be reported on a zonal level. Those data structures are often referred to as Level-of-Service matrices (LoS-matrices) or impedance matrices. LoS-matrices are typically reported for each transport mode separately (mode-specific LoS-matrices). By some functional relationship, the different elements may also be integrated in one index number per OD-pair (then typically called matrix of "generalized costs", or short "travel costs").

Working Definitions:

Zonal system: *Spatial partitioning of the study region.*

OD matrix: *Contains the number of trips between each pair of zones.*

Travel time matrix: *Contains the travel time between each pair of zones.*

LoS matrices or impedance matrices: *Contain the travel characteristics (monetary cost, in vehicle- time, access/egress time, waiting time, headway etc.) between each pair of zones.*

The fundamental building blocks of a strategic transport model are (i) a behavioural model of travel demand, and (ii) a physical model of network flows (as from now on also called (travel) supply model). Since these in turn often consist of multiple components, it is more adequate to talk of a strategic transport model system, which also emphasizes the fact that the interactions between different model components are an integral part of the strategic transport modelling problem.

The differentiation between travel demand/behaviour and physical network flows is not obvious. Separating strictly between "human behaviour" and "physical processes", one would have to include all behavioural processes that ultimately lead to detailed driving, walking, or other traveling actions in the travel demand and behaviour model, and one would have to include all physical processes in the urban system that respond to and interact with these actions (ranging from the physical reaction of a vehicle to acceleration and steering to the evolution of network-wide congestion patterns) on the physical network side. This, however, is hardly done due to the enormous modelling complexity that would be necessary to capture all processes that guide these human/physics interactions in detail.

Pragmatism hence dictates certain simplifications in the model system. The traditional way to structure strategic transport models is that of a four-step approach (Figure 2).

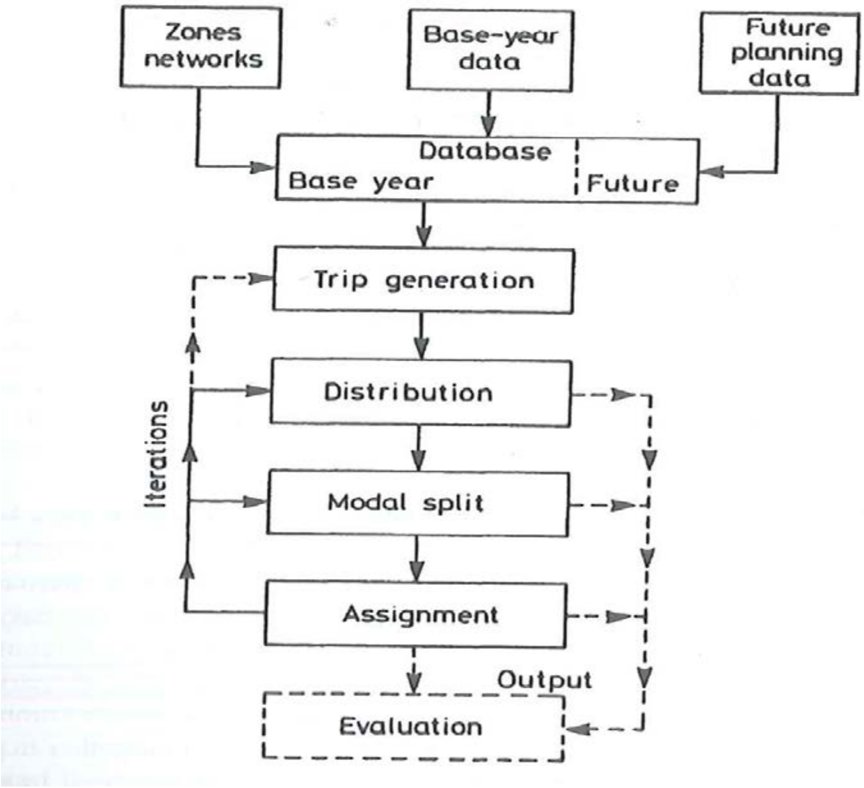

Figure 2. The classical four step model (source: Ortuzar and Willumsen (2011))

At the first step, trip generation (or trip frequency), the total amount of daily trips in the future year of interest, is estimated. These trips are distributed between origin and destination zones by a trip distribution model. In the third step, the resulting origin-destination (OD) matrix is further subdivided between transport modes by means of a mode split model. Finally, the mode-specific OD matrices, representing the travel demand, are input in the “network assignment package” that models the allocations of vehicles to road sections (network links). The assignment packages includes a route choice model with travel times as a central determinant. Travel times are traditionally calculated based on characteristics of the network (the physical environment as the length of links) and increases in travel times (delays) due to increases in traffic volumes.

That route choice and network flow propagation are modelled jointly in a traffic assignment package is not obvious and it is mainly due to the overwhelming success of the approach applied in four steps models. The simplification in the classical model structure can therefore be seen as historically grown based on what was adequate given the modelling capabilities and computational facilities of, say, the 1950s.

A more contemporary and more general way to look at the problem is as illustrated in Figure 3.

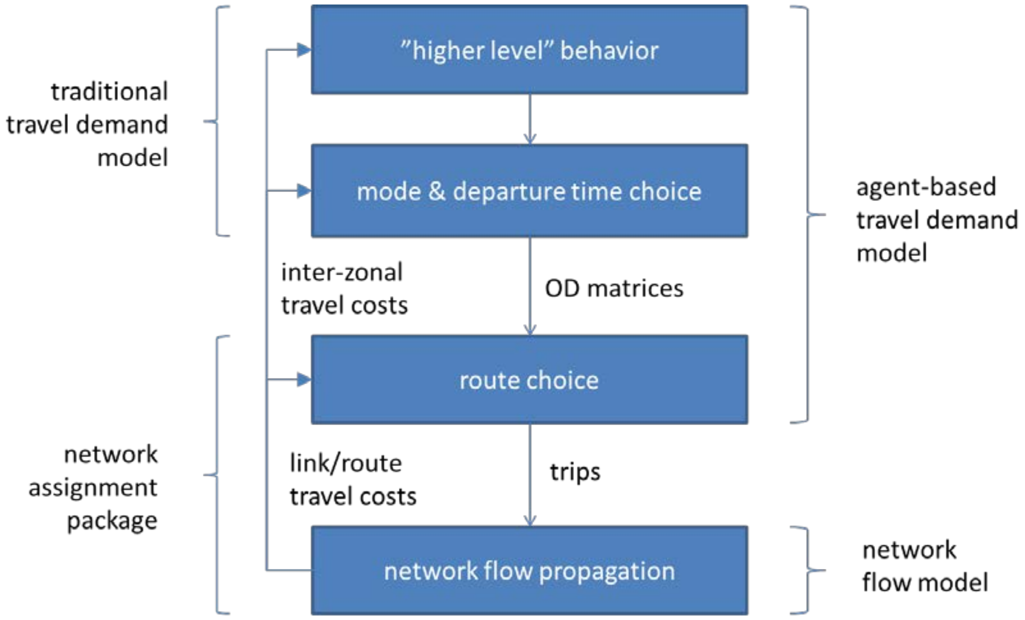

Figure 3: Strategic transport model system components (adopted from Berglund et al. (2014))

In terms of the traditional four-step model, what is labelled as "higher level" behaviour in this figure corresponds to stages one (trip generation) and two (trip distribution).[1] In terms of disaggregated activity-based demand model (see section 3.2.1), "higher level" behaviour corresponds to the choice of activities and corresponding locations. Mode choice corresponds to stage three of the four-step model, whereas departure time choice is often not explicitly modelled in this approach. Both choice dimensions are typically incorporated in activity-based demand model systems.

Route choice is an aspect of travel behaviour, such that its inclusion in a travel demand model appears more plausible from the behavioural modelling perspective. This is the case in the agent-based approach (for example as in MATSim; see section 4.6.2). Despite of its advantages, this approach is not yet widespread. Given that one of the main objective of this report is to investigate the feasibility of coupling a static demand model with a (dynamic) traffic assignment package, the more traditional perspective that includes route choice in a network assignment package is adopted in this report.

Travel behaviour that is more detailed than the route choice (car following, lane changing, and the like) is typically not included in the travel demand model but represented in the network flow model, both in traditional and agent-based models. The (generally accepted) justification of this simplification is that given that a traveller is able to follow a route, it does from a strategic planning perspective not matter what detailed driving actions were necessary to perform that trip.

The interactions between a traditional travel demand model and a network assignment package is most frequently in terms of OD matrices (output of the demand model, input to the network assignment) and travel time matrices (output of the network assignment, input to the travel demand model). More disaggregate data

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[1] For RTM it would also include the degree of access to a car which is modelled in an additional model component. RTM might therefore be described as a 5-step model (see more in section 4.5.1.).

structures are possible in the traditional approach, and they are characteristic for the agent based approach. In any case, the solution of the models systems is found by bringing the demand and supply side in an equilibrium or a relaxing state. This is usually achieved by iterating between the different components of the model system. The integration of all model components is essential for strategic transport models, which require the demand side to be endogenous and sensitive to conditions and changes of the network.

Working Definitions:

Travel demand model: *A model system describing typically if, where, and by which mode people travel. It typically takes network-wide measures of travel cost and reachability as inputs and predicts trips origin/destination on a network.*

Network assignment package: *A model system of route choice and network flows that takes origin/destination trips on a network as inputs and predicts network flows and travel times.*

Transport model (system): *A mutually coupled system of a travel demand model and a network assignment package.*

2.3 Motivation for more advanced traffic assignment model

The static network assignment packages used in conjunction with traditional demand models are limited in various regards. These limitations also apply to the current Norwegian RTM model system. Without getting into details, a number of deficiencies are mentioned upfront in order to motivate this report.

No time. Static traffic assignment packages model do not represent time or temporal dependencies, they aim at capturing stationary conditions, typically representing peak hour traffic. This makes it impossible to capture temporal interdependencies in the network.

Inadequate modelling of congestion. Static traffic assignment packages cannot describe congestion, only delay. They cannot capture spill-back (spatial spread of congestion), and they incorrectly predict delay inside of bottlenecks instead of upstream of them.

Limited heterogeneity. Static traffic assignment packages distinguish different demand segments through at most a handful of OD matrices and typically do not distinguish different vehicle classes at all. Being unable to distinguish travellers and vehicles puts severe limitations on appraisal and equity analysis.

No stochasticity. Static traffic assignment packages attempt to capture average conditions but neither represents uncertainty in their predictions nor do they capture variability of network conditions and travel behaviour. The assessment of infrequent events such as network breakdowns becomes impossible.

3 Typology of transport model systems

3.1 General classification of transport models

This section classifies transport models in terms of how they represent time (Section 3.1.1), their resolution (Section 3.1.2), and how they deal with uncertainty (Section 3.1.3). This is a rather conceptual but important classification.

3.1.1 Static-, quasi-dynamic and dynamic transport models

This classification refers to the temporal dimension of the transport model.

Static transport models do not incorporate the notion of time. All represented processes are instantaneous. Events do not occur at particular points in time but are at most specified in terms of frequencies, in which case the model system can be interpreted as representing a particular time interval during which stationary conditions are assumed. Time-of-day variations can at most be captured in terms of independent model systems per time slice (for instance, one model representing morning and evening peak hour each plus one off-peak model).

Dynamic transport models explicitly account for the notion of time and the temporal interdependence of the processes included in the model system. On the travel demand side, this comprises the sequencing of activities and their annotation with a time structure. Dynamic network assignment packages account for the time-dependency of the number of vehicles starting in particular OD pairs on particular routes and model the time-dependent evolution of the resulting congestion and delay.

Quasi-dynamic transport models feature a simplified representation of time. Strictly speaking, every transport model simplifies time in one way or the other and hence all dynamic transport models would have to be labelled as quasi-dynamic. For the purposes of this report, a model is called quasi-dynamic if it represents dynamics by linking a set of static models per time slice through a simplified temporal coupling logic. An example of this would be the combination of a dynamic travel demand model with a number of static network assignment models per consecutive time slices.

Working definitions:

Static transport model: *A transport model that does not account for time and typically represents stationary conditions within a time-slice.*

Dynamic transport model: *A transport model that explicitly accounts for temporal effects in all transport processes it represents.*

Quasi-dynamic transport model: *A middle ground between static and dynamic models that uses a set of static models that are temporally linked in a simplified way.*

3.1.2 Macro-, meso-, and microscopic transport models

This classification is about the level of aggregation regarding decision makers, vehicles and elements of the network.

Microscopic transport models maintain the integrity of all entities throughout the modelling process. On the travel demand side, these entities are the behavioural travellers. On the network supply side, these entities are the physical representations of the travellers, including their transport means (vehicles, buses, trains …). This approach is sometimes also called "fully disaggregate", and its microscopic elements are labelled as "agents". Microscopic transport models are evaluated (used for predictions) by explicitly simulating the interactions of all entities they represent.

Macroscopic transport models are defined in terms of aggregate quantities. On the travel demand side, these comprise be (real-valued) trip-frequencies. In the network assignment package, this means that both route and link flows are continuous quantities. Macroscopic transport models are often specified in terms of system of equations, and their predictions are obtained by solving these systems through mathematical programming techniques.

Mesoscopic transport models are characterized by some kind of aggregation taking place within an otherwise microscopic model system. On the travel demand side, this could be the aggregation of the output of a disaggregate travel demand model into OD matrices. In the network assignment package, this could be the aggregation of individual car-following behaviour into link performance functions that simultaneously describe the movement of entire groups of vehicles. The solution of mesoscopic transport models typically relies on explicit process simulation.

Working definitions:

Microscopic transport model: *Maintains the integrity of all entities and is solved by explicit simulation of process interactions.*

Macroscopic transport model: *Represents travel demand and network flows as real-valued quantities and is solved as a mathematical program.*

Mesoscopic transport model: *A simplified microscopic model where some entities or process interactions are represented in aggregated terms.*

3.1.3 Deterministic- and stochastic transport models

This relates to the presence of stochasticity in the model system and its outputs. This goes beyond uncertainty of input variables (population growth, fuel prices developments) for which sensibility analyses should be performed with any model framework.

In a **deterministic transport model**, there are no random elements. Evaluating the model several times with identical input parameters yields identical output parameters. This "reproducibility" is often considered as desirable by practitioners but also implies that the model is unable to account for uncertainty in its predictions. Deterministic transport models are typically macroscopic and hence solved rather efficiently through mathematical programming techniques.

Stochastic transport models contain random elements. The motivation for this approach is typically that one is uncertain about how these processes are about to evolve in reality[2], and hence one represents this uncertainty through stochasticity. Stochastic transport models hence define a whole distribution of outputs given a fixed set of input parameters. These output distributions are typically too high-dimensional to be solved for by mathematical programming techniques. One then resorts to Monte Carlo simulation. This means that one first generates a number of realizations from the model system's output distribution and then computes statistics of interest from these realizations in hindsight (often, means and variances). Practically, stochastic transport models are micro- or mesoscopic, and one simulation run of the model corresponds to one realization of the underlying output distribution.

Working definitions:

Deterministic transport model: *A (typically macroscopic) model that does not account for uncertainty (imperfect modelling) and attempts to represent average conditions.*

Stochastic transport model: *A (typically micro- or mesoscopic) model that accounts for uncertainty (imperfect modelling) and yields a distribution of predictions.*

3.2 Travel demand models

Travel demand models predict the demand for mobility. This presentation focuses on models of the mobility demand of individual persons.

A minimalistic instance of a congestion-sensitive strategic travel demand model predicts how many individuals, possibly stratified by socio-economic groups, wish to travel on average by what mode (for instance car, public transport, other) between the zones of a study region, given inter-zonal travel impedances such as costs or travel times. This minimalistic model hence represents the decision to travel at all plus destination and mode choice, and its output is a set of OD matrices, one per demand segment and mode.

Travel demand models are subsequently classified by the way in which they explain the occurrence of travel (Section 3.2.1), the way in which they represent time and temporal dependencies (Section 3.2.2), and their representation of traveller heterogeneity (Section 3.2.3). This classification is made concrete in terms of two examples given in Section 3.2.4.

3.2.1 Explanation of the occurrence of travel

A first classification of travel demand models is based on their assumptions about the mechanisms leading to the occurrence of travel.

The traditional way to model the generation and spatial distribution of travel is based on **zonal attraction**. This is the case in the classical gravity models where the amount of trips between two zones is based on the "size" (a function of area,

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[2] A note regarding the interpretation of uncertainty: It is not possible to distinguish between (i) an event being truly random and (ii) one being unable to predict that event because of a lack of understanding of its mechanisms (Laplace and Dale, 1995). Given the vast complexity of real transport processes, which are shaped by the joint travel behaviour of many individuals, it is certainly adequate to postulate a lack of complete process understanding on the side of the modeller. If or if not there also is true stochasticity within the transport system is a question that does not need to be addressed for the purposes of this report. The notion of "stochasticity" is hence used as a synonym for "imperfect predictability from the modeler's perspective".

population, facilities etc.) of each zone and the "distance" between the zones (the actual distance or a function of inter-zonal travel impedance). This approach is most often structured in two stages: Its first step predicts trip productions and attractions as functions of zonal properties like number of households or work places present in the zone. Its second step then distributes trip productions to different zones based on the attraction of the destination-zone and the generalized cost of travel needed to get from one zone to another. The vast majority of zonal-attraction-based models are macroscopic and deterministic (Ortuzar and Willumsen, 2011).

The more recent **activity-based travel demand models** (ABDMs) are based on the behavioural assumption that travel is undertaken in order to perform activities in different locations. Examples: work at the office, shop at the mall, socialize at a café. These models hence predict activities and associated locations. Travel demand then results from activities being located outside of the individual's dwelling. Most activity-based models are microscopic and stochastic (Bowman and Ben-Akiva, 1996).

The first two stages in the **four-step model**, which is outlined in Section 2.2, are traditionally based on zonal attractions. There exists, however, a large number of improvements over the classical four-stage approach, in which stages one and two are modelled based on behavioural assumptions that move them somewhat closer to ABDMs. The regional transport model in Norway (RTM), for instance, is in its structure a classical four step model with a zonal system. However, parameters used in the first three steps are estimated from disaggregated travel survey data. Through a segmentation regarding trip purpose, it is acknowledged that parameters (affecting the attraction of a zone) may differ across activity types (a zone with a lot of hotel (working places) is more attractive for leisure (commuting) trips). Further, the second step (distribution) in RTM is modelled together with the third step (mode split) by means of a nested logit destination-mode choice model. See section 4.5.1 for more details (Rasouli and Timmermans, 2014).

Working definitions:

Zonal attraction-based travel demand model: *Represents travel in terms of inter-zonal flows that are functions of zonal size of and generalized travel cost between zones; the fundamental concept of four-step models.*

Activity-based travel demand model: *A behavioural representation of travel that acknowledges that travel demand is derived from activity demand.*

3.2.2 Representation of time and temporal dependencies

A second classification of travel demand models is based on their representation of time and temporal dependencies in the travel demand. For this purpose, it is instructive to first distinguish trip-based, tour-based, and all-day travel demand models.

Trip-based models approaches represent travel demand in terms of trips, which are annotated with an origin, a destination, a mode, and possibly additional trip attributes. **Tour-based models** represent travel demand in terms of trip sequences starting and ending at the same location. **All-day models** represent travel demand in terms of complete trip sequence for entire days.

While trips may or may not be annotated with starting times, it is difficult to imagine tours or all-day travel plans, both of which consist of trip sequences, without a time dimension. This is reflected by the fact that most **static travel demand** models are trip-based and most **dynamic travel demand models** are tour- or all-day travel plan based. While a continuum of intermediate approaches exists, it is again instructive to explain this classification comparing the four-step model to the activity-based approach.

Four-step models are traditionally static and trip-based. They consequently apply to a stationary analysis period, typically the morning or evening rush hour, for which they predict the rate at which individuals travel from each origin to each destination by each considered mode. While it is possible to model travel demand independently per time slice, it is not possible to establish a temporal interdependency between trips in different time slices.

Activity-based models are typically dynamic and tour- or all-day travel plan based. They hence predict trip sequences that have a temporal structure. The ability to link trips also ensures logical consistency between trips, for instance in that starting a second trip is only possible after the first trip is completed or in that driving to the shopping mall by car also requires using the same mode on the return trip.

Working definitions:

Trip-based travel demand models *operate based on independent trips between origins and destinations. Trips may be annotated with departure times or desired arrival times.*

Tour-based travel demand models *operate based on trip sequences that start and end at the same location. Trips comprising a tour naturally follow a temporal sequence that may be annotated with additional temporal information.*

All-day travel demand models *operate based on all-day trip sequences and include a time dimension.*

3.2.3 Representation of traveller heterogeneity

A third classification of travel demand models is based on their ability to account for heterogeneity in the traveller population (in particular their socio-demographics) when predicting travel demand. It turns out that this classification is strongly related to the choice of a microscopic vs. a macroscopic modelling approach.

Travellers are different in many ways – for instance age, gender, income, car ownership, marital status, ethnicity – and many of these dimensions may play a role when it comes to strategic planning that aims at, for instance, cost-benefit analysis or an equity assessment. The combinatorial complexity of adequately representing these dimensions has led to essentially two approaches.

The traditional approach is to perform a problem-specific **stratification into a limited number of population segments**. This inevitably comes with a certain aggregation bias, and it also requires performing the stratification before any analysis can be performed. This representation is typically chosen in conjunction with (static and macroscopic) four-step models, where trip production and attraction are then computed separately per population segment. It is, however, also possible to apply activity-based demand models per population stratum (Ortuzar and Willumsen, 2011; Ben-Akiva and Lerman, 1985).

A more recent approach is **population synthesis**. It samples synthetic individuals based on a mechanism that ensures that the resulting synthetic population is statistically consistent with the real population. Statistical consistency means here that all summary statistics available from the real traveller population are reproduced in the synthetic population; it does not mean that there is a one-to-one mapping between real and synthetic individuals. Synthetic populations are almost exclusively used in conjunction with ABDMs, which are then used to predict activity, location, and trip sequences for each individual (Müller and Axhausen, 2010; Farooq et al., 2013).

Working definitions:

Population stratification: *Representation of the traveller population in terms of a relatively small set of homogeneous subgroups.*

Synthetic population: *A set of synthetic individuals that is in all of its statistical properties consistent with the real population.*

3.2.4 Examples of practically relevant travel demand models

The spectrum of existing travel demand models is as broad as the processes these models attempt to capture are complex. For instance, there exists a continuum of models ranging from the (first three steps of the) classical four-step approach to fully dynamic and disaggregate model systems that are often based on highly developed discrete choice models (Vovsha et al., 2004; Rasouli and Timmermans, 2014).

The "classical" four-step model, as it is presented in standard transportation textbooks, is static, aggregate, deterministic, and trip-based. It is safe to label this simple representation of travel demand as a legacy model.

The travel demand model component of the Norwegian RTM is one of many further developments that are rooted in the classical four-step approach. It represents destination and mode choice (stage two and three) jointly through a discrete choice model. This goes beyond the four-step model in that (i) the model is rooted in behavioural considerations rather than in physically motivated trip distribution, principles and (ii) interdependencies between destination and mode choice are captured. For further details about RTM, see Section 4.5.1.

On the other end of the spectrum is DaySim[3] located, which is an example of a full-fledged ABDM. It has evolved over about two decades from seminal research into a freely available software package that is also extensively used in consultancy. The fully disaggregate DaySim model system comprises detailed submodels for population synthesis, mode choice, choice of intermediate stops, day pattern activity generation, time of day/activity scheduling, destination choice, and household auto availability (Bowman, 2012).

3.3 Traffic assignment models

The vast majority of traffic assignment packages take (time-dependent) OD matrices as inputs, equilibrate in one way or another route choice, and calculate (time-dependent) link flows, link travel times, and inter-zonal impedances. This review hence also concentrates on route choice being the sole dimension of travel behaviour. A few notable exceptions to this rule are presented at the very end of this section.

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[3] http://jbowman.net/

The two constituent building blocks of a network assignment package, a route choice model and a network flow model, are subsequently presented in Sections 3.3.1 and 3.3.2. Their combination into a network assignment model is described in Section 3.3.3 and exemplified in Section 3.3.4.

3.3.1 Route choice models

A route choice model requires at least an origin, a destination, and a set of route alternatives to choose from. The choice of a route follows more or less behavioural principles and is guided by the routes' properties, foremost cost in the form of (congestion-dependent) travel time (Prato, 2009).

The vast majority of **stochastic route choice models** can be phrased in terms of a discrete choice model. This is particularly convenient when integrating the route choice model into an "upstream" travel demand model system that is also based on discrete choice theory. Given a set of routes connecting an OD pair, a (typically congestion-dependent) utility is computed for each route. Often, random utility theory is deployed, where uncertainty in the modelling of utilities is reflected by modelling them as random quantities, resulting in a probabilistic choice distribution.

Deterministic route choice models essentially assume that utility is perfectly modelled and hence correspond broadly to a random utility model with vanishing stochasticity in the utility. [4]

Stochastic route choice models are generally considered to be more realistic than their deterministic counterparts, but they also are more difficult to specify and calibrate. Two problems stand out.

- The specification of the random component in the utility function depends in a rather complicated way on the overlap of routes. While the underlying modelling principles are well-understood, the specification of both realistic and operational models remains a challenge, in particular due to the typically combinatorial number of routes (Frejinger, 2007; Ben-Akiva et al., 2004).
- How to define the choice set is anything but clear, even though this can have a strong effect on the resulting route choice. The main difficulty here is that typical random utility models assign a positive choice probability to every route that is included in the choice set, but the size of this set needs to be limited again due to the combinatorial number of all possible routes (Flötteröd and Bierlaire, 2013; Frejinger and Bierlaire, 2010).

Working definitions:

Deterministic route choice models *assume that the trip-maker selects a path that has minimum cost as defined in the model.*

Stochastic route choice models *assume that the trip-maker selects a path of minimum subjective cost. The uncertainty about this subjective perception is represented by also allowing for the choice of routes that have higher than minimum cost in the model.*

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[4] However, subtle differences should be noted. The usual specification of a deterministic route choice model states that "no route with higher than minimal cost is used", whereas the limiting case of a stochastic route choice model where stochasticity in the utility approaches zero predicts more specifically a uniform choice distribution over all routes of minimum cost.

The differentiation between **static and dynamic route choice models** is rather straightforward, in that dynamic models evaluate route costs (and hence utilities) at particular points in time. One typically distinguishes between **reactive travel times** (deriving travel times from the instantaneous network conditions at the time of starting a trip) and **predictive travel times** (taking into account that the experienced network conditions depend on when a vehicle has reached a particular location in the network) (Barcelo, 2010).

Working definitions:

Static route choice models *do not account for time, neither when evaluating route costs nor when predicting route choice.*

Dynamic route choice models *account for the time-dependence of travel times and predict accordingly time-dependent route choice.*

Microscopic route choice models select an individual route per vehicle (and hence are able to account for vehicle and/or driver characteristics in the route choice). **Macroscopic route choice models** distribute vehicle flows deterministically across the routes – deterministic macroscopic route choice models concentrate the flows on routes of minimum cost, whereas stochastic macroscopic route choice models *deterministically* ensure that the share of vehicle flow on a route equals the probability of choosing that route (Watling and Hazelton, 2003). The notion of a **mesoscopic route choice model** is unusual; it would apply when vehicles are grouped into packets, for which a single common route is then selected.

Working definitions:

Microscopic route choice models *are defining discrete route choices "by individual".*

Macroscopic route choice models *are defining flow splits for a continuum of individuals.*

3.3.2 Network flow models

A minimalistic network flow model specification consists of (i) a topology where links are connected through nodes, (ii) a definition of flow entry and exit points, and (iii) some definition of how links perform under congestion.

Static network flow models assume that route flows propagate instantaneously through the network. The vast majority of these are based on volume-delay functions that compute link travel times from link flows. These models, although still widely applied, are inadequate to model congested conditions: they predict flows beyond capacity, they do not capture the spatial propagation of queues, and they implicitly assume that delay is experienced inside a bottleneck, not upstream of it. These deficiencies can be (but rarely are) corrected by modelling static conditions as the limiting (long-term) conditions of a dynamic model. In practice, static network flow models are virtually exclusively macroscopic and deterministic (Ortuzar and Willumsen, 2011).

Dynamic network flow models come in a variety of guises. Macroscopic instances are typically based on the Kinematic Wave Model, and specifically on the Cell-Transmission Model as its most popular numerical solution scheme. Simpler macroscopic flow models lack realism; more complex ("higher-order") models are typically considered too complex to be applied for network modelling. Microscopic instances move individual vehicles through detailed network geometries according to driving rules of car-following, lane changing, and gap acceptance. Mesoscopic instances trade precision for speed and often move groups of vehicles according to aggregate speed/density relationships but maintain the identifiability of individual vehicle units. Both microscopic and mesoscopic network flow models are usually stochastic, with the mesoscopic mechanisms often "averaging away" some of the stochasticity that is explicitly captured in microscopic driving rules (Barcelo, 2010; Hoogendoorn and Bovy, 2001).

Working definitions:

Static network flow models *assume instantaneous network flows and only approximate delay but no congestion.*

Dynamic network flow models *capture the spatio-temporal dynamics of traffic flow and derive delay from explicitly modelled congestion.*

Working definitions:

Microscopic network flow models *represent vehicle-vehicle and vehicle-infrastructure interactions at the level of individual vehicles.*

Mesoscopic network flow models *result from aggregating some laws of movement within a microscopic model while leaving the disaggregate vehicle representation intact.*

Macroscopic network flow models *represent vehicle movements in terms of continuum flows.*

3.3.3 Network assignment models

The main classification criterion here is time.

Combining a **static route choice model with a static network flow model** yields the typical static assignment package implementing the 4th stage of the four-step model. This class of models is typically macroscopic and deterministic. The interpretation of the solution algorithm is typically in terms of a mathematical program that aims at satisfying some equilibrium condition (Sheffi, 1985).

Combining a **dynamic route choice model with a dynamic network flow model** leads to what is commonly labelled as "dynamic traffic assignment" (DTA). Typical configurations are (i) macroscopic route choice and macroscopic network flows, (ii) microscopic route choice and meso- or microscopic network flows. The fully macroscopic approach is most often again tackled from the mathematical programming side, whereas the meso-/microscopic approach is more frequently taken from the heuristic perspective of explicitly emulating demand/supply interactions (although efforts exist to also introduce mathematical rigor into this process) (Barcelo, 2010; Nagel and Flötteröd, 2012; Peeta and Ziliaskopoulos, 2001).

Intermediate approaches exist that most often simplify the network flow dynamics in that they specify a number of in the first instance independent static assignment problems per time slice but then again introduce simplified dynamic coupling mechanisms that mimic the carry-over of vehicle queues from one time slice to the next (Bliemer et al 2013).

Working definitions:

Static traffic assignment model: *An assignment model that does not include the notion of time. Can be interpreted as representing stationary conditions. Typically applied to study peak hour traffic.*

Dynamic traffic assignment model: *An assignment model that explicitly includes the time dimension and captures inter-temporal dependencies*.

Quasi-dynamic traffic assignment model: *A set of static assignment models (per time slice) that are coupled through supplementary yet simplified dynamical expressions.*

Working definitions:

Microscopic traffic assignment model: *Models that predict the route choice and movement of individual vehicles.*

Mesoscopic traffic assignment model: *Mostly microscopic models that represent route choice and/or vehicle movement at the more aggregate level of vehicle groups.*

Macroscopic traffic assignment model: *Models where the traffic assignment is based on a continuum of vehicles and where vehicle dynamics are based on macroscopic flow principles.*

3.3.4 Examples of practically relevant network assignment packages

Frequently encountered combinations of the previously laid out dimensions are

- static, macroscopic, deterministic;
- dynamic, macroscopic, deterministic;
- dynamic, mesoscopic or microscopic, stochastic.

Many commercial network assignment packages come as parts of entire model suites, allowing the user to select between static and dynamic assignment models and/or between different resolutions (micro, meso, macro). Examples of such suites Vision Traffic Suite (PTV) [5], Cube (Citilabs) [6], Emme/Dynameq (Inro) [7] and Aimsun (TSS)[8], TransModeler (Caliper)[9].

The network assignment package of the Norwegian RTM model is a typical representative of a static and macroscopic approach. The commercial software Cube Voyager is used. It takes as input mode-specific OD matrices and returns inter-zonal travel costs (LoS-matrices). Travel times are modelled through network delay functions. In order to reflect within-day dynamics, the model is evaluated independently for different time slices.

The network assignment module of the MATSim multi-agent transport simulation[10] is dynamic and mesoscopic. Time-of-day dependent route choice is performed by microscopically represented travellers. Network flow dynamics are represented mesoscopically, in that traffic flow dynamics along road segments are aggregately

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[5] http://vision-traffic.ptvgroup.com/en-us/products/

[6] http://citilabs.com/software/products/cube

[7] http://www.inro.ca/en/products/

[8] http://www.aimsun.com/wp/

[9] http://www.caliper.com/transmodeler/

[10] http://www.matsim.org/

approximated using principles borrowed from queueing systems (Charypar, 2008; Osorio and Flötteröd, forthcoming). More details about MATSim are provided in Sections 4.5.2 and 6.2.

Some microscopic network assignment packages include a mesoscopic mode, meaning that the user can select between a microscopic and a mesoscopic network assignment. Examples of these are Aimsun and Transmodeler. Some microscopic "assignment" packages focus exclusively on the network flow dynamics and consider route choice as exogenous. Examples of such packages are Paramics or Vissim, which focus strongly on local traffic dynamics, for instance at intersections or on freeway stretches that do not allow for a route choice. Such packages may allow for the insertion of a user-specified route choice model through a proprietary API (application programming interface).

4 Coupling of travel demand and traffic assignment models

A strategic transport model consists of two main building blocks: A travel demand model and a network assignment package. It has already been made clear in Section 2 that both components interact in that either of them provides input to the other: The travel demand predicted by the travel demand model enters the network assignment package, and the network performance measures predicted by the assignment package in turn enter the travel demand model. These interdependencies add a great deal of complexity to the model system as a whole.

The objective of the following presentation is to elaborate on if and how different types of travel demand models and network assignment packages can be integrated into one strategic transport model system. This depends on the properties of each component, the relevant dimensions of which have been laid out in Section 3. Strongly related to these model properties are the properties of the data moved back and forth between the model components. The size and complexity of the resulting model system also raises computational concerns, which may enforce otherwise undesirable simplifications.

Sections 4.1 presents the relevant data structures through which a travel demand model and a network assignment package may interact, drawing from Nagel and Flötteröd (2012). The following essential dimensions of their integration into one strategic transport model system are subsequently discussed: representation of time (Section 4.2), resolution (Section 4.3), and representation of uncertainty (Section 4.4), building on Flötteröd and Bierlaire (2012). The discussion is made concrete through the presentation of two real model systems in Section 4.5.

4.1 Relevant data structures

4.1.1 Representations of travel demand

Travel demand is the output of the travel demand model and the input of the network assignment package. One can distinguish two typical data structures.

Classically, travel demand is represented through **OD matrices**. These may be time-dependent, typically in the form of separate OD matrices per time slice. The pure trip count information contained in each of these matrices (per demand segment and/or time slice) can be annotated with additional demand parameters, such as socio-demographic summary statistics per OD matrix.

A more recent approach is to replace the aggregate OD matrix information by disaggregate **trip lists**, which contain one entry for each “one” in the OD matrix.

Given that OD matrices for large study regions contain many almost-zero entries,[11] this approach may have computational advantages. More importantly, it offers a higher resolution when representing time (which can be made a real-valued attribute of the trip) and the possibility to annotate trips with arbitrary demand information, for instance in terms of driver income (relevant at the route choice level) or vehicle type (important for instance in the presence of vehicle-specific tolls or network access constraints).

One step further goes the use of trip-sequence lists, which represent **all-day travel plans**. However, this data structure is only of use if both the travel demand model and the network assignment package are capable of handling trip sequences, which essentially makes them unique to the agent-based approach, which is illustrated in terms of the MATSim model system in Section 4.5.2.

4.1.2 Representations of network impedances

Network performance (impedance) is the output of the network assignment package and the input of the travel demand model.

Classically, network performance is represented through **inter-zonal impedance matrices** (also called "level-of-service matrices" or "skim matrices"). These may be time-dependent, typically by defining separate matrices per time slice. Matrices may also be distinguished by impedance measure: Apart from travel time, monetary costs such as tolls come to mind. Impedance matrices per travel demand segment are also thinkable, for instance in the presence of vehicle-specific tolls or speed limits. This representation has the same structure as an OD-matrix-based travel demand representation.

Virtually every network assignment package internally also computes network performance measures at the link level (in particular travel times), which can be output directly, leaving the (possible) aggregation step into inter-zonal impedances to the travel demand model. This has advantages in terms of spatial resolution, for instance when it comes to the modelling of intra-zonal travel.

If the network assignment package is capable of assigning individual trips, it also becomes possible to write out the travel times that were actually experienced by individual trip makers. This further enables the annotation of trips with additional information (such as "experienced stop-and-go traffic"). However, this representation of network performance constitutes an incomplete counterpart to the trip-list based travel demand representation unless all possible paths considered by a trip maker are evaluated, including those alternatives that were never chosen in the assignment package. A computational limitation to the trip-based approach results therefore from the fact that the number of routes through a network grows combinatorially with the number of links in that network, making it applicable only in conjunction with rather constrained route choice sets.

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[11] Both the number of trips and the number of zones grow roughly linearly with the network size. The number of zone-to-zone relations hence grows quadratically with the network size, and the ratio of number of trips to number of zone-to-zone relations sinks anti-proportionally with the network size.

4.2 Coupling models with different representations of time

Coupling a static travel demand model to a static network assignment package is (in terms of time representation) straightforward, given that both models refer to the same analysis period. The same holds in principle to the coupling of a dynamic travel demand model to a dynamic network assignment package, although here the need to maintain consistent time resolutions (meaning typically consistent time bin sizes) comes in as an additional complexity. Both OD matrices and trip lists are possible demand data structures in either setting, and both inter-zonal impedance matrices and link/trip travel time lists can be used to represent network performance.

Coupling a static travel demand model to a dynamic network assignment package can make sense if the static travel demand represents a peak hour and the off-peak traffic is rather low. In this configuration, the static travel demand is spread out over the analysis period (uniformly in the simplest case). This still allows to capture the spatiotemporal dynamics of congestion build-up and dissipation in the dynamic assignment package. A series of independent static demand predictions per time slice could be used to create a (possibly even all-day) temporal demand profile, allowing also for an all-day analysis within the dynamic network assignment package. The realism of this approach is limited by the independence assumption across time slices in the travel demand model and (hence) does not make full use of the network performance information provided by the dynamic assignment package. Travel demand can again be represented by OD matrices or trip lists, and both inter-zonal impedance matrices and link/trip travel time lists are feasible to describe network performance.

Coupling a dynamic travel demand model to a static traffic assignment package is an in practice rather frequent approach, arguably due to the historical role and great market penetration of static assignment packages. See, for instance, the transport modeling suites referred to in Section 3.3.4. In this configuration, the time-dependent demand is discretized into time slices and the average demand per time slice is fed into separate static assignment packages. Often, only one or two time slices representing the peak hour(s) are considered. This approach comes with all weaknesses of using static assignment packages, as enumerated in Section 3.3. Static assignment packages typically accept only OD matrices (and no trip lists) as inputs and output network performance measures in terms of inter-zonal impedance matrices and/or link travel times.

4.3 Coupling models with different resolutions

Coupling a macroscopic travel demand model to a macroscopic network assignment package, which have mutually consistent representations of travellers and network performance measures in terms of real-valued quantities, is rather straightforward. Data exchange is based on OD matrices as demand representations and inter-zonal travel time matrices or link travel times as descriptions of network performance. If the demand model is capable of producing separate OD matrices per demand segment and/or per mode, the network assignment package should be able to handle these different classes. Likewise, the different types of travel costs (time, monetary cost, summary representations in terms of (dis)utility) produced by the macroscopic network assignment package should be compatible to the network performance measures expected by the travel demand model.

Coupling a macroscopic travel demand model to a meso- or microscopic network assignment package requires disaggregating the travel demand before feeding it into the network assignment package. For this purpose, each OD matrix produced by the travel demand model is taken as a representation of the expected number of trip makers. Discrete trips, as needed by the meso- or microscopic assignment, are then created in a manner such that their number corresponds on average to what the OD matrix prescribes (e.g. by sampling or rounding). Often, this disaggregation step is performed by the network assignment package, which then accepts real-valued OD matrices as inputs. However, despite of the disaggregate representation of trip-makers at the network level, the resolution at which travel demand information can be attached to individuals is limited by the number of different (demand-class specific) OD matrices produced by the demand model. The representation of network performance measures is, on the other hand, typically unproblematic and based on impedance matrices or link-specific data.

Coupling a disaggregate travel demand model to a macroscopic network assignment package requires to aggregate the travel demand before feeding it into the network assignment package. The ability of macroscopic assignment packages to handle heterogeneous demand representations (in terms of many class-specific OD matrices) has computational limitations. This aggregation hence comes typically with information loss, in that no matter how rich the original output of the disaggregate travel demand model may be, it is aggregated rather coarsely. The representation of network performance measures is at the basic level of travel times and costs again rather unproblematic and based on impedance matrices or link-specific data. However, the resolution of subgroup-specific network performance measures that can be provided to the travel demand model is limited to the granularity at which the travel demand can be distinguished at the network level, i.e. depending on the number of different OD matrices used.

Coupling a disaggregate travel demand model to a meso- or microscopic network assignment package does, ideally, not require any intermediate aggregation of the travel demand: Every single trip of an individual in the travel demand model can be processed individually by the network assignment package. Socio-demographic information about the traveller is hence available at the network level. In the route choice model, this means that heterogeneous values of time and other person-specific attributes such as trip purpose or income can be accounted for. In the network flow model, the trip-maker's vehicle type is uniquely identified, meaning that vehicle-specific tolls or restrictions are experienced exactly by those individuals owning the respective vehicles. Further, information about the network experience of a traveller can, at least in principle, be made available to the travel demand model at the level of individual travellers.

A fully disaggregate transport model system hence appears to be able of avoiding any aggregation bias. This capability, however, can only be exploited if the representations of travel demand and network performance also maintain this level of resolution. The use of aggregate OD matrices to represent travel demand, although possible, is therefore not adequate. Such a configuration would require an (unnecessary) aggregation step of the disaggregate travel demand into one or several OD matrices, which then would (unnecessarily) have to be disaggregated again in the network assignment package. Trip lists, on the other hand, are an adequate travel demand data structure. Things are somewhat different when it comes to the representation of network performance, which defines the attributes of the behavioural alternatives in the travel demand model. Since person-specific information is available anyway in the (fully disaggregated) travel demand model, it is for many purposes sufficient to output only non-person specific information (in particular link travel times and costs).[12]

4.4 Coupling models with different representations of uncertainty

A more subtle but by no means irrelevant question is how to couple models with different representation of uncertainty. It is fair to say that this question is not yet fully addressed, even scientifically, which makes it even more important to at least create some awareness of its implications. This is the objective of this section.

If both the travel demand model and the network assignment package are deterministic, then the model system resulting from their combination is also deterministic.

As soon as one component in the model system is stochastic, the entire model system is stochastic. If, for instance, the travel demand model is stochastic but the network assignment package is deterministic, then the output of the network assignment package is only deterministic given a particular realization of the travel demand model's output – overall the network assignment package makes stochastic predictions due to the stochasticity of its inputs. A symmetric statement holds for the case of a deterministic travel demand model and a stochastic network assignment package.

Despite of the increasing acceptance of the fact that (adequately designed) stochastic model systems come with the advantage of representing modelling uncertainty and hence allow at least in principle to account for this uncertainty when using model systems for strategic planning, truly stochastic transport model systems have not yet entered general practice. A possible cause for this is that the presence of stochasticity in such model systems adds yet another level of complexity that may be seen more as a hindrance in the analysis than an added value. Another (arguably more rational) reason may be that either the demand model or the network assignment package expects input values representing average conditions: Discrete choice models typically expect the attributes of the alternatives (in particular travel times or inter-zonal impedances) to be expected values. OD-matrix based network assignment packages interpret these matrices as average trip levels per time slice. Identifying and adequately characterizing the effect of allowing for randomness in such parameters is more a research question than a matter of model application. Stochasticity in the demand model or the network assignment package may therefore be removed (typically by filtering or switching off random number generators) in an attempt to obtain an overall almost deterministic model system, the predictions of which may then be taken as average values.[13]

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[12] These observations make a strong case for moving the route choice model out of the assignment package and into the travel demand model, cf. Section 2: This information would naturally make all person-specific information available to the route choice model and would only leave the representation of the "physical environment" of the travellers to the network assignment package, which accordingly would be reduced to a representation of network flows. This is the approach of MATSim, as described in Section 4.5.2.

[13] One perspective on this approach is that it attempts to resolve problems that are a consequence of combining incompatible model system components (one providing stochastic outputs, the other expecting deterministic inputs). The closest to a coherent stochastic integration of all model system

Table 1 summarizes the discussion so far, focussing on representation of time and model resolution. Note that this table judge not the capabilities of the model system as a whole (this will be the topic of Section 5) but only the adequacy of combining different types of travel demand models and network assignment packages.

Table 1: Coupling models with different time representations and resolutions.

		Traffic assignment package		
		Static macro	**Dynamic macro**	**Dynamic meso/micro**
Travel demand model	**Static macro**	Adequate.	Adequate for studying peak-period congestion dynamics, but dynamic network performance data cannot be utilized by demand model.	Adequate for studying peak-period congestion dynamics, but dynamic network performance data cannot be utilized by demand model.
	Dynami	Suffers from simplistic representation of congestion.	Adequate.	Adequate.
	Dynamic	Suffers from simplistic representation of congestion. May suffer from coarse representation of traveler heterogeneity in the network.	May suffer from coarse representation of traveler heterogeneity in the network.	Adequate if demand is represented through trip lists.

Appendix A2 provides further intuition through an example.

4.5 Examples of practically relevant transport model systems

This section illustrates the coupling of a travel demand model and a traffic assignment package into a strategic transport model in terms of two concrete examples. Section 4.5.1 outlines the official Norwegian transport model for regional transport (RTM; Madslien et al., 2005; Rekdal et al., 2012) and Section 4.5.2 describes the MATSim transport model, which has been implemented as a prototype model for the Trondheim region (Flügel and Kern, 2014; Bockemühl, 2014). Additionally, Section 4.5.3 summarizes some relevant insights gained in a related research project that was commissioned by the Swedish Road Administration (Trafikverket) (Berglund et al, 2014).

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components appears to be the agent-based approach, due to its structure: Instead of combining "layers" of models for different purposes, it inserts individual models of travel behaviour into one mobility model of the physical environment. The interface for an exchange of stochastic data is here given by a model of "agent learning" that attempts to mimic how real travellers cope with an unpredictable environment.

4.5.1 The Norwegian Regional Transport Model

RTM ("Regional Transport Modell") is the official Norwegian transport model system for personal traffic on a regional level.

By the working definitions that were established in Section 3, RTM can be classified as static, macroscopic and deterministic. Its static and macroscopic demand model component "TraMod_by" is trip-based and relies on zonal attraction in combination with a population stratification. Its network assignment package, Cube Voyager[14], is also static and macroscopic. The model system is solved numerically (without simulation).

RTM can be considered as an "enhanced" four-step model which includes an additional mode component on car accessibility and where step 2 (trip distribution) and 3 (mode choice) are represented jointly in one discrete choice model. Figure 4 illustrates its model structure and indicates the typical data flows.

As a first step RTM stratifies the population of each zone. Besides gender, age group and family type, the degree of access to a car constitutes a segment. It is predicted taking into account the LoS from the traffic assignment model (car ownership and access is relatively low in zones with relative bad LoS for cars).

The subsequent trip generation model predicts the number of trips by means of a Poisson model. A multinomial logit model splits the demand into trip purposes. Parameters underlying these models are estimated on disaggregated travel survey data (NTS). In application, the model multiplies the estimated trip number per person by the zonal population data per segment that comes from the upstream segmentation model.

The number of trips per day can be optionally subdivided into four time periods. Typically, the following periods are applied: a morning rush from 6-9 o'clock, and off-peak day period from 9-15 o'clock, an afternoon rush from 15-18 o'clock and an off-peak evening/night period for the rest of the day. Total demand is distributed across time periods proportionally to exogenously defined shares, which are derived from the national travel survey (NTS).

The third component in RTM is the model for mode and destination choice (MD-model). It is a nested logit model, which calculates the distribution of total trips into destination zones and transport modes. Destination choice is based on zonal attractions and modal split is based on LoS-data calculated in the traffic assignment model (in the first iteration step free-flow LoS is used). The LoS per transport mode are computed separately for rush periods and for off-peak periods. Similar to the trip generation model, parameters in the MD-model was originally estimated on disaggregated choice data based on NTS but is applied in conjunction with a zonal system by multiplying predicted individual-level choice probabilities by the number of trips from each zone. This results in OD-matrices per time period, transport mode and trip purpose. An additional time choice model allows optionally for a further refinement of the temporal structure of the travel demand (Rekdal et al 2012; see also section 6.1.).

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[14] Cube Voyager is similar to the EMME packages. EMME is still used for traffic assignment with RTM by some consultants in Norway.

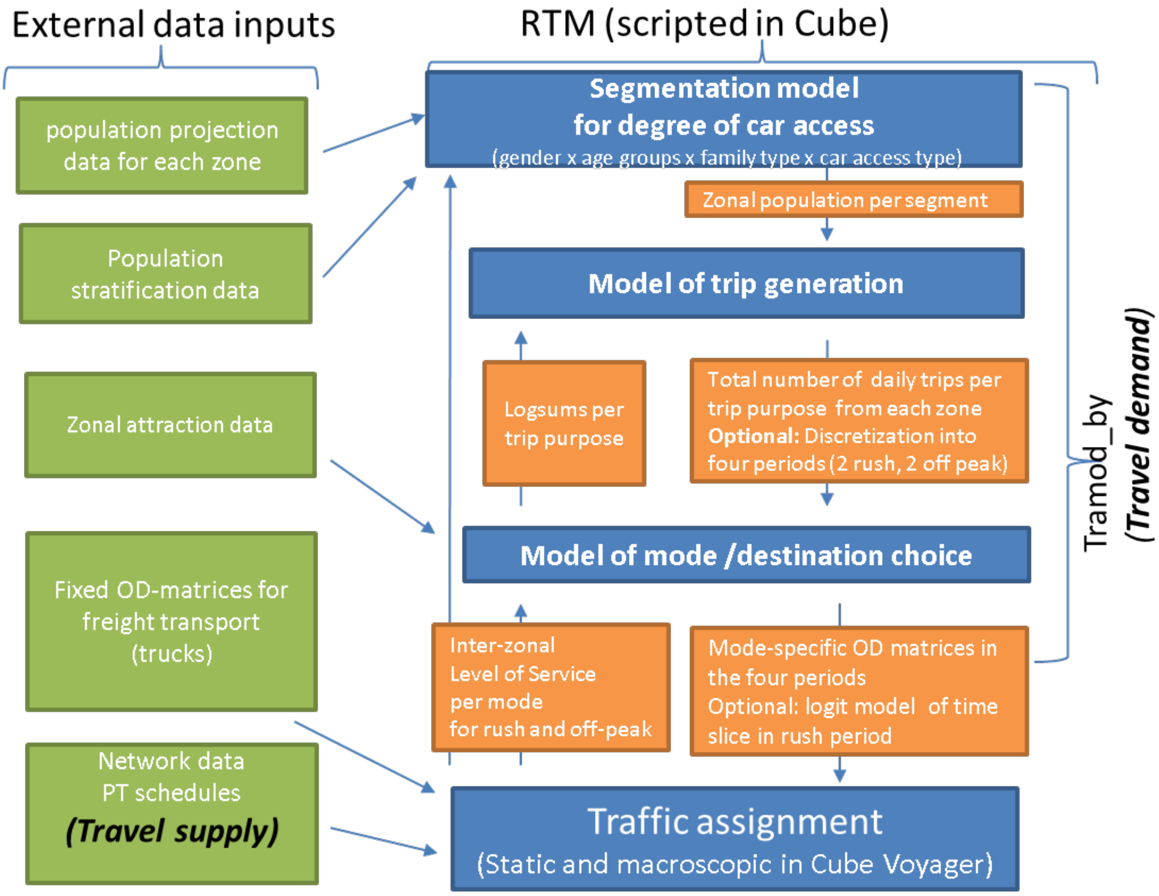

Figure 4: Structure and data flow of the RTM model

RTM's static traffic assignment model Cube Voyager, in which the road and PT network data are encoded, takes these OD-matrices as input data. In addition, fixed OD matrices for trucks are included. The assignment model produces updated (delay-sensitive) travel times, which the model reports on an inter-zonal level back to the MD-model. Travel times is aggregated again into just two sets (rush and off-peak) and the MD-model calculates utility functions for these two periods.

Through logsums (accessibility measures), there is also a feedback to the trip frequency model. This takes into account that trip frequency increases (reduces) when travel times/LoS is improved (worsened).

Iterating between the travel demand model and network assignment package may lead to an equilibrium state of mutual consistency between travel demand and network supply. Since RTM is a deterministic model system, this equilibrium is a "point solution". The model system output is typically reported in terms of OD-matrices, LoS-variables (among travel times) and network conditions (e.g. link volumes).

4.5.2 MATSim – Multi-agent transport simulation

MATSim ("Multi-agent transport simulation toolkit"; Raney and Nagel, 2006; Nagel and Flötteröd, 2012; Flötteröd et al., 2012) provides a framework for large-scale agent–based traffic simulations. By the working definitions that were established in Section 3, MATSim is a dynamic, microscopic and stochastic transport model.

As a first step, a synthetic population has to be generated; different techniques are available for this purpose, depending on data availability. Exact coordinates are given to locations for home, work, leisure, etc., as MATSim does not work with zones.

MATSim's travel demand model is fully disaggregated (individual agent make up a synthetic population) and activity-based. However, MATSim focuses, at least in its standard form, on travel behaviour being comprised of mode, time choice, and (multi-modal) route choice. The occurrence of demand, including destination choice, is modelled by optional "upstream" model components. Some of these are fully integrated with MATSim (e.g., Horni, 2013); others have been developed independently (Bekhor and Dobler, 2011; Ziemke et al., 2015). The travel demand model produces all-day travel/activity plans.

MATSim does not have a separate network assignment package. Instead, it includes route choice in the travel demand model, which requires modelling the "physical environment" of the agents merely in terms of a network flow simulation. This simulation is mesoscopic, in that it maintains the integrity of all travellers but represents their mobility by somewhat aggregate laws of motion[15]; this approximation is essential when it comes to the simulation of large urban areas or even whole countries (Cetin and Nagel, 2003). The network flow simulation reports not only time-dependent link travel times but also a detailed account of every single event having occurred in the network. The latter information is instrumental when it comes to linking travel experience to individuals in the synthetic population.

MATSim iterates between the travel demand model (including route choice) and the traffic flow model. Due to its disaggregate (agent-based) design, these iterations can be interpreted as mimicking a day-to-day learning process of individual travellers, where, in every simulated day,

1. each traveller selects a travel plan based on previous experience ("replanning");
2. all travellers execute their plans simultaneously in the physical model ("mobility simulation");
3. each traveller assesses the performance of the executed plan ("scoring").

This process is iterated until the system stabilizes (fluctuates only unsystematically from one iteration to the next), and the corresponding predictions are considered as representative for the long-term behaviour of a real transport system, for which similar behavioural adaptation processes are postulated.

Figur 5 outlines the MATSim model system. The "input" to the system consists of exogenous parameters (defining in particular the physical environment through a network and facilities) and the output of an upstream travel demand model ("initial plans"). MATSim then iterates through the replanning – mobility simulation – scoring steps until stationary of the simulation process is postulated and performance measures of interest are extracted.

A current status and possible developments of a MATSim model implemented for the Trondheim region is described in Section 6.3.1. Section 6.3.3 further describes the possibility to use MATSim as a platform to couple different types of travel demand and traffic assignment models.

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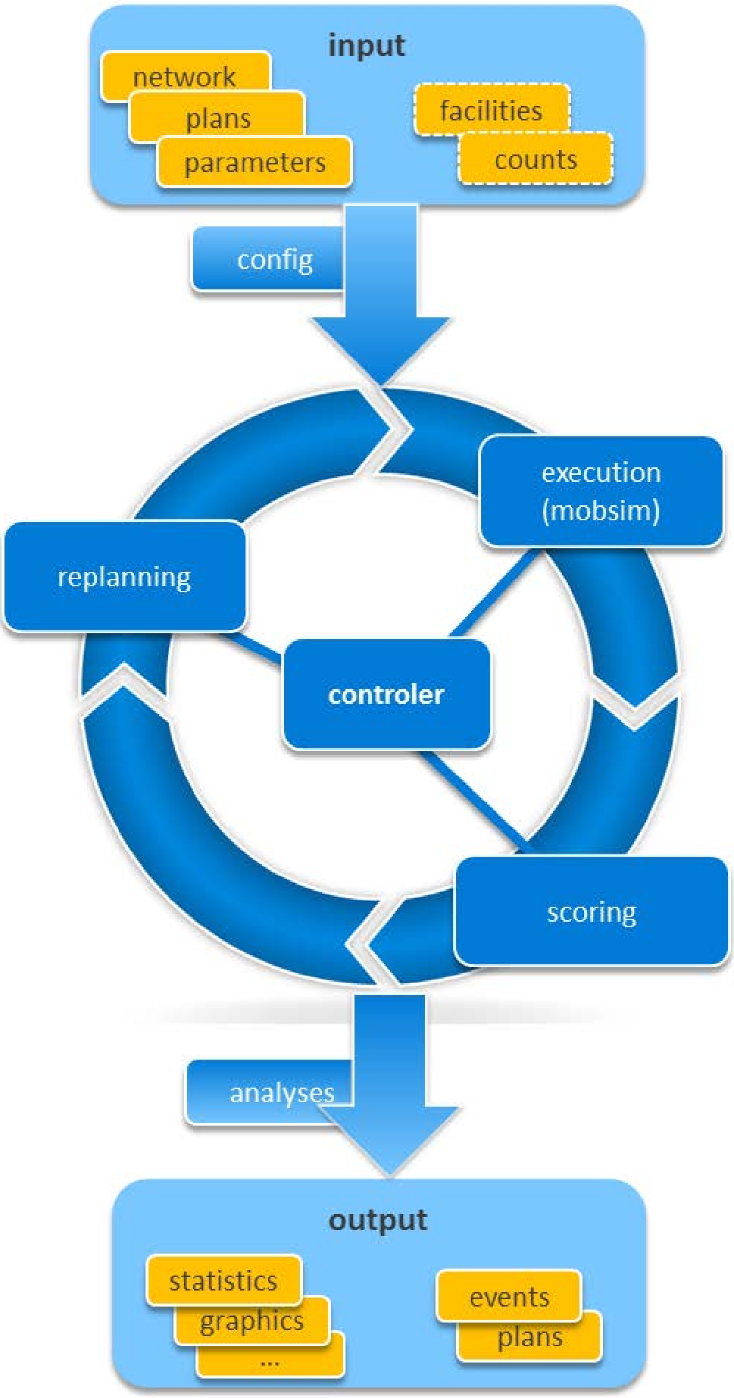
[15] For instance, not all vehicles are moved individually on a road stretch but (i) an empirical vehicle density is computed for that stretch, (ii) this density is inserted into a speed-density curve and an average speed is obtained, (iii) each vehicle is moved forward according to this average speed or a variation thereof.



Figur 5: MATSim model system

4.5.3 Recent experiences from a Swedish study

The Swedish Road administration has during the year 2013 commissioned the project IHOP in order to investigate possibilities to replace the static network assignment package EMME in its strategic transport model system by a network model that (i) captures spatial congestion and (ii) may also be dynamic (Berglund et al, 2014). The Swedish travel demand model SAMPERS is overall comparable to the Norwegian model, with a probably stronger rooting in (behavioural) discrete choice modeling. It is, however, not labelled as "activity-based" (Beser Hugosson and Algers, 2002).

The IHOP project prototypically integrated a simplified SAMPERS version (REGENT) with a macroscopic (Visum DUE) and a meso/microscopic (Transmodeler) dynamic network assignment package. The integration was realized through OD matrices (one demand segment, several time slices) and inter-zonal travel time matrices. Both integrations succeeded, with no network package turning out obviously superior. The discussion about how to develop this integration further, possibly also with alternative network assignment packages, is subject of an ongoing discussion (Berglund et al 2014).

A practically noteworthy observation made in the course of the project was that it is not obviously straightforward to integrate a network assignment package that was designed as commercial standalone software into a larger software framework. In particular, commercial software packages are "canned" in that their source code is not available. Minor modifications to the software that would have greatly simplified its integration could therefore not be performed but could only be submitted as "feature requests" to the developers of the commercial software product.

The IHOP report summarizes the positive experience in this project as follows (shortened and freely translated from Berglund et al 2014):

"[…] Examples of comparable international efforts are lacking, and the project has been challenging independently of this. […] The results of our tests are promising but not completely free of problems.

Dynamic network assignment packages have other requirements on the network data than static models. The tests we have performed show that with overall moderate efforts it was possible to obtain flow and travel time predictions that were mostly but not always in the right orders of magnitude. An operational full-scale implementation will require additional efforts, in particular for the encoding of traffic signals and the modeling of intersection delays. […].

Dynamic network assignment packages have higher computational requirements than static models, but the computational performance we have reached suggests that the computing time for a dynamic assignment [of Stockholm] can be brought down to around 24h. […] Dynamic models produce travel times per time interval. Depending on the length of the analysis period and the time resolution, the number of matrices can become very large. […] Our experiments show that the tested assignment softwares can read and write these matrices very effectively and without problems.

We could observe that the integration with a travel demand model yields a model system of demand/supply interactions that appeared to converge with both tested softwares. We can therefore state that the fundamental technical requirements for the replacement of a static by a dynamic assignment package are given."

5 Evaluation of methods for network assignment

The evaluation of a network assignment package is only possible with respect to a particular objective. This text hence first lays out possible strategic application contexts of network assignment packages in Section 5.1. The technical requirements that may arise from these applications are then presented in Section 5.2. Based on this, Section 5.3 finally recommends concrete network assignment package types for all identified application fields.

5.1 Possible application contexts of traffic assignment packages

Adopting the overall objective of supporting strategic transport planning, one can still face a number of different starting points when thinking about adequate traffic assignment packages.

Two important and interrelated application contexts at the network level need to be mentioned.

A first question relates to the (expected) level of congestion in the network. This is particularly important if one is interested in **studying the effect of congestion-mitigating measures** (road capacity expansions, the introduction of road pricing rings around the city center, the redirection of substantial traffic streams for instance from through-city-traffic onto bypasses). If congestion can be expected to be low then there is little added value in accounting for it in the model system. This in turn renders its detailed representation in the network assignment package unimportant. Given that without congestion there is only limited physical coupling between the network conditions of different time slices, a static network assignment package may be fully sufficient. If congestion cannot be expected to be negligible, a network assignment package that captures spatiotemporal congestion dynamics is needed. Virtually all packages that come with this capability are also dynamic.

Another question very related to the first one is if one intends to **study the effect of intelligent transportation systems (ITS)**. Since the introduction of such systems mostly comes with the intention to (also) provide congestion relief, the network assignment package again needs to be able to describe the build-up and dissipation of congestion. Beyond this, the benefits of ITS are strongly dependent on information availability (E.g.: Who receives the real-time congestion information?), technical equipment (Who will then follow a recommended path?), representation of time (Where are travellers in the very moment of an incident?), and individual properties (Who is willing and/or capable to at all react to a congestion warning?). Apart from time and congestion, a detailed representation of vehicle types, vehicle equipment, and drivers may become necessary. Further traffic control measures that fall under the umbrella of ITS are intelligent (traffic responsive) signals, the dynamic allocation of HOV (high-occupancy vehicle) lanes, and variable speed limits. Vehicle-to-vehicle and vehicle-to-infrastructure communication may also need to be accounted for. These measures require a representation of vehicles and infrastructure that goes down to the level of detailed vehicle movements and hence require a disaggregate (at least meso- if not microscopic) representation of network flows.

One may disregard the above considerations as being more a traffic engineering problem than one of strategic transport planning. However, it is conceivable that a strategic planning model should also be able to capture the long-term benefits of ITS measures.

When focusing on travel behaviour, two again interrelated and relevant application contexts require attention.

Travel demand management recognizes that the efficiency of supply-side measures (capacity improvements, ITS) is limited. Travel demand management hence aims at affecting travel behaviour in a way that leads to an overall improved system performance. Travel demand management may comprise campaigns to promote using public transport in order to reduce the number of vehicles on the road, the introduction of staggered working hours to spread out peak traffic, and the introduction of road pricing. In any case, a good understanding of the (expected) response of travellers to the demand management measure is essential. This requires an adequate level of behavioural model resolution. Two key aspects to be considered here are (i) the fact that the different trips made by a traveller are interconnected in a rather complex manner and that (ii) the responses of different travellers to the same travel demand measure may be very different. Item (i) calls for a dynamic behavioural model, and item (ii) requires a disaggregate behavioural model. ABDMs meet these requirements and are (hence) considered the most adequate behavioural modelling approach in this application context. As explained in Section 4 (and summarized in Table 1), the best match of an ABDM in a strategic transport model system is a dynamic and disaggregate network assignment package.

Similar observations hold when it comes to **equity and winner-and-losers analysis**. Focusing on the effect of a measure on (the welfare of) individuals, it is essential to adequately represent the heterogeneous and complex interrelations between socio-demographics and mobility, calling again for a disaggregate behavioural model. Since similarly complex processes guide the perception, valuation, and use of time, the model should also be dynamic. ABDMs are hence again considered as the most adequate option. The use of a synthetic population has in this context an important practical advantage over group-specific OD-matrices: These matrices need to be defined before a model-based investigation is performed, meaning that the a priori design of the demand representation already frames the set of possible (group-specific) answers that can be given. A synthetic population, on the other hand, requires no a priori aggregation, meaning that summary statistics over arbitrary subsets of the demand can be computed after the model has been evaluated. This is particularly important when it comes to equity analysis, where the winners and losers of a particular measure may be identifiable only in hindsight (Flötteröd et al., 2012). Again, an ABDM is best matched by a dynamic and disaggregate network assignment package. The discussion above applies also to Cost-Benefits analysis that take into account the heterogeneity of users (e.g. account for income differences).

The need for disaggregated demand models is somewhat lower for **Cost-Benefit analysis that apply "unit values"** to transport improvements (e.g. apply the same Value of Travel Time Savings for every minute saved in certain transport mode). In this approach, time savings contribute equally much to the wealth of society independent of whom they are experienced by. It can be seen as the standard approach to CBA in Norway and many other countries. A macroscopic modelling approach seems sufficient for this purpose as long as it can provide accurate (aggregate) estimates (as net time savings). As most macroscopic models are static, the calculation of travel times in congested areas is, however, prone to imprecisions. Another issue with static models (based on volume-delay-functions) is that they cannot distinguish between congested and un-congested travel. This information, however, is important for economic appraisal as travel time savings in congested traffic is valued higher than in uncongested traffic (in Norway the multiplication factor is estimated to be 3.5 for short distance car trips (Ramjerdi et al 2010)). A dynamic and meso/microscopic traffic assignment model is naturally the best approach to provide the necessary information to distinguish between travel time savings in congested and uncongested traffic.

5.2 Model capabilities and practical features of different assignment packages

In the following, a number of network assignment package properties are discussed that deserve consideration independently of a concrete application context.

5.2.1 Robustness and accountability

Strategic decisions are by definition long-term. The longer the time horizon until the measure under consideration takes effect, the larger the influence of unforeseeable processes that may affect the transport system. One hence is interested in making **robust decisions** and in coming to **accountable conclusions**.

Robustness refers to the management of uncertainty in the model system. This uncertainty can be classified into (i) uncertainty in the (exogenous) boundary conditions (inputs) of the model system and (ii) uncertainty in the (endogenous) processes inside of the model system. Uncertainty in boundary conditions refers to the limited predictability of input variables needed by the model. These may comprise socio-demographics (income development, migration), oil prices and economic growth, and weather-induced network deterioration. Such uncertainty should be accounted for by repeatedly evaluating the model system with different realizations of these boundary conditions. This poses no particular requirements on the transport model system (Ross, 2006). Things are different, however, when it comes to the representation of uncertainty within the processes of the model system. An example of this is travel time variability, which results from complex demand/supply interactions and has a systematic effect on network performance and travel behaviour. In theory, such effects are best captured by a stochastic transport model system. In practice, the understanding of how uncertainty propagates through a complex transport system is still limited, and hence it is difficult to adequately account for. However, even if one is not able to precisely model all sources of uncertainty, one still is interested in a model system that is capable of indicating that its predictive power is exhausted beyond a given time horizon. Arguably, disaggregate simulations are by design the most adequate approach to address strategic transport planning problems in the presence of uncertainty.

For practical applications it has to be noted that simulation based models (i.e. stochastic models) do not produce robust fixed point results. This is because random seeds affect the prediction from a single model run implying that two model runs with same input data (population, network and boundary conditions) may yield different predictions. To obtain robust information relevant for decision making, distributions of prediction should be calculated by repeating the simulation several times. In case of Cost-benefit analysis for instance, this may imply that one is calculating a distribution function of the cost-benefit ratio of a police measure; this allows to report a probability of one project being more preferable over another. This arguable enrichers the information available to the decision makers.

Robustness of results may also relate to the marginal impact of input variables on the system solutions. E.g. slightly adjusting the Value of Time should not change the complete pattern of route choice. This however might be the case in deterministic model that are unconstrained and poorly segmented (e.g. all-or-nothing assignment models).

Accountability refers to the model being transparent and at least conceptually understandable. This is absolutely necessary, given that a model as complex as a transport system cannot be applied as a "black box" – it is fair to say that an analyst that is capable of interpreting its outputs and identifying inconsistencies comes as an integral part of such a prediction system. The more intuitive the workings of a model, the easier it is for the analyst to make sense of its outputs. A more abstract model requires an equally abstractly trained analyst to adequately deploy it. Microscopic simulations, which attempt to truthfully mimic real-world processes, have the clear advantage that their workings have real counterparts, which supports intuition. On the other hand, the relatively large number of fine-grained processes evaluated in a micro-simulation makes it difficult to intuitively understand its detailed cause-effect relationships. In addition, the inherent stochasticity of meso-/micro-simulators requires some statistical training to be adequately managed. The opposite statement is true for macroscopic simulations: their typically mathematical problem formulation is rather difficult to understand, but once it is understood it reveals relatively clearly the underlying cause-effect mechanisms. Mesoscopic model systems provide, once again, a middle ground between both extremes.

The often (but not always) guaranteed solution uniqueness of macroscopic model may be seen as a practical advantage that eases interpretation when comparing scenarios. However, it comes with the danger of ignoring other solutions of the systems that may be equally valid. Stochastic models (correctly) allow for different system solutions.

5.2.2 Richness in analysis

In a nutshell, the more disaggregate the predictions of a model system, the richer the analysis it allows for. Aggregation always implies some information loss in a sense that the detailed (disaggregated) information gets lost in the aggregated data structure. While aggregating is always possible, the necessary information for disaggregation might not be available. For instance, a per-minute flow pattern can be easily aggregated into hourly flow rates, but it is not possible to infer backwards the minute-by-minute flow dynamics from an hourly average. Equivalent statements as for (dis)aggregation in time hold for (dis)aggregation in space and for population heterogeneity. This even carries over to deterministic vs. stochastic model systems: While it is straightforward to average stochastic predictions into a mean value, it is not possible to extract distributional information (e.g. in the form of uncertainty bands) from deterministic point predictions (Flötteröd and Bierlaire, 2012). In summary, microscopic transport model systems allow for the richest analysis, followed by mesoscopic models, followed by macroscopic models.

5.2.3 Computational efficiency

It is often argued that an increased level of disaggregation also comes with higher computational requirements. This statement, however, is inadequate as a general observation because it depends strongly on the problem under consideration.

On the travel demand side, an increased level of population heterogeneity calls for an increased number of stratified submodels, with the computational load increasing roughly linearly with the number of strata. A microscopic model, on the other hand, maintains a constant computational requirement because it is based on a synthetic population that may exhibit arbitrary heterogeneity (one may attach as many background variables to an agent as one likes). The same observation can be made on the network supply side. The larger the number of commodity flows (e.g. demand segments, origin/destination relations, vehicle classes) to be tracked on the network, the larger the computational effort in a macroscopic assignment package. Again, a vehicle microsimulation is by design insensitive to an increase of vehicle hetereogeneity; every simulated vehicle is a realization from an arbitrary distribution.

More important than the degree of disaggregation is the model's time resolution: static models are generally faster than dynamic models.

5.2.4 Implementation and calibration, use and maintenance

A strategic transport model is, no matter what type of model one selects, a highly complex system that requires large amounts of data to be set up and calibrated, as well as expert knowledge to be used and continuous improvements to be maintained. This puts concerns about the computational run times of a transport model system somewhat into perspective; it is more adequate to assess the sum of the time it takes to prepare the model for a particular analysis purpose plus its run-time – with the latter then easily becoming by an order of magnitude smaller than the time invested in preparing the computations.

Dynamic models are based on time-dependent input data, require the calibration of parameters guiding their dynamical mechanisms, and call for an understanding of these mechanisms by the analyst. Examples are time choice models on the travel demand side and network models that are based in realistic traffic flow theory. All of this is not required in static models. Similarly, the more disaggregate a model, the more input data is necessary to initialize all model processes, the more parameters need to be calibrated for the different processes, and the more domain knowledge is needed on the analyst's side to make sense out of the interactions of all of these processes. Examples are fine-grained behavioural model systems that explain trip-making through processes as complex as inter-household negotiations about who takes the car (Bhat et al 2012) or microscopic traffic flow models that mimic the car-following and lane-changing decisions of individual drivers (Toledo, 2008).

In summary, dynamic models require more effort than static models, and disaggregate models require more effort than aggregate models.[16]

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[16] A difference between commercial and free, open-source software packages is also noteworthy: Commercial products come at a financial cost but typically also with some kind of guaranteed support, which is unavailable for free software. However, open-source software puts no limits to one's own

5.2.5 Flexibility and extendability

Flexibility and extendability refer to the possibility to update the model system in reaction to future requirements. This is a nontrivial aspect of a present model selection effort, given the difficulty of anticipating the requirements to come. It is important because the "life span" of a strategic transport model system is in the order of decades, which renders spontaneous investments in completely new model systems out of the question.

This has a technological and a modelling dimension. Technologically, it is advantageous that the model system is extendable, in the sense that one is able to replace components (e.g. a fixed by an adaptive signalling system or a simple by a more sophisticated destination choice model) through some kind of API (application programming interface). This is typically the case. Things are more severe on the modelling side, in that certain modelling paradigms are virtually impossible to enrich: Turning a static into a dynamic model system or turning a macroscopic into a meso-/microscopic model system is difficult to impossible without the danger of introducing problematic ad-hoc modifications.

In summary, the choice of a static model system essentially excludes future opportunities for dynamic modelling, and the choice of a macroscopic model system puts strong restrictions on analysing increased detail and heterogeneity.

5.3 Evaluation summary and synthesis

The choice of a network assignment package for a strategic transport model system can be based on the following three considerations.

- **The planned application context of the model system.** The requirements of different application contexts, which are elaborated in Section 5.1, are strong indicators of desirable (and of unnecessary) model properties.
- **Properties of the available (or to-be-developed) travel demand model.** Section 4 establish the compatibilities of different types of travel demand models and network assignment packages.
- **Further model capabilities and practical features.** A number of such criteria is provided in Section 5.2.

Table 2 and table 3 summarize these considerations.

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modifications of the program, whereas commercial software is typically "canned" and changes need to be requested from agreed to by the vendor.

Table 2: Evaluation of network assignment packages for application purposes

	Static macro	Dynamic macro	Dyn. meso/micro
Congestion mitigation	Inadequate (S)	Adequate	Adequate
ITS	Inadequate (S,A)	Inferior (A)	Adequate*
Travel demand management	Inferior (A)	Acceptable	Adequate
Equity analysis	Inadequate (A)	Inferior (A)	Adequate
Standard Cost-benefit analysis	Adequate if congestion low	Adequate	Adequate**

Reasons (S): Static, (A): Aggregated; *micro-level might be necessary **if distributions of predictions are compared

Table 3: Evaluation of network assignment packages on general model capabilities and practical features

	Static macro	Dynamic macro	Dyn. meso/micro
Robust and accountable	Yes but potential biased (S)	Sensitive	Stochastic*
Richness in analysis	Limited (S,A)	Moderate (A)	High
Computation times	Fast**	Slow	Slow***
Implementation, calibration, use & maintenance	Simple (S,A)	Moderate (A)	Involved
Flexibility and extendibility	Low	Moderate	high

Reasons (S): Static, (A): Aggregated; *single model runs not robust **slow if number of segments high ***micro-level may be too slow for large scenarios

Dyn. meso/micro assignment models are most applicable for all application purposes considered in section 5.1. The main reason goes back to the explicit modelling of congestion dynamics and the disaggregated nature allowing a great richness in analysis. The evaluation for “travel demand management” and “equity analysis” rests on the assumption that they are coupled with corresponding disaggregated demand models. If they are coupled with macroscopic demand models (e.g. as when RTM would be coupled with Aimsun meso, see section 6.2.) the identification of winners and losers, for instance, is likely to get lost in the aggregated data structure of a macroscopic demand model.

As mentioned in 5.1, static macro models are conceptually appropriate for Cost-Benefit analysis that apply unit values (as the typical practice in Norway). However, the analysis may suffer from imprecise calculation of travel times in congested networks. Imprecision may not only have a direct bias to user benefits, e.g. the quantification of travel time savings, but may also bias the prediction of behavioural changes effecting the total benefits of a policy measure. Cost-Benefit analysis with static/macro models may also imply the danger of averaging away all stochasticity (modelling imperfection) in the system. Comparing "fixed-point" results may wrongly incline suggestions like "Project A is certainly better than Project B". A statement that would only be valid under the (heroic) assumption of a perfect model. The correct use of stochastic models for cost-benefit analysis is a rather unexplored but highly interesting and important research topic (a recent contribution is Kickhöfer (2014)).

Static/macro models have in general the lowest requirements in practical use and are – arguable for historical reasons – still much better known (and much more often applied) among (by) consultants. Dynamic meso/micro assignment models are more demanding with respect to implementation, calibration and usage and require more expert knowledge on part of the users. If the corresponding budget-, time-, data constraints are not too tight, and human resource are available, then a dynamic meso-/microsimulation offers both the greatest application range and the most flexible and far-sighted model structure.

The question of a micro- versus a mesoscopic traffic flow model comes down to the level of details required in the analysis and the computation cost one is willing to take. Microscopic traffic flow models may be needed for specific ITS analysis. On the other hand, those models may be impractically for large city scenarios (with several hundred-thousand of vehicles). For most strategic application purposes mesoscopic traffic models seem to provide enough detail and are able to provide acceptable running times (below 48 hours) even for very large scenarios (up to 10 million vehicles).[17]

Recently, a conference paper by Bliemer et al. presents a quasi-dynamic model that takes ground in a static assignment but seemingly overcomes several weakness of classical assignment models (Bliemer et al., 2013). In their own evaluation of assignment models for strategic transport planning purpose, Bliemer et al. present their quasi-dynamic model as an ideal middle ground between unrealistic static/macro models and dynamic microscopic simulation models that "are not able to deal with very large networks and may not have the capability of providing robust results for scenario analysis" (quoted from abstract). In our evaluation, this model can be included into "dynamic/macro" models and may indeed be a good middle ground model. However it does not provide the level of detail of micro/meso models that actually are - at least in a mesoscopic instance - applicable for large network scenarios (see for instance Meister et al., 2010).

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[17] Hybrid models that can split the network in a micro and a meso part (as possible in Aimsun) seem interesting, especially for ITS application purposes that only apply to some part of the network.

6 Possibilities for future developments of Norwegian models

In this section, we sketch upon possible improvement and developments of some Norwegian models.

6.1 Refining the time slices in RTM

In section 4.5.1.we described the data flow between the static demand model in RTM (TraMod_by) and the static assignment model (Cube Voyager).

The demand model in RTM has traditionally been a "day-model" (producing stationary conditions for a whole day). The recent version Tramod_by allows to subdivide the total number of trips emanate from each zone in smaller time periods (with given data from the national travel survey, NTS). As mentioned in 4.5.1., typically four periods, two rush and two off peak, are applied. TraMod_by can make use of time-dependent LoS as input. In its current version only two different sets of LoS are utilized; one for rush (being the LoS representative for 7-8 o'clock) and one for off-peak. However, the intra-day variation in network conditions in urban areas are typically more complex than that (e.g. LoS between 6 and 7 o'clock normally is different than between 8 and 9 o'clock). Therefore, one might want to look at possibilities to calculate more time-differentiated LoS in the traffic assignment model.

As Cube Voyager is a static model, it reads in OD-matrices independent of the time period it is referring to. Hence, it can read and process OD-matrices for a whole day, 4 periods a day or single hours[18]. To iterate TraMod_by and Cube Voyager on an hourly level, TraMod_by (trip generation and mode-destination model) would have to be applied at an hourly level as well. The current practice is that one iterates (only) for the four periods separately.

Another feature of TraMod_by is that the resulting OD-matrices for rush traffic (typically a period of 3 hours; e.g. 6-9 o'clock) can optionally be decomposed into three OD matrices of one hour (6-7, 7-8 and 8-9 o'clock) (Rekdal et al., 2012). This is done by a simple logit model applied to the "elastic" share of the OD matrices (the researcher has to define what share of the OD-matrix is "elastic", i.e. prone to shifts within rush-hours). Figure 6 below illustrates the data flow when the optional model is applied.

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[18] It seems necessary to adjust only the volume-delay functions such to fit with the applied period.

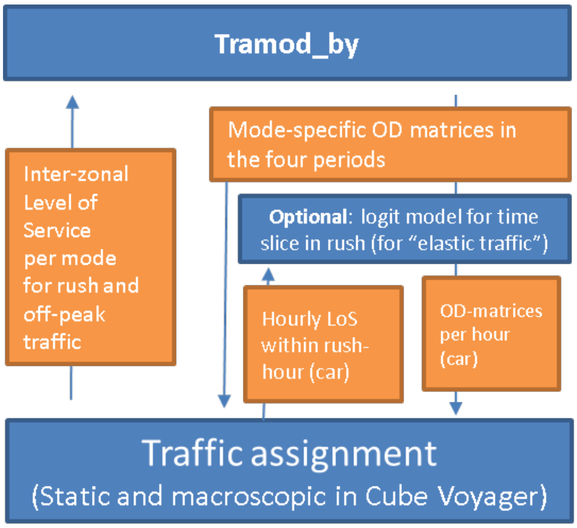

Figure 6: Dataflow in RTM with the additional logit model for time slices

This additional logit model for time slice in rush traffic assumes uncorrelated utility functions with cost and time as (only) explanatory variables for each of the three time slices. The alternative specific constants in the model are not calibrated and need to be determined case-by-case. The additional model is not an integrated part of RTM and has – to our knowledge - just been applied in one real-world application and only for car traffic (Rekdal et al 2012). The model is also rigid it that the total amount of trips in the four periods is predefined (there are no shifts from/to rush-hours to/from off peak periods.

Therefore, it would be an idea to change the integrated trip generation model such that it can account for the different number of total trips across the hours of a day (rather than to split OD matrices in an additional model after they have been produced in TraMod_by). If the trip generation model could predict the total number of trips (per trip purpose and segment) on an hourly level, the MD-model could split these trips in mode specific OD matrices taking into account hourly LoS from the assignment packages. In principle, this would result in 24 submodels that would then account for the intra-day variation in travel demand and network conditions. However, there are several practical challenges and limitations involved in this approach

- The current trip generation model is in its kind a "full day"-model and is not calibrated such that it is able to estimate trip generation per hour. In order to be able to predict meaningful pattern of intra-day trip variation, data about desirable activity starting times would probably be needed[19]
- Static models for trip generation on an hourly basis are likely to be restrictive as departure time choice and scheduling consideration (i.e. dynamic effects) get more important
- Computational costs increase substantially when running separate model for all sub-periods (at max 24 periods); and computational costs for just 4 periods are already high for big regions

Summing up, the current subdivision in four periods does not offer sufficient information over travel time variation over a day - at least for typical applications in

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[19] Those are available in NTS but not utilized in RTM.

congested urban areas. The additional model for time slice choice on an hourly level is not well integrated in the RTM system (and seem to require a lot of manual work). A trip generation model that can produce trips on an hourly level such to allow iterating between demand and supply model on hourly bases was suggested to obtain better estimates of intra-day variation in travel times. However, the static nature of the RTM system sets rather strong restrictions on how precise such a model can get.

6.2 (Re-)coupling of Aimsun meso with Tramod_by

As outlined in sections 3.3 and 5, static traffic assignment models have several limitations and do in general not provide precise information about traffic flow and travel times in congested urban areas.

The Norwegian Road Administration (SVV) has bought a licence of Aimsun meso for more detailed analysis of traffic assignment in urban areas (see SINTEF 2013b) [20]. The current state-of-practise is that OD-matrices from TraMod_by are further adjusted/decomposed by means of a build-in-application in Cube in order to fit the finer zonal system and short time slices in Aimsun meso (typically 15 minute). The decomposition of matrices in that application is based on some simple parameters that are manually chosen (see Malmin 2014 for a description).

Figure 7 illustrates the data flow between Tradmod_by and Aimsun_meso.

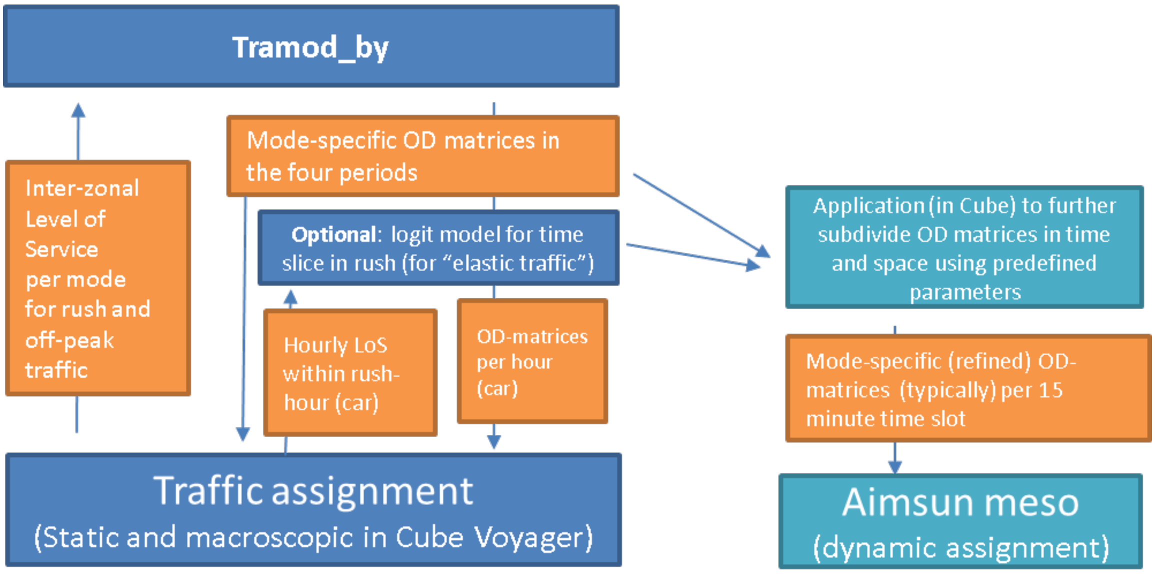

Figure 7: Typical dataflow from RTM to Aimsun meso

Because of its dynamic approach (and the finer spatial resolution), the traffic assignment model in Aimsun meso has several advantages over the static assignment in Cube Voyager and is capable to produce more precise and detailed LoS. However, Aimsun meso models only route choice and not destination-, mode- or departure time choice such that it does not adjust demand according the LoS that it produces.

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[20] Consequently, an unknown number of consultant firm in Norway have acquired a license as well.

In the current procedure, there is no recoupling of Aimsun meso to TraMod_by such that Aimsun meso remains a post-processing tool and is not an integrated part of RTM. This is problematic for cost-benefit analysis as the network conditions predicted by Aimsun meso are not (necessary) consistent with the demand side.

A natural way to improve over the current sequential procedure would be to return the (congestion-dependent) travel times to TraMod_by and to update OD-matrices in TraMod_by with that information. Then the updated OD-matrices (via the application) could again be read into Aimsun meso. In principle, this should lead to "improved" equilibrium state with more detailed information and more realistic calculations of traffic flow and travel times.

Such an approach should be technical feasible (and the results from Sweden (see section 4.5.3.) seem to support this view). In principle, a successful implementation would replace the static assignment model with a dynamic one.

However, the following problems/challenges are evident/likely.

- The different time slices in TraMod_by (4 periods a day or at best 1 hour) and Aimsun meso (typically 15 minutes) implies that the data flow between the models is not "smooth".
- The current application to refine matrices by predefined values is (presumable) not very precise; more advanced methods to disaggregate OD matrices would be warranted.
- The current MD-model in TraMod_by works only with two sets of LoS (rush, off-peak). This means that LoS data from Aimsun meso need to be aggregated. This involves an information loss and the dynamic information in consecutive LoS matrices (with 15 minutes time slice) gets lost. Note that this would also – however to a lower degree - be the case when TraMod_by would be estimated for each hour separately (see section 6.1.).
- The MD-model in TraMod_by is static such that the dynamic information cannot be utilized (even if time slices would correspond to each other). In particular, effects on departure time choice cannot be modelled. The "pseudo-dynamic" model of time slice choice within rush in TraMod_by should get finer time slices and would probably need more sophisticated utility formulation in order to utilize the dynamic information (e.g. the error term of the utility function of time slices should be correlated).
- The macroscopic nature in TraMod_by does not allow to map vehicles (in Aimsun meso) with decision makers in the demand model. As a consequence route choice cannot depend on travellers characteristics.
- Computational costs (as discussed already in 6.1.) may also be an issue.

Summing up, a (re-)coupling between Aimsun meso (or another DTA package) and TraMod_by seems desirable in order to improve the modelling of congestion and to improve the calculation of travel time. There are some (unsolved but presumably solvable) issues regarding (automatic) data transfer and technical coupling between the two models. However, even if the recoupling could be achieved the following disadvantages of the approach should be noted: The static and macroscopic nature of TraMod_by implies information losses and the dynamic information from the DTA cannot fully be utilized. It is also impossible to map vehicles (in Aimsun meso) with decision makers in the demand model (this is possible in the agent-based model described in the next section).

6.3 Possible developments with MATSim in Norway

6.3.1 MATSim prototype model for Trondheim

We have described general workings of MATSim in section 4.5.2.

The Institute of Transport Economics has in cooperation with Julia Kern from TU-Berlin and Frederik Bockemühl from Hasselts University build a first prototype of a MATSim model for the region of Trondheim (Flügel and Kern 2014).

The road network data for the Trondheim region is imported from the Elveg data bank and includes close to 100.000 link and close to 50.000 nodes[21]. Figure 8 illustrates the network.

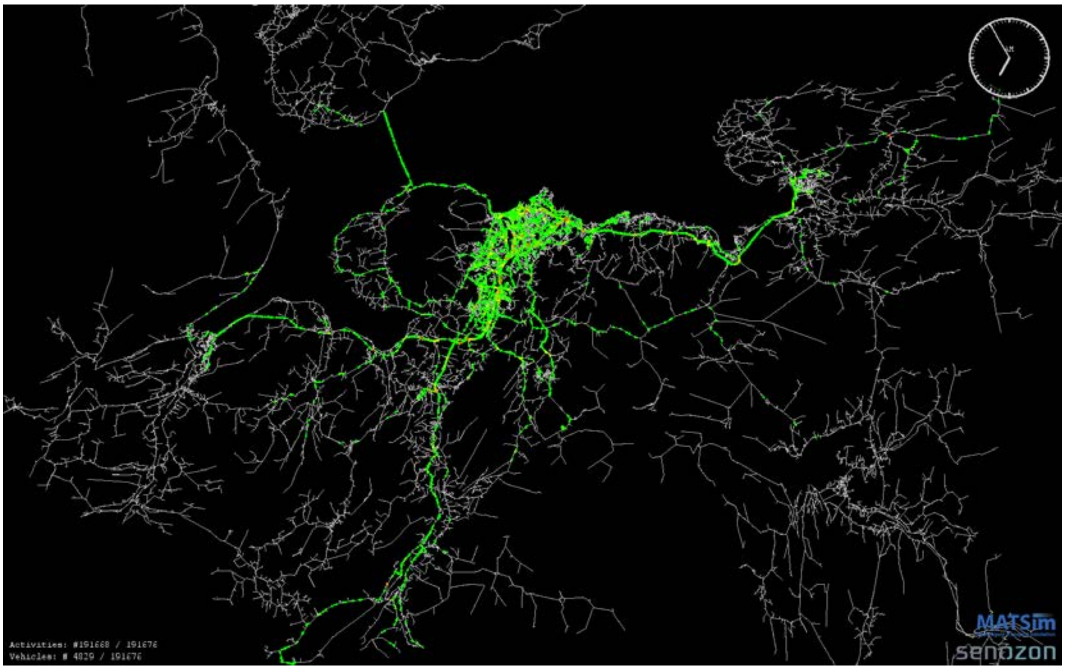

Figure 8: Network and simulated traffic i Trondheim and surroundings for 06:55:00 o'clock (source Flügel et al 2014).

The following link characteristics could directly be inferred from the data bank: the allowed driving direction, the number of lanes, the link length and the speed limit (which was used as free flow driving speed in MATSim). The lane capacity (maximum number of cars that can drive through a link per hour), which is needed for MATSim, was assumed to be 1800 per lane. Existing toll stations with their current toll structure were coded manually in the network file. The PT network is not implemented. The same applies to walk/cycle. Agents that take one of these modes are "teleported" with travel times being calculated with predefined speed per transport mode. A ferry for car drivers (north-west of Trondheim) is implemented as a regular street with free flow speed of 15 km/h.

The initial demand is derived from the travel diaries from the National Travel Survey from year 2009. 4453 respondents are scaled up to 191676 agents; that is, one respondent makes up around 43 agents. The reported home location and location of

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[21] Arguably, the network is too detailed (for our purpose) with many minor links in suburban areas that are hardly used in the model. Reducing the network might speed up computation times somewhat.

activities (for which "exact" X-Y coordinates where assigned to respondents from NTS) where randomized a bit to avoid "clusters". This worked fine for Trondheim city but some geographical clusters remained in the rural areas (with only a few representative respondents). Departure time was also randomized a bit around the reported departure time (respondents tend to round departure times to full 10 or 15 minutes in NTS). The randomization of location and departure time helped to reduce the number of "identical agents" which would drive the same routes to same time. The model differentiated only between work and "other" activities. Desirable working hours were specified to be 8 hours. The demand consists only of private cars (no trucks).

Standard utility functions were applied but in the calibration process, the default values for disutility from travel time spend in different transport modes were adjusted such that the model would reproduce the observed market shares. Figure 9 shows the plot between simulated traffic (in the reference scenario) and real-world counts (of private cars).

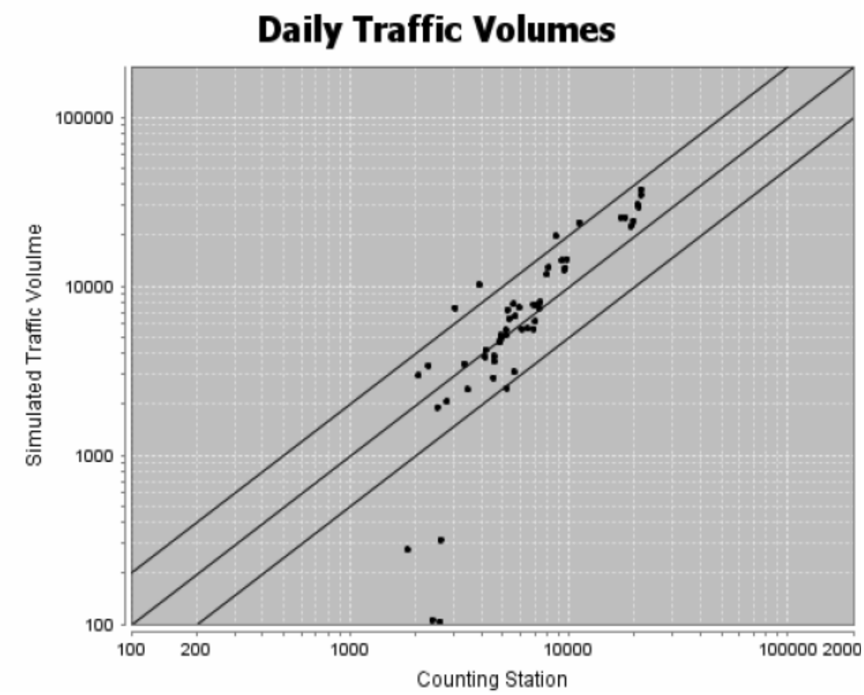

Figure 9: Comparison between simulated and real traffic (source: Bockemühl 2014)

The overall level of congestion found in Trondheim city was low (which might be related to the fact that trucks and busses are not simulated). However, in the morning and afternoon rush several queues emerge especially on the motorway (that many commuters use). Figure 10 illustrates how congestion is building up on a section of the motorway between 6:55:00 and 7:15:00 o'clock as simulated in MATSim.

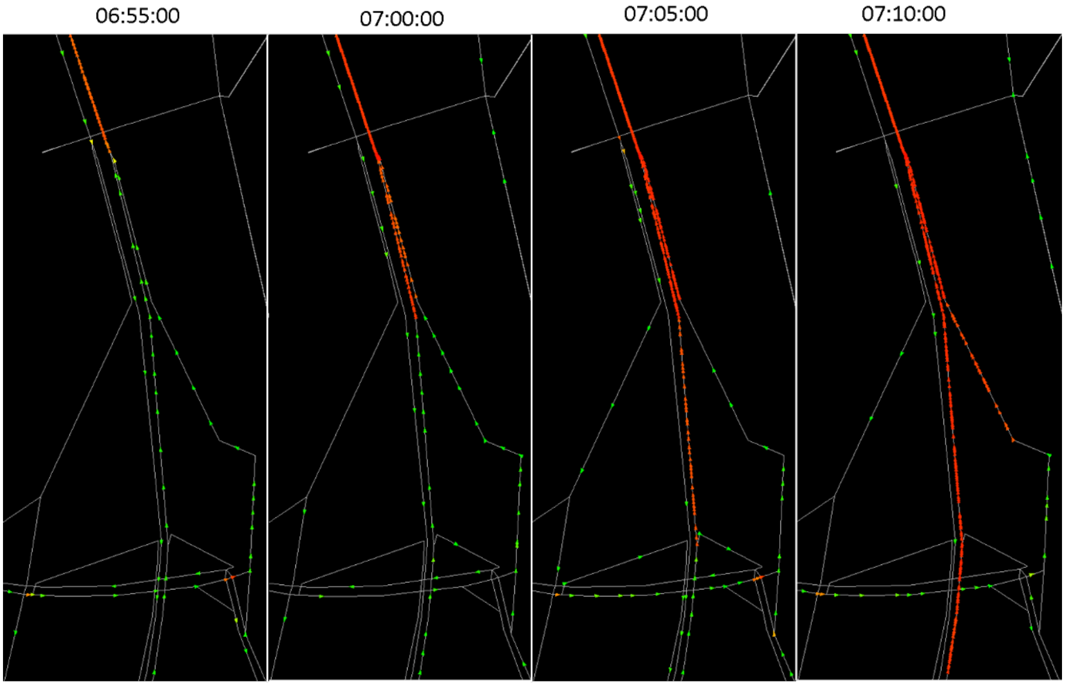

Figure 10: Illustration of queuing on a motorway in MATSim; red cars indicate reduced speed due to congestion (source: Flügel et al 2014).

The standard behaviour modules in MATSim (section 4.5.2) where included in the Trondheim model. That is, agent react to policy measures by three choice dimensions: changing route, changing transport mode and changing departure time.

To test if MATSim predicts reasonable behavioural changes, a small case study was performed. Additional tolls on streets (bridges and tunnels) to Trondheim city centre were coded in the network and three congestion price structures were tested. Figure 11 illustrates the effect.

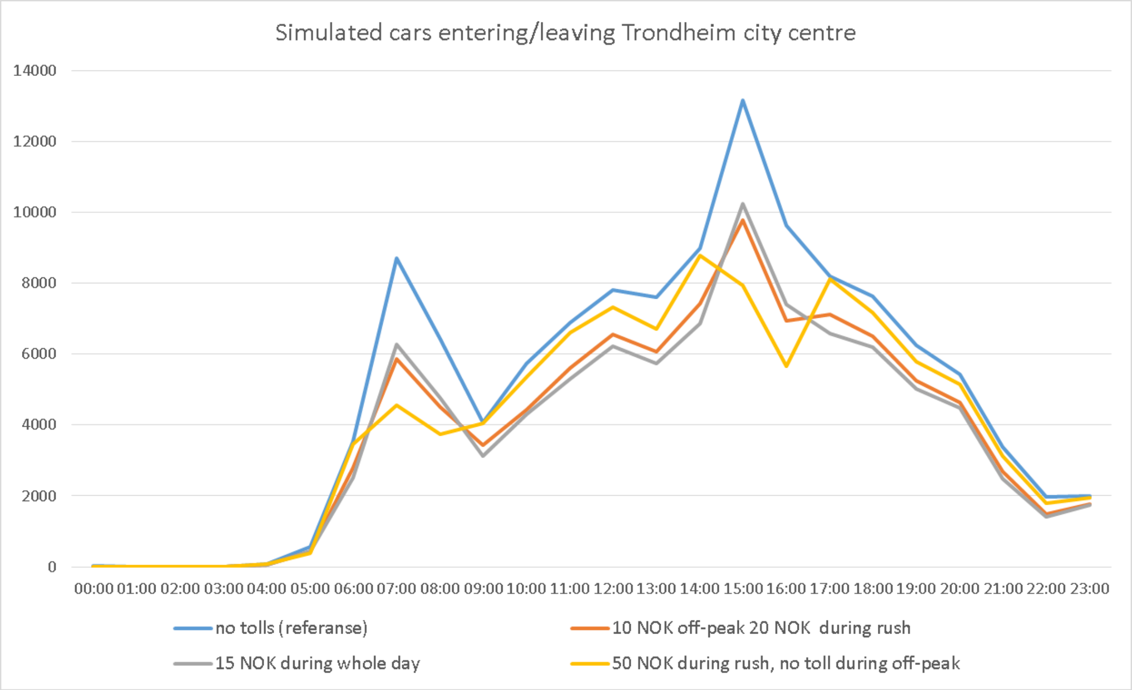

Figure 11. Cars entering/leaving Trondheim city centre in reference scenario and three congestion pricing scenarios.

Compared to the reference scenario without tolls, the number of cars is reduced in all toll scenarios. Some agents change transport modes and some agents that would otherwise have driven through Trondheim centre, changed their route. Comparing the three different congestion-pricing structures, it is also evident that agents change departure time. The effect between the 15 NOK flat scenario and the 10 NOK off-peak and 20 NOK rush scenario is small (relatively few agents change departure time) while the effect in the 50 NOK rush (and no toll in off-peak) is substantial. Actually, in this scenario traffic is higher before 15:00 and after 17:00 (implying that many agents changed departure time to avoid the high congestion pricing).

6.3.2 Validating and extending the MATSim model for Trondheim

The prototype model for Trondheim described in the previous section is not validated sufficiently and is in its current form (simulating only private cars) limited. The following steps should be undertaken to improve the model.

- Validate the applied link capacities
    - Link capacity per lane was assumes to be 1800 vehicles per hour per lane. While this might be a good average value, the real capacity across links is likely to differ. Given that good external data exists, one should adjust these numbers (at least for important links with potentially a lot of congestion).
    - The link capacity can (and arguable should) also be adjusted to account for “missing information” in the model. On the supply side these are for instance traffic lights and pedestrian crossings which are not coded in the model but which are likely to effect the link capacity in real-life. On the demand side one can try to offset for that one does not simulate busses, taxes and trucks in the current model by reducing the road capacity for private cars. This should yield more realistic pattern of congestion especially in the city centre (where congestion is too low in the current model).

- Incorporate more demand input data
  - The initial demand is only derived from NTS and a relatively high scaling factor had to be used (1:43). Additional data sources could be exploited as the commuting data base to get a more precise and better representation of the demand.
  - One should also include more activity types (the current model only distinguishes "work" and "other"). NTS provides the detailed activity types/trip purposes.
- Customizing utility function to fit "Norwegian" preferences better
  - The standard utility functions are used and one should try to change the implicit willingness-to-pay values to fit the Norwegian preferences better.
- Calibration with Cadyts ("Calibration of dynamic traffic simulations")
  - Cadyts is an open-source calibration tool for micro-simulation models (Flötteröd 2009, 2011). It adds and subtracts utility on a micro-level such to make simulated link volumes closer to the observed link volumes.
- Implementation of simulation of public transportation
  - This is pretty straightforward in MATSim, but requires to code the PT network with all stations and all timetables
  - This would also improve the precision of the mode choice model underlying MATSim.
- Accounting for freight transport.

A successful implementation of these points would yield a state-of-the-art *tactical* transport model for the Trondheim region[22]. It could be used for detailed and dynamic analysis in traffic assignment and (short-term) demand changes, e.g. in the context of testing detailed congestion pricing schemes and other applications purposes where static models have obvious difficulties. It could also be used to validate the traffic assignment and travel times obtained in RTM, and by this - presumably - identify some potential biases in the calculations with RTM.

6.3.3 Towards a state-of-the-art strategic transport model with MATSim

As the standard MATSim model as described in 6.3.1 and 6.3.2 does not include destination choice and trip frequency choice it cannot be used for long-term scenarios in which total demand and the spatial distribution of demand are changing substantially. Simply scaling up the synthetic population might not be sufficient, as land use pattern are likely to change over time as well.

As already pointed out in 4.5.2., there exist modules for destination choice in MATSim (Horni, 2013). In order to utilize this module one needs facility data (information about where e.g. shops, working places etc. are located). The inclusion of destination choice has been incorporated in some real-world MATSim models (Tel Aviv), but it is arguably still on an rather experimental level. (and has therefore not been integrated in a standard MATSim model).

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[22] Given sufficient input data, it is also straightforward to transfer the model codes to other areas. Thus, an Oslo model (or arguable a national model) could be implemented given that input data can be gathered.

Hence, one might argue to replace the demand model of MATSim with a full-fletched activity based model (as DaySim or Albatross)[23]. This is possible as MATSim is build up as a module approach where different model components can be shifted out. This is also true for the assignment model (the meso model can be replaced by a microscopic traffic flow model if one wishes). In this sense, one can use MATSim as a platform to combine different demand and traffic flow models. There MATSim represents a flexible model core that can be adjusted after model requirements in the future.

In case resources to build a workable full-fletched activity-based demand model in Norway are not available, one could also make efforts to couple TraMod_by with MATSim. The idea is that trip frequency, destination choice and mode choice could be modelled in TraMod_by and that departure time choice, route choice and dynamic traffic flow could be modelled with MATSim. Inconsistency in the data structure of these models is a challenge and similar shortcomings as discussed for coupling TraMod_by with Aimsun meso (section 6.3.2.) would probably apply.

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[23] As the national travel survey is personal based (not household based) one should probably opt for an ADBM that works on a personal level (not on a household level).

7 Conclusions

Transport processes, i.e. movements of persons and goods in space and time, are by nature dynamic. Decisions on the demand side are made in a dynamic context of reaching and scheduling activities at desirable starting times. The network performance (representing the short-term supply side) depends on traffic flow propagations resulting from dynamic interactions of many vehicles and the given infrastructures. Travel times experienced by travellers in urban areas can vary significantly over the day due to congestion patterns which are both depending on human behaviour (in particular mode, departure time and route choice) and complex physical processes in the network.

Static assignment models are inadequate to calculate traffic flows and travel time in congested urban areas. Assuming instantaneous network flows, these models are not capable of accounting for spatiotemporal dynamics of traffic flow. Most static assignment models are based on volume-delay-functions (VDF) which predict travel time delays as an increasing function from traffic flow but independent of the traffic density (level of congestion). This makes travel times estimates in congested traffic conditions unreliably. The same applies to estimates of traffic flow, which come with the additional danger that the model may predict traffic flow beyond capacity, i.e. traffic assignment that is physically not possible. Another shortcoming of these models, especially severe in the context of urban areas, is that these models cannot capture congestion spill-backs. This makes the calculation of travel time and prediction of route choice for links upstream of bottlenecks biased.

For a strategic transport model, i.e. a model systems that couples a travel demand model with a traffic assignment (or traffic flow) model component, an obvious question relates therefore to if and how the static assignment component can be replaced with a dynamic one. Dynamic traffic assignment (DTA) models come in various resolutions and instances, reaching from (aggregated) macroscopic models to (fully disaggregated) micro-simulation models. The adequateness of possible couplings is strongly related to the data structures of the model components. A static/macroscopic travel demand model, as the Norwegian TraMod_by, produces OD-matrices which is a natural fit to static/macroscopic assignment models that produce inter-zonal travel cost matrices (as Emme or Cube Voyager). Coupling a static/macroscopic travel demand model with a dynamic meso/microscopic assignment model (e.g. coupling TraMod_by with Aimsun meso), data structures are not directly compatible. To achieve a technical coupling, methods to disaggregate demand (by exogenous data) are required and for the iterative process, the detailed measures of network performance must be aggregated again before they can feedback to the travel demand model. This will always come with information losses.

For strategic transport models, the questions about appropriate traffic assignment models is therefore inevitably connected to the question about appropriate travel demand models. The best fit to a dynamic meso/microscopic assignment model is a demand model that can fully utilize the dynamic and detailed network performance measure that it produces. The best travel demand models are therefore also dynamic and disaggregated. Activity-based demand models (ABDM) based on all-day trip (activity) lists come in mind. These models have a strong behavioural foundation and can be built on a synthetic population enabling a high degree of traveller's heterogeneity.

Our evaluation of traffic assignment models found that dynamic meso/micro models are most appropriate for all application purposes in congested urban areas. The biggest advantages are connected to the realistic modelling of congestion and the richness in analysis (allowing to aggregate results in any desirable way). Those models have some practical challenges/disadvantages. They require more detailed input data, are more demanding with respect to implementation, calibration and usage and set high requirements (expert knowledge) on the users.

The stochasticity of dynamic meso/micro models is argued to be conceptually favourable but in can involve some challenges in practical applications. In particular, stochasticity affects the prediction from a single model run such that distributions of predictions (rather than fixed point predictions) should be compared. This might be time-consuming in particular for cost-benefit analysis where many alternatives/scenarios need to be compared to each other.

MATSim, which has in Norway been prototypically implemented for the region of Trondheim, is a model system that can be used for dynamic and detailed traffic flow and (short-term) travel demand modelling. Its integrated approach avoids information losses and guarantees a one-to-one mapping of decision makers and vehicles. As the standard model in MATSim does not include trip generation and destination choice, it should be coupled with full-fletched ABDM or land use models such to make it applicable for long-term strategic transport modelling purposes.

As dynamic and meso/microscopic transport model systems are feasible and favourable, the choice of which type of strategic transport model to apply amounts to how much simplification one is willing to accept. Even if most (current) application purposes seemingly allow for simplifications (as arguable in ("standard") cost-benefit-analysis that only are meant to provide rough estimates of aggregated measures), pragmatic decisions for simple models put bounds on possible future developments. This is because it is virtually impossible to make a static model dynamic and ad-hoc modifications (as the time-slice logit model in TraMod_by described by Rekdal et al., 2012) are likely to be insufficient to truly account for the dynamic nature of transportation processes.

All strategic transport model systems are very complicated and the knowhow of the users are essential for successful modelling and result interpretation. For a possible transition in Norway to more advanced models it is therefore inevitable to educate (potential) users in the theory and practice of these new methods; international collaborations are an effective mean towards this goal.

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Appendix 1

A.1.1: Working definitions in Norwegian

Strategisk transportmodell: *En modell med endogen etterspørsel som er implementert for mer langsiktige prognoser på minst et regionalt nivå.*

Taktisk transportmodell: *En modell med delvis endogen etterspørsel som er implementert for mer kortsiktige prognoser på minst et bydelsnivå.*

Operasjonell transportmodell: *En modell med eksogen etterspørsel som er implementert for kortsiktig og detaljert trafikkavviklingsanalyse, vanligvis på vegstreknings- eller kryssnivå.*

Sonesystem: *Romlig oppdeling av regionen som undersøkes.*

OD matrise: *Inneholder antall turer mellom hvert sonepar.*

Reisetidsmatrise: *Inneholder reisetiden mellom hvert sonepar.*

LoS-matrise: *Inneholder egenskaper ved reisen (kostnad, ombordtid, tilbringertid, ventetid osv.) mellom hvert sonepar.*

Etterspørselsmodell: *Et modellsystem som beskriver om, hvor og med hvilket transportmiddel folk reiser. Den tar vanligvis reisekostnader og reisetider fra nettverket som inndata og predikerer antall reiser og deres opprinnelse/destinasjon i et nettverk.*

Trafikkavviklingsmodell/nettverksmodell: *Et modellsystem av rutevalg og trafikkflyt som tar opprinnelse/destinasjon av reiser som inndata og predikerer trafikkavvikling og reisetider.*

Transportmodell (system): *Et gjensidig koplet system av en etterspørselsmodell og en trafikkavviklingsmodell.*

Statisk transportmodell: *En transportmodell som ikke tar hensyn til tid og vanligvis representerer stasjonære forhold innen en forhåndsbestemt tidsperiode.*

Dynamisk transportmodell: *En transportmodell som eksplisitt tar med tidseffekter i alle transportprosesser den representerer.*

Kvasi-dynamisk transportmodell: *En mellomting mellom statiske og dynamiske modeller som bruker et sett av statiske modeller som er tidsmessig knyttet sammen på en forenklet måte.*

Makroskopisk transportmodell: *Representerer etterspørsel og nettverksflyt i aggregerte tall og løses i et matematisk program.*

Mikroskopisk transportmodell: *Opprettholder integritet til alle enheter og løses ved eksplisitt simulering av prosessinteraksjoner.*

Mesoskopisk transportmodell: *En forenklet mikroskopisk modell der noen enheter eller prosessinteraksjoner er representert ved aggregerte vilkår.*

Deterministisk transportmodell: *En (typisk makroskopisk) modell som ikke tar hensyn til usikkerhet (ufullkommen modellering) og forsøker å representere gjennomsnittsforhold.*

Stokastisk transportmodell: *En (typisk mikro eller mesoskopisk) modell som tar hensyn til usikkerhet (ufullkommen modellering) og produserer en sannsynlighetsfordeling av predikasjoner.*

Soneattraksjonsbasert etterspørselsmodell: *Representerer reiser i form av flyt mellom soner beregnet som en funksjon av egenskaper på soner og generaliserte reisekostnader mellom soner; det grunnleggende konseptet i 4-trinnsmodeller.*

Aktivitetsbasert etterspørselsmodell: *En adferdsrepresentasjon av reiser som erkjenner at etterspørselen etter transport er avledet fra etterspørsel etter aktivitetene.*

Reisebasert etterspørselsmodell: *Opererer basert på uavhengige turer mellom opprinnelsessteder og destinasjoner.*

Reisekjedebasert etterspørselsmodell: *Opererer basert på tursekvenser som starter og ender på samme sted.*

Heldagsbasert etterspørselsmodell: *Opererer basert på heldaglige reisesekvenser og inkluderer en tidsdimensjon.*

Segmenteringsmodeller: *Representasjon av den reisende befolkningen i form av et relativt lite sett med homogene undergrupper.*

Syntetisk befolkning: *Et sett av syntetiske individer (agenter) som i alle dets statistiske egenskaper er i samsvar med den virkelige befolkningen***.**

Deterministisk rutevalg: *Antar at den reisende velger ruten med lavest kostnad som definert i modellen.*

Stokastisk rutevalg: *Antar at reisende velger ruten med lavest subjektiv kostnad. Usikkerheten rundt denne subjektive oppfatningen er representert ved at man åpner for valg av ruter som har høyere kostnad enn laveste kostnad som definert i modellen.*

Statisk rutevalg: *Tar ikke hensyn til tid på døgnet, verken ved vurdering av rutekostnader eller når den predikere rutevalg.*

Dynamisk rutevalg: *Tar hensyn til tidsmessig avhengighet av reisekostnader og predikerer tidsavhengig rutevalg.*

Mikroskopisk rutevalg: *Definerer diskrete valg av enkelte reisende/kjøretøy.*

Makroskopisk rutevalg: *Definerer oppdeling i nettverksflyten for grupper av reisende/kjøretøy.*

Statisk trafikkflytmodell: *Antar momentane nettverksstrømmer og beregner bare forsinkelse i reisetider, men ikke omfanget av kø.*

Dynamisk trafikkflytmodell: *Fanger opp den romlige, tidsmessige dynamikken i trafikkflyt og utleder forsinkelse gjennom å modellere kø eksplisitt.*

Mikroskopisk trafikkflytmodell: *Representerer kjøretøy-kjøretøy og kjøretøy-infrastruktur interaksjoner på det enkelte kjøretøynivå.*

Mesoskopisk trafikkflytmodell: *Aggregerer noen bevegelser innenfor en mikroskopisk modell, men lar den disaggregerte representasjonen av kjøretøyene være intakt.*

Makroskopisk trafikkflytmodell: *Representerer bilens bevegelser i form av aggregerte strømmer.*

Statisk trafikkavviklingsmodell: *En modell som fordeler kjøretøyene på lenkene uten å inkludere tidsbegrepet; kan tolkes som den representerer stillestående forhold.*

Dynamisk trafikkavviklingsmodell: *En modell som fordeler kjøretøyene på lenkene ved å eksplisitt ta hensyn til tidsdimensjonen, og som fanger opp tidsmessige avhengigheter.*

Kvasi-dynamisk trafikkavviklingsmodell: *Et sett av statiske avviklingsmodeller (en per forhåndsbestemt tidsperiode) som er koblet dynamisk sammen på en forenklet måte.*

Mikroskopisk trafikkavviklingsmodell: *En modell som predikerer veivalg og bevegelse av det enkelte kjøretøy.*

Mesoskopisk trafikkavviklingsmodell: *En i bunnen mikroskopisk modell som representerer veivalg og/eller kjøretøybevegelse på et mer aggregert nivå av kjøretøygrupper.*

Makroskopisk trafikkavviklingsmodell: *En modell hvor fordelingen av trafikken på lenkene er basert på en aggregert gruppe av kjøretøy, og hvor bilens dynamikk er basert på makroskopiske strømningsprinsipper.*

A.1.2: Illustration of couplings in terms of a departure time choice model.

The implications of coupling static/dynamic, aggregate/disaggregate, and deterministic/stochastic demand and supply models are illustrated in terms of a departure time choice model.

In a static travel demand model, the notion of departure time is meaningless due to the implicit stationarity assumption. In a dynamic travel demand model, departure time choice makes sense. However, the model has added value only if variability in the attributes of the alternatives (the departure times to select from) is captured. This information needs to be provided by the network assignment package. More generally, and also in terms of other behavioural dimensions: The notion of a traveller who is able to perceive time is of little value if the concept of time does not exist in the physical environment.

One could then add traveller heterogeneity (for instance, different values of time, car ownership, desired arrival times) to the travel demand model, either through a demand segmentation or in terms of a synthetic population. The usefulness of this approach depends again but less on the capabilities of the network assignment package. For many purposes, it may still be enough to run a network assignment package that only provides time-dependent travel impedances. However, once the travel demand model distinguishes driving or route choice behaviour, this information should also be reflected through an adequate degree of disaggregation in the network assignment package. The problems that may arise otherwise are suitable to also exemplify the (much more general) notion of aggregation bias.

Assume that there are N travellers, half of which (class 1) strictly prefer short routes while the other half (class 2) strictly prefers fast routes. The network consists of two routes only. Route 1 has a fixed length d_1 and a fixed travel time t_1. Route two is shorter (for convenience, assume that $d_1 - d_2$ is positive but not larger than N) but has a congestion-dependent travel time $t_2 = t_1 + n_2$, where n_2 is the number of travellers on route 2.

If the two traveller classes can be distinguished in the assignment package, then all class-1 travellers take route 2 because it is shorter. Since t_2 exceeds t_1 as soon as a single traveller takes route 2, all class-2 travellers take route 1. One hence has $n_1 = n_2 = N/2$.

Now consider a network assignment package that can model only a single traveller class. The approach of throwing both classes together and assuming a homogenous 50/50 preference for both distance and travel time may come to mind. The assignment package would then equilibrate the route costs $d_1 + t_1$ and $d_2 + t_2$, leading to $n_2 = d_1 - d_2$ and $n_1 = \mathrm{N} - n_2$.

For any network geometry other than one leading to $d_1 - d_2 = \mathrm{N}/2$, not only the network flows are wrongly predicted. Also, the behavioural model is inconsistently evaluated: The only travel time sensitive population segment (class 1) bases its route choice on travel times resulting from route choice that accounts for distance as much as for travel time.

Finally, one may want to account for travel time reliability in the departure time choice model. Loosely speaking, one wishes to capture that travellers may depart a bit earlier than on average necessary such that they are not late even if travel times are slightly higher than expected. The size of this «safety buffer» depends on the degree of variability in the travel time. This requires a model that can predict this variability. However, the realistic simulation of travel time variability within a network assignment package is only a slowly emerging capability. While closing this gap is an important topic for research, current practice hardly accounts for it.

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