Liikenne 2023

Tieteellinen vuosikirja

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Viime vuosikerran johdannossa synkistelin Liikennesuunnittelun Seuran ja Yhdyskuntasuunnittelun seuran yhteistyön mahdottomuutta. Rationalismin ja utilitarismin kaapuun ja kvasitaloustieteellis-kvantitatiiviseen insinööritieteeseen sitoutuneen liikenne"tekniikan" ja "pehmeämmän", ihmis- ja nyttemmin biolähtöisen, monitieteisemmän, kvalitatiivisen ja myös estetiikkaa huomioivan kaupunkisuunnittelun yhteistyölle ei näkynyt mahdollisuuksia. Liikennesuunnittelu on vihreässä siirtymässä 2020-luvulla yhtä tärkeää kuin se oli auton voittokulkua siloittavana uutena amerikkalaisena tieteenä 1960-luvulta lähtien. Insinöörien maailmassa on toki seksikäämpää rakentaa jotain uutta, komeaa ja äänekästä, kuin ajaa alas ja muokata uudelleen, vähemmän saastuttavaksi. Vaikka yllä mainitut paradigmaattiset erot yhä pääosin vallitsevatkin, liikennesuunnittelun vääjäämätön tärkeys osana yhdyskuntasuunnittelua, puhumattakaan Suomen runsaasta yhdistysverkostosta, auttoi. Läheltä katsottuna talot voivat olla kaukana toisistaan, mutta kauempaa katsottuna ne ovat samaa kaupunkia. Tulevaisuuden tutkimuksen seura, erityisesti sen Helsingin toimintaryhmä (TUTUHESA) on kiitettävän ennakkoluulottomasti hakeutunut yhteistyöhön sekä YSS:n että LSS:n kanssa, niin että aikanaan (vuonna 1974) eronneet ovat jopa tulleet TUTUHESAN saattelemana järjestäneeksi yhdessä yleisötilaisuuden nyt syksyllä 2023. Sille näyttäisi tulevan myös jatkoa.

Edelleen YSS ja LSS käyttävät samaa, Tieteellisten Seurain Valtuuskunnan jäsenilleen tuottamaa digitaalista julkaisualustaa, mikä helpottaa muun muassa yhteistenkin arvioitsijoiden rekrytointia. Vuoden 2024 Liikenne-vuosikirjaan tarkoitetut artikkeli- ja katsauskäsikirjoitukset tuleekin toimittaa yksinomaan, siis vain ja ainoastaan, internet-osoitteeseen liikenne.journal.fi (vaatii kirjautumisen).

Artikkelit

Kun informaation yksityisyyttä Euroopassa suojeleva, laillisesti velvoittava Tietosuoja-asetus annettiin 27.4.2016 ja tuli voimaan 25.5.2018, käytiin Suomessakin aiheesta vilkasta keskustelua. Asiantuntijat myivät osaamistaan varoittelemalla vaaroista ja avoimen datan yhteisöt ja Aalto-yliopisto aloittivat vuonna 2016 (edelleen järjestettävät) kansainväliset MyData-konferenssit. Nyt, reilu viisi vuotta myöhemmin, käytämme laajempia henkilötietomääriä tietoisemmin kuin ennen, mutta olemme myös huomanneet, että sanktioita Tietosuoja-asetuksen vajaasta toteutuksesta ei kovin helposti rapise.

Osana liikenteen digitalisaatiota perinteisen mekaanisfyysisen insinööriosaamisen pitäisi lähentyä tietotekniikan ja uuden lainsäädännön osaamista. Joukkoliikenne on perinteisesti keskittynyt ihmismassojen liikutteluun mekaanisella kalustolla, mahdollisimman kustannustehokkaasti. Yksittäisen matkustajan oikeuksia tärkeämpää on ollut tämän matkustusoikeuden toteaminen.

Koska liikenne yhdistää monia toimi- ja tieteenaloja, Liikenne-vuosikirja julkaisee toisinaan artikkeleita, joissa liikenneasioita käsitellään jonkun muun tieteenalan kuin liikennetekniikan näkökulmasta. Artikkelissaan "Henkilötietojen käsittelyn läpinäkyvyys ja joukkoliikenteen mobiilisovellukset", Mickelson et al. huomauttavat oikeusopin näkökulmasta, että henkilötietojen käsittely ei ole joukkoliikenteen mobiilisovelluksissa kovinkaan läpinäkyvää, eivätkä tietosuojaselosteet ole kovinkaan helposti saatavilla. Monissa joukkoliikenteen sovelluksissa käyttäjän henkilötietoja valuu kolmansille osapuolille, jopa Euroopan talousalueen ulkopuolelle. Tyypillisesti yksittäinen matkustaja ei ymmärrä tai jaksa huolestua henkilökohtaisten tietojensa käytöstä, saati yhdistelemisestä, joten on tutkijoiden asia nostaa asia esiin.

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Rautatieasemat 1800-luvulta lähtien, varsinkin Euroopassa, Venäjällä ja Aasiassa ovat olleet kaupunkien komeita ja keskeisiä rakennuksia, kansakunnan keskusvallan symboleja. Vaatimattomampienkin juna-asemien ympärille on kehkeytynyt vuosien ja vuosikymmenien mittaan kaupankäyntiä ja muuta toimeliaisuutta, kuten Pohjois-Amerikassa 1800-luvulla. Kehittymättömämmän yhdyskuntarakenteen oloissa kaupunki on kasvanut vähitellen aseman ympärille. 1900-luvun puolella, kun asiakas- tai matkustajakeskeisyydestä, saati matkaketjuista ei vielä ollut kuultukaan, "kilpailevien liikennemuotojen" kuten linja-autojen asemat tehtiin monesti aivan eri puolelle kaupunkia. Toki vanhojen kaupunkien kaavoitus- ja maanomistusolot asettavat reunaehtojaan, mutta Suomen mitassa on edelleen surkuhupaisen selvää, miten vähän suurta VR:ää ja pieniä linja-autoyrityksiä tai edes Matkahuoltoa on kiinnostanut mahdollistaa tai edes opastaa matkustajia siirtymään junasta pitkän matkan bussiin tai toisin päin. (Nykyään Matkahuollon reittiopas voi kyllä sisällyttää junan matkaketjuun, mutta VR:n vastaava ei tarjoa kaupunkien välisiä bussiyhteyksiä.) Tällaista taustaa vasten ei ole ihme, että nykyisin vallalla oleva systeeminen näkemys matkustajaliikenteestä yhteys- ja palvelujärjestelmänä ei toteudu käytännössä helposti. Joukkoliikennesuunnittelijaa on perinteisesti kiinnostanut enemmänkin linjan matka-aika ja linjastoverkko, tai detaljina vaikkapa bussilaiturien järjestelyt, kuin yksittäisen asemarakennuksen suunnittelu. Se on ollut arkkitehtien ja kiinteistötalouden maailmaa. Tätä tutkivat Rusanen & Wiest katsausartikkelissaan "Analysis of multimodal passenger terminal design and its effects on transfer penalty", keskittyen lähinnä liikennemuodon tai linjan vaihtoihin julkisen liikenteen matkaketjussa. Rationalismiin ja utilitarismiin sitoutuneen liikennesuunnittelun kielellä vaihtoon kuluvaa aikaa ja vaivaa voidaankin kutsua "siirtosakoksi" (transfer penalty), kuten tässäkin artikkelissa tehdään. Yleiskieliseen korvaan se kuulostaa yhtä liioittelevalta kriisiytymiseltä kuin liikennepyskologian tapa kutsua tieliikenteessä liikkujien kohtaamista konfliktiksi. Kirjoittavat päätyvät toteamaan kohteliaasti, että liikenneterminaalien suunnittelulla on tärkeä rooli paitsi siirtokokemukseen, myös matkustustyytyväisyyteen ylipäänsä.

Kolmannessa joukkoliikenneaiheisessa artikkelissa "E-Bus Scheduling". Elmas & Zabrin pureutuvat akkukäyttöisellä sähköllä kulkevien kaupunkibussien operointiin. Sähköbussin energiakustannus on polttomoottoribussiin verrattuna houkutteleva, paikallisten päästöjen vähentymisestä puhumattakaan.

Liikennetekniseen keskusteluun on jo kehkeytynyt oma keskustelun alansa, jonka voinee kääntää suomeksi suunnilleen sähköauton aikataulutusongelmaksi. Polttomoottorista sähköllä kulkeviin busseihin siirryttäessä ei muutu vain voimanlähde. Tarvitaan myös operoinnin uudelleenjärjestelyjä, sillä sähköbussin ajokilometrit yhdellä latauksella ovat tällä hetkellä pienemmät kuin yhdellä tankkauksella. Ajojärjestelyt ja kuljettajien ajoajat täytyy suunnitella toisin.

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Suomalaisen sosiologian päävirta harrasti niin sanottua empiiristä sosiaalitutkimusta reikäkorttikoneiden ajasta aina 1990-luvulle saakka. Kvantitatiivisia kyselyitä tehtiin ja analysoitiin huolella, jotta saataisiin mahdollisimman hyvin kohderyhmää edustavia otoksia. Vastaavat menetelmät ovat edelleen käytössä liikennetutkimuksessa, vaikka aiheena olisi niinkin laadullinen asia, kuin asukkaiden kokemus liikkumiseen liittyvästä hyvinvoinnistaan. Artikkelissaan "Travel barriers affecting subjective wellbeing in Tampere, Finland" Sjögren et al. osoittavat, että matkustamisen koetut esteet ovat yhteydessä kaupunkilaisen subjektiiviseen hyvinvointiin. Vaikka tulos ei ehkä aiheuta suuria lööppejä iltapäivälehdissä, artikkeli toimii myös hyvänä oppimateriaalina empiirisen sosiaalitutkimuksen huolellisessa soveltamisessa liikennealalle.

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1800- ja 1900-lukujen taitteessa länsimaiden parempi väki - pieni eliitti - harrasti polkupyöräilyä. He käyttivät vaikutusvaltaansa myös saadakseen parempikuntoisia teitä, joita myös alkava autoliikenne otti käyttöönsä, sekin toki aluksi vain kesäisin. Autoilun voittokulku eteni rinta- ja reunamaissa kovin eri tahdilla, mutta joka tapauksessa liikenteellisesti pyöräily marginalisoitui 1900-luvun mittaan lähinnä vapaa-ajan harrastukseksi, joitain poikkeuksia lukuun ottamatta, kuten Oulu tai Kiina. Marginalisoitumisen vuoksi suomalaisessakin kaupunkisuunnittelussa pyöräteitä tai -kaistoja (kävelykeskustoista puhumattakaan) on tehty viime vuosikymmeninä sinne mihin on mahtunut tai missä autoliikenne on havaittu vähäiseksi. Valtion rahoilla on toki kaupunkiseuduille ja kyläkeskuksiin tehty valtaväylien kylkeen laadukkaita "kevyen liikenteen väyliä", kuten jalankulku- ja pyöräteitä kutsuttiin vielä 2000-luvun alkuun saakka. Maantiet, moottoritiet ja ohitustiet vain tapaavat olla erillisiä siitä taajaman sisäisestä liikkumistarpeesta, jonka takia ihmiset pyöräilevät. Nykyään tiedostetaan jo Suomessakin, että polkupyörällä pitäisi päästä turvallisen tuntuisesti ja helposti hahmotettavaa reittiä pitkin monista paikoista moniin paikkoihin. Tästä lähtee polkemaan Talvitie & Kuivalaisen artikkeli "Efficient bicycle networks and expansion strategies". He esittelevät kaupunkien arviointikehikkoja pyörävihamielisestä pyörädominoivaan ja mittaustapoja pyöräilyverkon yhdistävyydelle, ajosuunnille (miten suoraan paikasta toiseen pääsee pyöräväylää pitkin) ja verkon kattavuudelle eli pyöräväylien saatavuudelle. Pyöräilyverkon tiheyden kasvattamiselle he esittävät samankaltaisesti relisienssi- vs. investointien taloudellisuus perusteita. Argumentaatio kuulostaa saman tyyppiseltä kuin aikanaan Kekkosen Suomen kansallisessa tehtävässä rakentaa koko maan kattava maantieverkko.

Peruskirjallisuuskatsaukset

Toinen tämän vuosikirjan pyöräilyartikkeli tulee jatkaneeksi Liikenne-vuosikirjassa 2022 aloitettua keskustelua pyöräilyn ja kelin yhteydestä. Viime numerossa Juga et al. testasivat empiirisesti mallia, jossa kolmen pyörälaskuripisteen perusteella seurattiin pyörämäärien kausivaihtelua Helsingissä, kun tekijöinä olivat lämpötila, ilman kosteus ja lumen määrään. Pyöräilyn kausivaihtelu todettiin suureksi, samoin kuin se, että talvikunnossapito olisi tärkeä elementti mallissa, koska lumen sademäärällä ei näyttänyt olevan vaikutusta pyöräilymääriin (Liikenne-vuosikirja onkin juuri oikea foorumi julkaista ensimmäisiä versioita tutkimuksesta).

Kirjallisuuskatsauksessaan "Relationships between weather and cycling" Kane & Kythreotis tarkastelevat yleisemmin ja elementaarisemmin vastaavia, sangen intuitiivisia, tekijöitä (tulevaisuudessa, kun Liikenne-vuosikirja on tunnetumpi ja digitaalisempi, kirjoittajat huomannevat saman aihepiirin artikkelit julkaisussa, johon ovat kirjoittamassa). Sen lisäksi he pohtivat myös kovariansseja eli muiden muuttujien välisiä suhteita - pyörämatkan tarkoitusta pyöräilijälle, alueen ja pyöräilijöiden sosiodemografisia, henkilökohtaisia tekijöitä sekä rakennetun ympäristön vaikutusta. Metodologisesti kirjoittajat kritisoivat suoraviivaista tapaa selittää ihmisen subjektiivista toimintaa yksinomaan objektiivisilla mittareilla. Kritiikki yltää myös omaan kirjallisuusaineistoon, joka tuppaa olemaan kovin länsimaista ja kotoisin globaalista pohjoisesta. Ilmiö on hyvin yleinen kaikessa länsimaisessa akateemisessa kirjallisuudessa.

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Tavaraliikenne on yksi perinteinen aihe liikennetekniikassa ja tietenkin logistiikassa. Nettiostoskelun lisääntyminen lisää pakettien kuljetusta, samalla kun perinteisten kirjekuorien ja korttien postitus vähenee. Babjak & Yung käyvät läpi 130 akateemista julkaisua siivilöivässä kirjallisuuskatsauksessaan “Zero emission freight transport and impacts on last mile delivery” pääasiassa kuljetusketjun viimeisen, asiakkaalle kuljettamisen, vaiheen vaihtoehtoja. Ne ovat jalkakäytävällä tai tiellä kulkevien jakelurobottien ja ilmassa kulkevien droonien etuja ja heikkouksia verrattuna perinteiseen polttomoottorikäyttöiseen kuorma-autojakeluun, suoraan asiakkaille tai erilaisiin jakelupisteisiin. Onkohan Suomessa edes kokeiltu kirjoittajien kuvaamia “emoaluksia”, joista lähtee pienempiä robottijakelijoita viemään tavaroita sille ihan viimeiselle mailille.

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Perinteisessä liikenne- ja tieteknisessä tai jopa liikennejärjestelmätarkastelussa on keskitytty enemmänkin väyliin, liittymiin ja näiden kykyyn välittää ajoneuvoliikennettä mahdollisimman sujuvasti, ja tietenkin päästöjä. Muissa kaupunkisuunnittelun kannalta tärkeissä tieteenaloissa, kuten arkkitehtuurissa ja yhdyskuntasuunnittelussa on puolestaan keskitytty rakennuksiin ja muuhun maankäyttöön, sekä ihmisiin asukkaina, työntekijöinä, vapaa-ajan harrastajina. Se välitila liikennejärjestelmän ja kaupunkirakenteen välillä, jossa autoilija ja matkustajat astuvat ulos autosta ja jättävät sen tekemään pääasiallista tehtäväänsä, siis sitä, johon se käyttää enimmän aikansa eli odottamaan pysäköitynä seuraavaa lähtöä, milloin ja mihin tahansa, jää marginaaliin. Arkkitehtuurissa autojen pysäköinti on jotain likaista ja rumaa, joka halutaan peittää pois näkyvistä, maan tai rakennuksen alle. Jäljelle jää kiinteistötalous, joka yrittää sovitella autojen pysäköinnin suuria kustannuksia olosuhteiden mukaan, tietoisena siitä, että kukaan ei halua kantaa lopullista vastuuta pysäköinnin markkinahintaisista investointi, kunnossapito- ja peruskorjauskustannuksista. Niinpä uusissa asuinkohteissa se yrittää minimoida ja yrityskohteissa maksimoida autopaikkojen määrän. Tämä kaikki tuottaa kysyntää edulliseksi subventoituun julkiseen pysäköintiin kadunvarsilla ja muilla yleisillä alueilla. Niinpä onkin kiinnostavaa lukea viimeisestä peruskirjallisuuskatsauksesta klassisesta San Franciscon joustavan hinnoittelun kokeilusta reilun kymmenen vuoden takaa. Keskustan koealueella oli lähes 20 000 autopaikkaa, joista alle puolet kadunvarressa. Eurooppalaisittain halpoja suurkaupungin kahden-kolmen dollarin tuntihintoja muutettiin kuuden viikon välein nostamalla niitä 25 sentillä jos yli 80% autopaikoista oli varattuna tai pudottamalla 50 sentillä, jos kysyntää oli alle 60% paikoista. Kunnan tavoitteena oli siis pitää pysäköintikysyntä 60% ja 80% välillä päiväsaikaan. Nykyisen eurooppalaisen digitaalisen pysäköinninmaksun aikana "SF Park" ei vaikuta kovinkaan dynaamiselta, mutta jonkinlaista hintajoustoa haluttuun suuntaan San Franciscossa kyllä havaittiin. Tästä kirjoittaa katsauksessaan Huber, otsikolla "Dynamic parking pricing: implementation in North-America".

Suomenkin pysäköintialalla on pitkään keskusteltu pysäköinnin dynaamisen hinnoittelun käyttöönottamisesta - teknisestihän se ei olisi vaikeaa. Suurilla kaupungeilla ei Suomessa kuitenkaan näytä olevan asiassa kunnianhimoa, eikä ehkä riittävän toimivaa yhteistyötä suurten kaupallisten pysäköinti- ja pysäköinninmaksuoperaattorien kanssa. Hyvinvoinnin oloissa muutokset tapahtuvat kriisien kautta. Koronan jälkeen osassa Helsingin ydinkeskustan p-laitoksista on ollut arki-iltaisin ja viikonloppuisin hyvinkin edullista pysäköidä.

Lopuksi

Yksi Liikenne-vuosikirjan missioista on tarjota mahdollisuus suomenkieliseen liikennealan akateemiseen julkaisemiseen ja siten ylläpitää omalta pieneltä osaltaan pienen kielialueen kirjallista keskustelua. Selvää kieltä valtavirrasta kuitenkin puhuu se, että tämän vuosikirjan artikkeleista vain yksi oli kirjoitettu suomeksi ja sekin enemmän oikeusopillisesta kuin perinteisen liikennetutkimuksen näkökulmasta. Kaikki muut artikkelit oli kirjoitettu englanniksi, Sjögren et al.'ia lukuun ottamatta vieläpä amerikanenglanniksi. Näin ehkä kunnioituksesta modernin eli tässä yhteydessä 1900-luvun liikennetekniikan alkuperämaata kohtaan. Kirjoitetaanhan esimerkiksi Aalto-yliopiston englanninkielisen maisteriohjelman nimi amerikkalaisittain “Spatial Planning and *Transportation* Engineering” (kursiivi kirjoittajan). Johtuneeko professorien taustoista, että muissa suomalaisissa liikennealan ylemmissä opinahjoissa (esim. Tampereen ja Oulun yliopistot) käytetään brittimuotoa *transport* (näin myös käytännön liikennesuunnittelijoita tuottavassa HAMK’ssa), kun taas Lappeenrannan teknillinen yliopisto näkyy käyttävän molempia muotoja vaihtelevasti, ehkä tahattomasti. Joka tapauksessa, odotamme jatkoa ja uusia käsikirjoituksia mielenkiinnolla - suomeksi, erilaisiksi englanneiksi - ja tietenkin myös ruotsiksi. Aivan mahtavaa olisi, jos tulevissa vuosikirjoissa viitattaisiin julkaisuihin, jotka on kirjoitettu myös muilla kuin anglo-amerikkalaisilla ja eurooppalaisilla kielillä. - Nykyopiskelijoiden ja tutkijoiden äidinkielien kirjo Suomessa mahdollistaisi tämän.

Henkilötietojen käsittelyn läpinäkyvyys ja joukkoliikenteen mobiilisovellukset

Mickelsson, Sini, OTM, Turun yliopisto, Oikeustieteellinen tiedekunta. Carlsson, Robin, tekniikan ylioppilas, Heino, Timi, tekniikan kandidaatti, Rauti, Sampsa, diplomi-insinööri, Leppänen, Ville, filosofian tohtori, Turun yliopisto, Teknillinen tiedekunta

Tiivistelmä

Joukkoliikenteen käyttäminen on monelle kansalaiselle välttämättömyys, joten joukkoliikenteen mobiilisovelluksien toiminnan tulee olla avointa ja luotettavaa. Tässä artikkelissa tutkimme henkilötietojen käsittelyn läpinäkyvyyden toteutumista suomalaisissa joukkoliikenteen mobiilisovelluksissa havainnoimalla empiirisesti sovellusten tietosuojaselosteiden saavutettavuutta ja sisältöjä sekä analysoimalla teknisillä työvälineillä sovellusten tekemiä tietojen siirtoja. Henkilötietojen käsittelyn läpinäkyvyydessä vaikuttaisi tutkimuksemme perusteella olevan selkeitä puutteita: yli kolmella neljäsosalla tutkituista neljästätoista sovelluksesta ei ollut helposti saatavilla sellaista tietosuojaselostetta, joka kuvaisi henkilötietojen käsittelyä kyseisessä sovelluksessa. Havaitsimme myös, että osa sovelluksista lähetti henkilötietoja kolmansille osapuolille ja Euroopan talousalueen ulkopuolelle, vaikka sovellusten tietosuojaselosteissa ei tiedotettu tästä selkeästi käyttäjille.

1. Johdanto

Kuntalainen hyödyntää joukkoliikennettä päästäkseen lääkärin vastaanotolle paikalliselle terveysasemalle. Hän huomaa ostaessaan lipun joukkoliikenteen mobiilisovelluksen kautta, että kyseisen sovelluksen käyttöehdot ovat pituudeltaan useita A4-arkkeja tiivistä tekstiä. Tottuneesti henkilö navigoi ostamaan lippua lukematta ehtoja. Kyseessähän on julkinen, luotettava toimija eikä hänellä ole varaa muuhun kuljetukseen kuin paikallisbussiin. Jos kyseinen sovelluksen käyttäjä olisi lukenut käyttöehtojen henkilötietojen käsittelyä koskevan osion, hän olisi huomannut, ettei niiden sisältö oikeastaan lainkaan selvennä sitä, miten henkilötietoja käsitellään sovelluksessa. Joukkoliikenteen mobiilisovellus voi lähettää käyttäjää koskevia tietoja useille eri tahoille ja maantieteellisiin sijainteihin ilman, että käyttäjällä on siitä selkeää tietoa tai ymmärrystä.

Henkilötietojen käsittelyn läpinäkyvyydestä säädetään Euroopan unionin yleisessä tietosuoja-asetuksessa (TSA). Tässä artikkelissa tutkimme, onko joukkoliikenteen mobiilisovelluksissa tietosuojalainsäädännön edellyttämällä tavalla helposti saatavilla tietoa henkilötietojen käsittelystä. Tarkastelemme myös, lähettävätkö mobiilisovellukset käyttäjää koskevia tietoja kolmansille osapuolille ja Euroopan talousalueen ulkopuolelle ja arvioimme, tiedotetaanko näistä siirroista tietosuojalainsäädännön edellyttämällä tavalla käyttäjää. Tarkastelun kohteena ovat erityisesti tietosuojaselosteiden helppo saatavuus sekä tiedonsiirroista ja tietojen vastaanottajista tiedottaminen. Saavutettavuus on ylipäätänsä koko henkilötietojen käsittelystä tiedottamisen toteutumisen edellytys. Tietojen siirtoihin on puolestaan kiinnitetty erityistä huomiota oikeuskäytännössä viime vuosina (C-311/18, Facebook Ireland and Schrems; Itävallan tietosuojaviranomaisen ratkaisu 22.12.2021; TSV 30.12.2021; TSV 27.4.2023; Irlannin tietosuojaviranomaisen ratkaisu 12.5.2023).

Metodologisesti artikkeli hyödyntää kahta, toisiaan täydentävää lähestymistapaa. Tutkimuksessa tarkasteltujen läpinäkyvyysvaatimusten määrittämisessä on hyödynnetty lainopillista lähestymistapaa eli muodostettu systemaattinen tulkinta siitä, mitä vaatimuksia lainsäädäntö, oikeuskäytäntö ja viranomaisohjeistukset asettavat henkilötietojen käsittelyn läpinäkyvyydelle. Lainopillisella lähestymistavalla on tutkimuksessa pääasiallisesti taustoittava rooli: lainsäädännöstä ja muista oikeuslähteistä johdetut vaatimukset tarjoavat viitekehyksen, mitä vasten joukkoliikenteen mobiilisovellusten toimintaa ja henkilötietojen käsittelyä koskevaa tiedottamista voidaan analysoida. Artikkelin keskiössä olevassa empiirisessä tutkimuksessa läpinäkyvyysvaatimusten toteutumista arvioidaan sekä havainnoimalla sovellusten tietosuojaselosteiden saavutettavuutta ja sisältöjä että tutkimalla sovellusten tekemiä tietojen siirtoja verkkoliikenneanalyysin avulla.

Julkisten toimijat eivät aina kaikilta osin ole onnistuneet antamaan tietosuoja-asetuksen edellyttämällä tavalla läpinäkyvästi tietoa verkkosivuillaan ja mobiilisovelluksissaan henkilötietojen käsittelystä (Heino ym. 2022; Carlsson ym. 2022; TSV 13.12.2022). Tutkittaviksi valittiin joukkoliikenteen mobiilisovellukset, sillä joukkoliikennepalvelut ovat osa kaikenikäisten ihmisten arkea, ja joukkoliikenteen käyttäjiin lukeutuu myös haavoittuvaan ihmisryhmään kuuluvia käyttäjiä kuten lapsia ja vanhuksia. (Traficomin tutkimuksia ja selvityksiä 1/2023, s. 70–71; Liikenneviraston valtakunnallinen henkilöliikennetutkimus 2016, s. 1.) Tulevaisuudessa matkamäärien ennustetaan myös entisestään kasvavan (Metsäranta – Weiste 2019, s. 12). Laajasti käytetyn julkisen palvelun tarjoajina joukkoliikenteen toimijoiden voisi myös olettaa hoitavan henkilötietojen käsittelyn ja sähköisten palvelujensa tietosuojan esimerkillisesti.

Seuraavassa luvussa taustoitetaan henkilötietojen käsittelyn läpinäkyvyyden merkitystä lainsäädännön ja aiemman tutkimuksen avulla. Tämän jälkeen esitellään tutkimusaineisto ja -menetelmät sekä tulokset. Lopuksi käydään läpi johtopäätelmät.

2. Tausta

Henkilötietona pidetään kaikkia tunnistettuun tai tunnistettavissa olevaan henkilöön eli rekisteröityyn liittyviä tietoja (TSA 4(1) artikla). Henkilötiedon käsitettä tulkitaan lähtökohtaisesti laajasti, joten monenlaiset yksilöön yhdistettävissä olevat tietotyypit katsotaan henkilötiedoksi (WP 136, s. 4–5; Korpisaari ym. 2018, s. 52–53, 61–62; Bygrave – Tosoni 2020, s. 113–114). Tietosuoja-asetus edellyttää, että rekisteröidyille on oltava läpinäkyvää, miten ja missä laajuudessa heitä koskevia henkilötietoja käsitellään. Henkilötietojen käsittelyyn liittyvien tietojen ja viestinnän on oltava helposti saatavilla ja ymmärrettävissä ja niissä on käytettävä selkeää ja yksinkertaista kieltä (TSA 5(1) artikla; TSA:n johdannon resitaalit 39 ja 58).

Henkilötietojen käsittelyn läpinäkyvyys on perinteisesti nähty keskeisenä edellytyksenä yksilön mahdollisuudelle valvoa ja vaikuttaa henkilötietojensa käsittelyyn (WP 260 rev.01, s. 5; COM(2010) 609 final, s. 6.). Läpinäkyvyyteen liittyvä oikeustieteellinen keskustelu on linkittynyt erityisesti tiedollisen itsemääräämisoikeuden ja suostumuksen käsitteisiin. Tiedollisella itsemääräämisoikeudella tarkoitetaan rekisteröidyn valtaa päättää siitä, miten ja mitä tietoa hänestä annetaan muille (Westin 1967, s. 7; Saarenpää 2011, s. 508; Voutilainen 2019, s. 33–36). Oikeustieteellisessä keskustelussa on kuitenkin epäilty rekisteröityjen tosiasiallista kiinnostusta ja kykyä ymmärtää monimutkaisista käsittelytoimenpiteistä annettuja tietoja ja eri käsittelytoimiin myöntymisen seurauksia (Blume 2012, s. 31; Buitelaar 2012, s. 178–179; Koops 2014, s. 252; Van Alsenoy ym. 2014, s. 189–190; van de Waerd 2020, s.13–14; Graef – van der Sloot 2022, s. 519–521). Erityisen ongelmallisena läpinäkyvyyden toteutuminen on nähty verkkoympäristöissä (Edwards 2014, s. 190–191). Ongelmia on pyritty ratkaisemaan muun muassa oikeudellisen muotoilun keinoin (Koolen 2021, s. 178–183).

Oikeuskirjallisuudessa on katsottu tietosuoja-asetuksen lähestyvän henkilötietojen käsittelyä erityisesti organisaatioiden vastuiden ja rekisteröityjen oikeuksien näkökulmasta (Hustinx 2017, s. 153–154; Docksey 2020, s. 560). Yksilön kontrollin maksimoimisen sijaan tavoitteena on nähty olevan ensisijaisesti henkilötietojen asianmukaisen käsittelyn varmistaminen (Hijmans 2020, s. 52). Läpinäkyvyydellä on kuitenkin nähty yleisesti olevan sekä tärkeä rooli tiedollisen asymmetrian tasoittamisessa eri osapuolten välillä (Koillinen 2012, s. 186–187; van de Waerdt 2020, s. 14) että legitimiteettiä luova vaikutus erityisesti julkisen hallinnon kontekstissa

(Koivisto 2021, s. 342). Henkilötietojen käsittelyn läpinäkyvyys voi lisätä luottamusta ja mahdollistaa rekisteröidyn sekä ulkoisten tahojen kontrollin (WP 260 rev.01, s. 4–5). Tietojen antaminen tietosuojaselosteen muodossa on ollut alan vallitseva käytäntö. Tietosuojaselosteet voivat muodostaa toimivan tiedonlähteen käyttäjän päätöksenteon tueksi, mikäli ne ovat helposti saatavilla ja antavat ymmärrettävää tietoa henkilötietojen käsittelystä.

3. Tutkimusaineisto ja -menetelmät

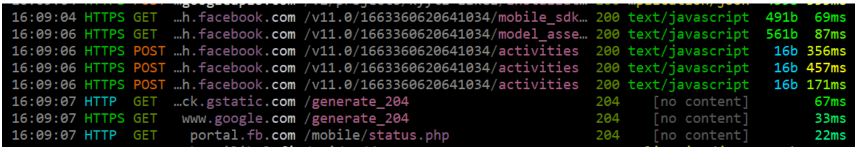
Tutkimukseen valittiin mukaan Suomen 15 suurimman kaupungin joukkoliikenteen mobiilisovellukset. Kunkin kaupungin joukkoliikennesovelluksen nimi selvitettiin, sovellukset etsittiin Google Play -kaupasta ja asennettiin testipuhelimelle. Tutkittaviksi valittiin 14 sovellusta. Joillakin alueilla käytössä oli useampi sovellus, ja esimerkiksi pääkaupunkiseudulla käytetään samaa sovellusta useammassa suuressa kaupungissa. Google Play -kaupassa latausmäärät vaihtelivat yli 1 000 000 latauksesta yli 500 lataukseen. Latausmäärien mediaanina oli yli 50 000 latausta.

Tutkimuksessa arvioitiin mobiilisovellusten vaatimustenmukaisuutta tietosuoja-asetuksesta, Euroopan tietosuojaneuvoston ja sen edeltäjän tietosuojaryhmän ohjeistuksista ja tietosuojaviranomaisten oikeuskäytännöstä tunnistettuja vaatimuksia vasten. Arvioidut vaatimukset edustavat subjektiivista tulkintaamme siitä, millaisia vaatimuksia eri oikeuslähteissä on esitetty henkilötietojen käsittelyn läpinäkyvyydelle eivätkä tulokset näin ollen välttämättä edusta absoluuttista totuutta tutkittujen tietosuojaselosteiden ja käytäntöjen lainmukaisuudesta. Vaatimusten täyttymistä arvioitiin dikotomisella asteikolla (täyttyy / ei täyty). Vaatimukset avataan yksityiskohtaisesti tuloksien yhteydessä.

Läpinäkyvyysvaatimusten täyttymistä arvioitiin kahta eri lähestymistapaa hyödyntäen. Ensinnäkin havainnoitiin Google Play -sovelluskaupassa saatavilla olevia tietosuojaselosteita, sovelluksen käyttöönoton yhteydessä henkilötietojen käsittelystä annettuja tietoja sekä sovelluksen käyttöliittymän kautta saatavilla olevia tietosuojaselosteita. Tietosuojaselosteet kerättiin tammikuussa 2022. Toiseksi mobiilisovelluksen verkkoliikennettä nauhoitettiin ja tarkasteltiin sen havainnoimiseksi, mitä henkilötietoja mobiilisovellus lähettää ja minne, ja näitä tietoja vertailtiin tietosuojaselosteissa esitettyihin tietoihin. Näin läpinäkyvyysvaatimusten toteutumista päästiin arvioimaan syväluotaavasti, monipuolisen aineiston valossa.

Ohjelmistotekniikan alalla mobiilisovellusten liikenteen nauhoittamista on käsitelty useissa tutkimuksissa, joita myös tässä käytetty menetelmä mukailee. Esimerkiksi Conti ym. (2018, s. 2658–2713) tarkastelevat erilaisia tapoja nauhoittaa mobiililaitteiden verkkoliikennettä ja Liu ym. (2015, s. 59–70) tutkivat keinoja tunnistaa henkilötietoja verkkoliikenteestä. Verkkoliikenteen sisältämien henkilötietojen ja niitä vastaanottavien kolmansien osapuolien selvittämiseksi toteutetussa koeasetelmassa älypuhelin yhdistettiin internetiin WiFi-tukiasemana toimivan Linux-tietokoneen kautta. Tukiasema säädettiin nauhoittamaan puhelimen verkkoliikennettä. Koska puhelimen käyttöjärjestelmän mukana on esiasennettuja sovelluksia, jotka tuottavat verkkoliikennettä, ja koska koeympäristö ei salli liikenteen aiheuttaneen sovelluksen tunnistamista tarkasti, käyttöjärjestelmän tyypillistä liikennettä eli taustakohinaa nauhoitettiin, ja tämä kohina poistettiin kaikista nauhoituksista. Kokeissa käytettiin Samsung Galaxy J5 SM-J530F-älypuhelinta, jonka käyttöjärjestelmänä oli Android 9.

Verkkoliikennettä nauhoitettiin mitmproxy- (Mitmproxy <www.mitmproxy.org>) ja tcpdump (Tcpdump <pwww.tcpdump.org>)-työkaluilla. Mitmproxy on avoimen lähdekoodin työkalu, jota voidaan käyttää verkkoliikenteen tarkasteluun, muokkaamiseen ja toistamiseen. Tcpdump puolestaan on verkkoliikenteen pakettien analysointiin soveltuva työkalu, joka lukee ja näyttää verkkoliikenteen pakettien sisällöt käyttäjälle. Mitmproxylla nauhoitetusta verkkoliikenteestä tutkittiin sekä verkkopyyntöjen sisältöä että vastaanottajaa. Jos pyyntö lähti analytiikkapalvelun osoitteeseen, pyynnössä välitetyt mahdolliset henkilötiedot kirjattiin ylös. Laitteen taustakohinasta eroteltiin ne pyynnöt, jotka ilmenivät ainoastaan sovellusten ollessa asennettuna ja käytössä. Lisäksi monissa pyynnöissä oli jokin muu selvä yhteys testattuun sovellukseen, esimerkiksi sovelluksen nimi osana lokitietoja tai pyynnön User-Agent-otsikkoa. Lisäksi laadittiin lista analytiikkapalveluista (kuten Google ja Facebook), joihin sovellukset välittivät henkilötietoja. Kuvassa 1 on esimerkkiote nauhoitetusta verkkoliikenteestä. Verkkoliikennettä nauhoitettaessa kutakin sovellusta käytettiin aktiivisesti noin 5–10 minuuttia, ja käytön aikana käytiin läpi sovelluksen keskeinen toiminnallisuus (sovellusten tarkemmasta käytöstä ja testatuista toiminnoista on olemassa tarkempi selostus, joka on pyynnöstä saatavilla).



Kuva 1. Esimerkki tutkituista sovelluksista nauhoitetusta verkkoliikenteestä. Liikenteessä näkyy yhteydenottoja Facebookin ja Googlen palvelimille.

4. Tulokset

4.1 Helppo saavutettavuus

Tässä alaluvussa tarkastellaan tietosuojaselosteiden ja muiden henkilötietojen käsittelystä annettujen tietojen valossa läpinäkyvyysvaatimusten toteutumista tiedon helpon saavutettavuuden osalta. Tietosuoja-asetus edellyttää, että henkilötietojen käsittelystä on tiedotettava rekisteröidylle *"helposti ymmärrettävässä ja saatavilla olevassa muodossa"* (TSA 12(1) artikla; TSA:n johdannon 39 ja 58 kohdat). Mobiilisovellusten osalta rekisteröidyn tietojensaanti tulee varmistaa monella eri tasolla. Ensinnäkin tietosuojaselosteen tulee olla löydettävissä sovelluskaupasta jo ennen sovelluksen lataamista (vaatimus 1.1) (WP 260 rev.01, s. 8; WP 202, s. 23). Jotta henkilö voisi tehdä harkitun päätöksen sovelluksen lataamisesta hänen tulisi saada ennakkoon tietoa siitä, miten henkilötietoja käsitellään sovelluksessa. Toiseksi sovelluksen asentamisen jälkeen on henkilötietojen keräämisen yhteydessä annettava linkki tietosuojaselosteeseen tai vaihtoehtoisesti annettava henkilötietoja koskevat tiedot samalla sivulla, jolla henkilötietoja kerätään (vaatimus 1.2) (WP 260 rev.01, s. 8). Käytännössä tämä tarkoittaa, että tietosuojaseloste tulisi tuoda käyttäjän tietoon, kun sovellus otetaan käyttöön ja esimerkiksi käyttäjätilin luomisen yhteydessä. Kolmanneksi tietosuojaselosteen on oltava sovellusta käytettäessä löydettävissä viimeistään kahden napautuksen päästä (WP 260 rev. 01, s. 8). Tässä tutkimuksessa on edellytetty, että tiedot ovat aina enintään kahden napautuksen päässä pääsivulta niin, että napautusten jälkeen avautuvalta sivulta löytyy suora viittaus henkilötietojen käsittelyyn tai tietosuojaselosteeseen (vaatimus 1.3).

Tutkituista 14 sovelluksesta kaikissa paitsi yhdessä oli Google Play sovelluskauppaan linkattu jonkinlainen tietosuojaseloste tai kuvaus henkilötietojen käsittelystä. Syynä puuttuvaan tietosuojaselosteeseen ilmeisesti oli, että sovelluksen kehittäjän mukaan sovellus ei kerää henkilötietoja (Applen App Storesta oli kuitenkin löydettävissä asiaa koskeva lyhyt seloste). Koska kyseisen sovelluksen käytön yhteydessä käsitellään ainakin jossain määrin muun muassa käyttäjän sijaintitietoa, tässä tutkimuksessa tulkittiin, että sovellukseen liittyy henkilötietojen käsittelyä.

Pelkästään saavutettavuutta tarkastelemalla ei saada totuudenmukaista kuvaa tilanteesta käyttäjän näkökulmasta. Rekisteröidyn näkökulmasta olennaista on, että tietojen tulee koskea nimenomaan kyseistä sovellusta: tiedoksi ei tulisi antaa esimerkiksi pelkästään sovelluksen omistavan tai julkaisevan organisaation yleistä tietosuojaselostetta, jos se ei anna täsmällistä kuvaa juuri sovelluksen piirissä tapahtuvasta henkilötietojen käsittelystä (WP 260 rev. 01, s. 8). Lisäksi henkilötietojen käsittelyä koskevat tiedot tulisi aina esittää selkeästi erillään muusta kuin tietosuojaan liittyvästä tiedosta kuten sopimusmääräyksistä tai yleisistä käyttöehdoista (vaatimus 1.4), jotta rekisteröity huomaa tiedot tehokkaasti (WP 260 rev. 01, s. 7). Taulukossa 1 on arvioitu tietosuojaselosteiden saatavuutta läpinäkyvyysvaatimuksia vasten huomioiden sen, kuvaako tietosuojaseloste kyseisessä sovelluksessa tapahtuvaa henkilötietojen käsittelyä ja onko tiedot annettu selkeästi erikseen muusta tiedosta.

Tietosuojaselostetta koskeva vaatimus / mobiilisovellus	Sovellusta koskeva tietosuoja-seloste on saatavilla mobiilikaupassa (1.1 ja 1.4)	Käyttöönoton yhteydessä annetaan selkeästi tiedoksi sovellusta koskeva tietosuoja-seloste (1.2 ja 1.4)	Käytettäessä on helposti löydettävissä sovellusta koskeva tietosuoja-seloste (1.3 ja 1.4)	Tiedot esitetään erillään muusta kuin tietosuojaan liittyvästä tiedosta (1.4 erikseen)
1.	täyttyy	täyttyy	täyttyy	täyttyy
2.	täyttyy	ei täyty	ei täyty	täyttyy
3.	ei täyty	ei täyty	ei täyty	ei täyty
4.	ei täyty	ei täyty	ei täyty	ei täyty
5.	täyttyy	täyttyy	täyttyy	täyttyy
6.	ei täyty	ei täyty	ei täyty	ei täyty

Tietosuojaselostetta koskeva vaatimus / mobiilisovellus	Sovellusta koskeva tietosuoja-seloste on saatavilla mobiilikaupassa (1.1 ja 1.4)	Käyttöön oton yhteydessä annetaan selkeästi tiedoksi sovellusta koskeva tietosuoja-seloste (1.2 ja 1.4)	Käytettäessä on helposti löydettävissä sovellusta koskeva tietosuoja-seloste (1.3 ja 1.4)	Tiedot esitetään erillään muusta kuin tietosuojaan liittyvästä tiedosta (1.4 erikseen)
7.	ei täyty	ei täyty	ei täyty	ei täyty
8.	ei täyty	ei täyty	ei täyty	ei täyty
9.	täyttyy	täyttyy	täyttyy	täyttyy
10.	täyttyy	ei täyty	ei täyty	täyttyy
11.	ei täyty	ei täyty	ei täyty	ei täyty
12.	ei täyty	ei täyty	ei täyty	täyttyy
13.	täyttyy	ei täyty	ei täyty	ei täyty
14.	ei täyty	ei täyty	ei täyty	ei täyty

Taulukko 1. Läpinäkyvyysvaatimusten toteutuminen tietosuojaselosteen saatavuuden, soveltumisalan ja esittämistavan osalta.

Tutkittujen joukkoliikennesovellusten perusteella helpossa saavutettavuudessa olisi paljon parannettavaa: sovellusta koskeva tietosuojaseloste löytyi sovelluskaupasta kuudessa tapauksessa, sovelluksen käyttöönoton yhteydessä kolmessa tapauksessa ja sovellusta käytettäessä käyttöliittymän kautta vain kolmessa tapauksessa neljästätoista tutkitusta sovelluksesta. Sovelluskaupan osalta seitsemän sovelluksen osalta oli sovelluskauppaan linkitetty vain kehittäjän yleinen tietosuojaseloste, joka ei koske kyseistä mobiilisovellusta, ja yhdessä tapauksessa seloste puuttui kokonaan. Käyttöönoton ja käytön yhteydessä 8/14 sovelluksista tarjosi henkilötietojen käsittelyä koskevat tiedot käyttöehtojen osana, mutta nämä eivät tietosisällöiltään vastanneet tietosuoja-asetuksen vaatimuksia. Kolmesta sovelluksesta tietosuojaselostetta ei ollut löydettävissä lainkaan käyttöönoton ja käytön yhteydessä.

Yhteenvetona ainoastaan kolme neljästätoista sovelluksesta täytti kaikki tässä tarkastellut saatavuutta koskevat vaatimukset eli sovelluskaupasta (vyöhyke 1), sovelluksesta käyttöönoton yhteydessä (vyöhyke 2) sekä sovellusta käyttäessä (vyöhyke 3) löytyi helposti kyseistä sovellusta koskeva tietosuojaseloste. Tuloksiin numeerisesti vaikutti se, että sama palveluntarjoaja toimi seitsemän sovelluksen osalta sovelluskehittäjänä.

Kuva 2. Kuvaus vyöhykkeistä, joissa rekisteröityjä informoidaan.

Kun tiedonhaku ulotettiin myös sovelluksen ulkopuolelle eli sovelluksen kehittäjän ja palvelun verkkosivuille (vyöhyke 4) jonkinlainen sovellusta sisällöllisesti kuvaava tietosuojaseloste löydettiin kaikkien sovellusten osalta. Kahdeksassa sovelluksessa käyttäjän tuli siis käytännössä suorittaa Google-haku sovellusta koskevan tietosuojaselosteen löytämiseksi. Huomiona myös, että yhden sovelluksen osalta selosteen keskeinen sisältö oli väite siitä, ettei henkilötietoja kerätä. Kaupunkien verkkosivuilta (vyöhyke 5) oli myös tyypillisesti löydettävissä vielä erillisenä jonkinlainen joukkoliikennettä koskeva asiakasrekisteriseloste.

4.2 Tietojen vastaanottajat ja siirrot

Seuraavaksi tarkastelun kohteena ovat mobiilisovellusten tekemät tietojen siirrot ja niistä tiedottaminen tietosuojaselosteissa. Käsittelyn asianmukaisuuden arviointi edellyttää ymmärrystä siitä, millä toimijoilla on pääsy tietoihin sekä kenelle niitä siirretään. Tietojen maantieteelliset sijainnit ja siirrot vaikuttavat myös siihen, miten riskialttiiksi käsittely mielletään. Tietosuoja-asetus edellyttää, että rekisteröidylle on kerrottava henkilötietojen vastaanottajat (vaatimus 2.1) (TSA 13(1)(a) artikla ja 14(1)(a) artikla). Käytännössä vastaanottajilla tarkoitetaan kaikkia tietojen käsittelyyn osallistuvia tahoja kuten käsittelystä päättävää osapuolta tai osapuolia (rekisterinpitäjät), palveluntarjoajia sekä luovutuksensaajia (TSA 4(1)(9) artikla; WP 260 rev.01, s. 37).

Lähtökohtaisesti henkilötietojen vastaanottajat tulee nimetä. Jos ilmoitetaan nimeämisen sijaan pelkästään vastaanottajien ryhmät, tiedot tulee antaa mahdollisimman tarkasti kertomalla vastaanottajan toiminnasta, toimialasta ja sen alaluokista sekä sijainnista (vaatimus 2.2). (WP 260 rev.01, s. 37.) Oikeuskäytännössä tiedonsiirtojen osalta on määritetty vielä lisävaatimuksena, että rekisteröidyille tulee kertoa esimerkiksi palveluntarjoajista niin, että hän ymmärtää, mitä henkilötietoja on siirretty ja mitä tarkoituksia varten (vaatimus 2.3) (Irlannin tietosuojaviranomaisen ratkaisu 20.8.2021, kohta 427).

Tutkimuksessa havaittiin, että tietojen vastaanottajia käsitellään tietosuojaselosteissa joko yleisellä tasolla (13/14) tai ei lainkaan (1/14). Vain yhdessä selosteessa mainittiin nimeltä yksi palveluntarjoaja, muissa tiedottaminen tapahtui mainitsemalla palveluntarjoajan tai luovutuksen tyyppi (esimerkiksi 10/14 tietosuojaselosteesta mainitsi luovutukset maksupalveluntarjoajille ja 12/14 viranomaisille). Erityisesti käytettyjen järjestelmä- ja analytiikkapalveluntarjoajien erittely ja kuvaukset jäivät tietosuojaselosteissa niin yleiselle tasolle, ettei käyttäjä saa selkeää kuvaa käsittelyyn osallistuvista osapuolista. Tutkituissa sovelluksissa 13/14 tietosuojaselosteesta avasi ainakin jollain tasolla tietojen vastaanottajia (vaatimus 2.1).

Verkkoliikennettä tarkastelemalla todettiin, että tutkituista 14 sovelluksesta puolet (7) lähetti henkilötietoja kolmansille osapuolelle. Tietoa vastaanottavia tahoja olivat virheenjäljitystyökalu Sentry (3 sovelluksessa), Meta (2 sovelluksessa), Microsoftin App Center (1 sovelluksessa) ja Amplitude-analytiikkapalvelu (1 sovelluksessa). Yhdessäkään tietosuojaselosteessa ei nimetty näitä vastaanottajia suoraan. Kahdessa tietosuojaselosteessa mainittiin "sopimuskumppanit", neljässä "järjestelmäpalvelujen tuottajat" tai "järjestelmätoimittajat" ja yhdessä mainittiin, että kerätään analytiikkatietoa sovelluksen kaatumisen yhteydessä, mutta ei eritelty, mikä taho sen vastaanottaa. Verkkoliikenneanalyysissä tunnistettujen vastaanottajien osalta ei annettu tietoa vastaanottajan toiminnasta, toimialasta ja sen alaluokista tai sijainnista (vaatimus 2.2) eikä siitä, mitä tietoja lähetetään ja mitä tarkoituksia varten (vaatimus 2.3).

Mikäli henkilötietoja siirretään ETA:n ulkopuolelle, tietosuoja-asetus edellyttää, että rekisteröidylle kerrotaan asiasta (vaatimus 2.4) (TSA artiklat 13 (1)(f) ja 14 (1)(f); WP 260 rev.01, s. 37–38). Lähtökohtaisesti siirtojen kohteena olevat kolmannet maat tulisi mainita nimeltä (WP 260 rev.01, s. 37–38) (vaatimus 2.5). Lisäksi rekisteröidylle on kerrottava tieto niistä perusteista ja toimenpiteistä, joilla varmistetaan siirretyille henkilötiedoille vastaava suojan taso kuin Euroopan talousalueella (vaatimus 2.6) (TSA 13 (1)(f) ja 14 (1)(f) artiklat; TSA 46–47 artiklat). Oikeuskäytännössä on tarkennettu edelleen, että henkilötietojen siirtoja koskevat tiedot on lisäksi annettava yhdistettynä henkilötietokategorioihin (vaatimus 2.7) (Irlannin tietosuojaviranomaisen ratkaisu 20.8.2021, kohta 427.)

Tarkastelluista 14 joukkoliikennesovelluksesta neljä lähetti hyvin suurella todennäköisyydellä henkilötietoja Euroopan talousalueen ulkopuolelle. Tietojen vastaanottajia olivat aiemmin mainitut Sentry ja Amplitude, joiden palvelimet paikantuivat Yhdysvaltoihin. Pilvipalvelujen aikakaudella on usein haastavaa paikantaa datan vastaanottajaa täysin varmasti. Käytimme henkilötietojen vastaanottajien paikannukseen iplocation.net-palvelua, joka puolestaan tarkasti palvelimien sijainnit kahdeksalta eri paikannuspalvelulta. Sekä Sentryn että Amplituden tapauksessa kaikki kahdeksan palvelua paikansivat tietojen vastaanottajan Yhdysvaltoihin. Yhdessäkään tietosuojaselosteessa ei kuitenkaan ollut mainintaa tiedonsiirroista ETA:n ulkopuolelle. Yhdessä tosin tehtiin varauma, että ETA:n ulkopuolisia siirtoja voidaan tehdä, mutta siirroista ei kerrottu vaatimuksien 2.5–2.7 edellyttämiä tietoja.

Sovelluksen analytiikassa lähettämä tieto	**Tiedon lähettäneiden sovellusten lukumäärä (max 14)**	**Prosenttiosuus sovelluksista (max 100%)**
IP-osoite	7	50,0
Puhelimen merkki	3	21,4
Puhelimen malli	3	21,4
Puhelimen käyttöjärjestelmä	5	35,7
Käyttöjärjestelmän versio	4	28,6
Näytön koko	2	14,3
Palveluntarjoaja (esim. Elisa)	1	7,1

Laitetunniste	1	7,1
Muu / tuntematon tunniste	2	14,3
Aikavyöhyke	1	7,1
Maa	2	14,3
Sijainti (kaupunki, alue)	1	7,1
Kieli	2	14,3

Taulukko 2. Sovelluksista kolmansille osapuolille lähetetyt henkilötiedot.

Taulukko 2 listaa tutkittujen joukkoliikennesovellusten kolmansille osapuolille lähettämät henkilötiedot. IP-osoite on numerosarja, joiden avulla voidaan pääsääntöisesti yksilöidä verkkoon yhdistetty laite ja sen käyttäjä. Vaikka IP-osoitteet ovat useimmissa tapauksissa vaihtuvia, on hyvin tavallista, että sama osoite säilyy samalla laitteella ja käyttäjällä yli kuukaudenkin ajan (ks. esim. Mishra ym. 2020). Erityisesti suurilla globaaleilla analytiikkapalvelujen tarjoajilla voi olettaa olevan tehokkaita keinoja yhdistää dynaamisetkin IP-osoitteet tiettyyn käyttäjään. Vaihtuvakin IP-osoite voidaan tulkita tunnistettavissa olevaa henkilöä koskevaksi henkilötiedoksi, kun esimerkiksi verkkosivuston ylläpitäjä voi tarvittaessa laillisin keinoin saada viranomaisen hankkimaan internetyhteyden tarjoajalta sellaiset lisätiedot, jotka vaaditaan IP-osoitteen liittämiseksi yksilöön (C-582/14, Breyer, kohta 49). Käyttäjän tunnistamisessa voivat toisiinsa yhdistettynä kuitenkin auttaa sellaisetkin tiedot, jotka yksinään eivät kytkeydy tiettyyn käyttäjään. Näitä ovat esimerkiksi monet laitteeseen ja verkkoselaimeen liittyvät tiedot, kuten puhelimen merkki, käyttöjärjestelmä ja laitteen näytön koko. Koska kansainvälisiä tietojen siirtoja koskevat tiedot esitettiin tietosuojaselosteissa hyvin yleisellä tasolla, ei selosteista myöskään löytynyt erittelyä mahdollisesti siirrettävistä henkilötietojen kategorioista.

Tuloksien perusteella joukkoliikennesovellusten tietosuojaselosteiden kuvauksissa olisi tietojen vastaanottajien osalta selkeytettävää. Tutkituissa tietosuojaselosteissa käsitellään tietojen siirtojen vastaanottajia joko yleisellä tasolla tai ei lainkaan. Verkkoliikenteen analyysin perusteella puolet sovelluksista lähetti tietoja palveluntarjoajille tai kolmansille osapuolille, mutta näitä osapuolia ei nimetty tietosuojaselosteissa tai kuvattu tavalla, josta käyttäjä ymmärtäisi niitä koskevat olennaiset tiedot. Tarkastelluista 14 joukkoliikennesovelluksesta neljä lähetti hyvin suurella todennäköisyydellä henkilötietoja ETA:n ulkopuolelle, mutta tietosuojaselosteissa ei kerrottu näiden tietojen siirtojen suojatoimenpiteistä tai siitä, mitä henkilötietotyyppejä siirrettiin ja mihin tarkoituksiin.

5. Yhteenveto ja päätelmät

Joukkoliikenteen mobiilisovelluksia koskevan tutkimuksemme tulokset osoittavat, että läpinäkyvyysvaatimusten toteutumisessa on puutteita tarkastelemiemme osa-alueiden eli saavutettavuuden ja tietojen siirtojen läpinäkyvyyden osalta. Havaitsimme, että yli kolmella neljäsosalla tutkituista sovelluksista ei ollut helposti saatavilla sellaista tietosuojaselostetta, joka kuvaisi henkilötietojen käsittelyä kyseisessä sovelluksessa. Verkkoliikennettä tarkastelemalla todettiin, että tutkituista 14 sovelluksesta puolet (7) lähetti henkilötietoja kolmansille osapuolille. Lisäksi tarkastelluista sovelluksesta neljä lähetti hyvin suurella todennäköisyydellä henkilötietoja Euroopan talousalueen ulkopuolelle. Tietosuojaselosteissa oli tietojen siirtojen osalta selkeitä puutteita sekä tietojen vastaanottajista että maantieteellisistä sijainneista tiedottamisessa.

Tutkimuksemme tulokset antavat viitteitä, että joukkoliikenteen mobiilisovellusten rekisterinpitäjillä ja sovellusten kehittäjillä ei ole välttämättä selkeää kuvaa siitä, miten helppo saavutettavuus tulisi toteuttaa mobiilisovellusten osalta. Mobiilisovellusten kehittäjille suunnatun tiiviin ja selkokielisen vaatimuslistan julkaiseminen todennäköisesti ohjaisi mobiilisovellusten läpinäkyvyyskäytäntöjä oikeaan suuntaan. Läpinäkyvyyden toteuttamisessa on tärkeää, että rekisterinpitäjät tuntevat henkilötietoja koskevat käsittelytoimensa ja siirtonsa. Käytännössä tämä usein edellyttää ymmärrystä myös palkatun palveluntarjoajan teknisistä ratkaisuista ja alikäsittelijöistä.

Useissa tapauksissa havaitsimme, että joukkoliikenteen mobiilisovellusten saatavilla oleva tietosuojaseloste tai muu tietosuojaa koskeva osio ei koskenut tutkittavaa sovellusta vaan esimerkiksi kehittäjätahon yleisten verkkosivujen tietosuojakäytäntöjä. Tietosuojaselosteiden tarkoituksen toteutumisen kannalta on tärkeää, että niiden sisältö koskee täsmällisesti juuri kyseistä mobiilisovellusta ja tarvittaessa erittelee sen suhteen mahdollisiin muihin tietosuoja- tai rekisteriselosteisiin. Esimerkiksi, jos kaupungilla on erikseen joukkoliikenteen mobiilisovellusta koskeva kuvaus ja joukkoliikenteen yleistä asiakasrekisteriä koskeva rekisteriseloste, tulisi selkeästi kuvata, mikä näiden kahden selosteen välinen suhde on. Tiedot tulisi antaa rekisteröidyn kannalta ymmärrettävällä tavalla (Voutilainen 2019, s. 99). Sovelluksen käyttäjän näkökulmasta selkeintä olisi käyttää yhtä palvelu- tai sovelluskohtaista tietosuojaselostetta.

Joukkoliikenteen mobiilisovellusten käyttäjäkunnalla ei usein käytännössä ole niiden käytölle markkinoilla tosiasiallista vaihtoehtoa. Käsittelyn piirissä on myös haavoittuvassa asemassa olevia ihmisryhmiä. Yhteiskunnan merkittävien palveluiden kuten joukkoliikenteen palveluiden yhteydessä tapahtuvan henkilötietojen käsittelyn tulisi olla avointa ja pitäytyä siinä, mikä on välttämätöntä. Tällaisten palveluiden kehittäjiltä tulisi edellyttää mahdollisimman tietosuojasensitiivisten ratkaisujen tekemistä, kuten esimerkiksi sellaisen analytiikkakehyksen valitsemista, missä analytiikkatietoa ei välitetä sovelluksesta kolmansille osapuolille tai Euroopan talousalueen ulkopuolelle. Läpinäkyvyydellä edistetään sekä yksilön tiedollisen itsemääräämisoikeuden toteutumista että lisätään palveluiden luotettavuutta kansalaisten silmissä.

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Analysis of Multimodal Passenger Terminal Design and its Effects on Transfer Penalty

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Abstract

With public transit systems becoming more and more sophisticated, the likelihood of passengers having to transfer between modes or lines increases. Transferring burdens, the passenger with added mental and physical effort, referred to as transfer penalty, which has a negative effect on the travel experience. The physical design of multimodal transfer terminals, such as train stations, can have a significant effect on transfer penalties but has received relatively little attention in practice. The aim of this review essay is to create an understanding of the ways in which the physical design of terminals can influence the transfer penalties experienced by passengers. Our findings show that terminal design can influence transfer penalties through actual and perceived walking and waiting times at transfer as well as the pure transfer penalty. We identified distinct categories of design elements and of other parts of the transit systems that urban designers can employ in influencing these aspects.

Introduction

As opposed to freight transport, passenger mobility depends on the free choice of the traveller. Instead of being an inanimate cargo in the system, humans are free-floating objects in the mobility system and will decide not only whether to travel at all but also the time, route and mode(s) for traveling, depending on their perceptions of costs and benefits of the available alternatives. National and global mobility strategies strive during the ASI-strategy to shift passengers from private car mobility towards more sustainable modes, such as public transit. As public transit systems become more and more sophisticated and extensive, an increasing share of trips requires transferring from one mode or line to another. Transfers can be seen as a double-edged sword. While strengthening the network effect of public transit and offering more connectivity to passengers, transfers also disrupt the travel experience and weaken the competitiveness of public transit as opposed to private car mobility, the latter being able to provide door-to-door services (Guo & Wilson, 2011). The facilities where transfers take place have a significant effect on passengers transfer experience and consequently on the perceived 'transfer penalty' (Iseki & Taylor, 2009). Therefore, the analysis of the design and integration of terminals or hubs and how they affect the travel experience is a crucial step to understand travel mode choices, to improve comfort and to nudge travellers to change their mobility behaviour.

While a lot of research has been done on network and schedule design, analysis of the actual physical design of terminals, while declared important (Cascajo et al., 2017; Guo & Wilson, 2011), specific design guidelines seldomly surpass the level of solely fulfilling the operational needs. This essay provides an assessment of multimodal hubs in the context of existing research, focusing mainly on passenger perception, in an attempt to create a more passenger-centric understanding of transfer, as subjected by Duca et al. (2022). Our key concern is how the physical design of terminals can influence passengers' travel experience and how passengers' perceptions of transfer can be influenced. We concentrate mostly on multimodal trips that include at least one stage in public transport. While travels only with individual traffic are usually multimodal as well (even a plain car trip needs access and excess on foot), terminal design matters much less there and is usually considered with the keyword 'parking'.

The remaining essay is structured as follows. First, we explain the significance and necessity of transfers in public transit systems. Second, we explore the concept of transfer penalties and transfer utility functions. This is followed by a review of the ways in which transfer terminal design can affect the magnitude of transfer penalties. After this, we present the practical design insights found in literature. The essay is concluded with a reflective section.

The role of transfers in the public transit system

The need for transfer arises from the characteristics of public transport network design. Conventional public transit consists of the provision of comparably high-capacity mobility that runs on set routes, at set schedules and serves distinct access points (stations). While other models, such as on-demand services, are experimented with and successfully implemented occasionally, most of the public transit fulfils the conventional criteria. Furthermore, there is an anti-proportionality between coverage density and travel speed, capacity and right of way between different modes and lines. Thus, a transit network usually relies on multiple layers that address different needs in connectivity and accessibility and together provide a network of interconnected services (Allard & Moura, 2015). As can be seen in many large cities, such as Helsinki Metropolitan Area, the heavy-rail modes (commuter-train, metro) usually fulfil the role of providing the backbone connection network in the city. Few people, however, live in proximity of a commuter rail or metro station and therefore rely on the close-meshed network of buses and trams to access these stations and transfer there to a 'higher level mode' or simply change lines. This becomes even more obvious when looking at intercity connections that offer point to point services between two stations but rely on an urban transport feeder system (Allard & Moura, 2015).

One of the biggest challenges of public transit trips is the first/last mile problem. How does the traveller get from their point of origin/destination to the station that serves as entry/exit point to the public transport service? Multiple solutions exist, many relying on individual micro-mobility, such as walking, cycling or e-scooters, but also Park & Ride solutions or drop-offs can play an important role. What all of these solutions have in common is that they make a transfer between modes necessary and rely on multimodal transfer terminals. To understand transfer behaviour, we must first consider the fact that there are different types of facilities for transfer. A crucial difference lies between *intermodal* and *intramodal* transfers. While in intermodal transfers the traveller changes the mode of transport, said mode stays the same in intramodal transfers, i.e., when changing between lines. Different types of transfer terminals for passengers involve distinct modes, depending on their function in the network. The requirements of each of the forms of transport involved should be considered when designing the physical station layout to reduce the negative perception of the transfer and fulfil the operational needs. This usually involves holding bays, parking, and waiting areas, drop-off zones, but also the connection between the different access points and an adequate guidance system for travellers.

While every station could be considered as a transfer station, since even a simple bus stop must be accessed in some way, we concentrate on terminals where transfers between a multitude of modes take place. This usually involves at least two different forms of public transport to can be called a transfer hub, even though both might be in the same mode (intramodal). Although our main focus is on the effect of terminal design on transfer experiences, easing the burden of transferring naturally benefits those passengers who are accessing or egressing the station on foot or via other individual modes.

Transfer penalty

Transfers confront the traveller with some unpleasantries. Next to the obvious loss of time due to walking and waiting, and the uncomforting need to change vehicles, Cascajo et al. (2017) define "mental effort and activity disruption" as two additional negative factors caused by transfers. Mental effort concerns how much alertness and mental work is needed for the transfer, for example, in remembering the right station for the transfer or checking for connection services, while activity disruption describes how much the transfer decreases the utility of the in-vehicle time. These negative aspects of transferring explain why travellers intend to reduce the number transfers as much as possible. In fact, passengers often accept a longer travel time if it means they can avoid a transfer (Allard & Moura, 2015). Therefore, in transport science and modelling, each transfer is usually attributed with a penalty to the rider's utility. Further observations have shown that riders are especially sensitive to the time spent out-of-vehicle (Cascajo et al., 2019), and the perception of how disturbing the transfer varies depending on the passenger's perception of the transfer facility. This influences travellers' choice of where and if to transfer. Therefore, instead of simply using a fixed penal value in the general transport utility function, there have been multiple approaches to further quantify the transfer penalty factors. These consist of (1) the actual time needed to make the transfer and (2) the econometric quantification of the transfer disutility due to loss of travel experience quality (Guo & Wilson, 2011). This created the wish to distil all factors into a 'transfer utility function', that is sometimes also described as 'transfer disutility function', since the results are usually experienced as "impediments" (Liu et al., 1997) in a multimodal trip. Iseki and Taylor (2009) propose a transfer penalty, expressed in generalized costs, including monetary costs, time, paid labour, discomfort, and inconvenience:

$$TP_b = (t_{walk} * w_{walk}) + (t_{wait} * w_{wait}) + TP_n$$

The transfer penalty (TP_b) can be described as the sum of the perceived waiting time, perceived walking time and the additional transfer penalty (TP_n) that contains the costs other than the easily quantifiable monetary and time costs (Iseki & Taylor, 2009). The factor w describes the relation between the actual time invest (t) and the perceived time invest for the traveller. This factorization is needed to acknowledge the differences in time perception, depending on the task and physical environment, but also in personal traits and preferences. Cascajo et al. (2019), for example, discovered that usually out of all factors within a transfer, users penalize waiting time the most.

The influence of terminal design on transfer penalties

The concept of transfer penalty in relation to the design of transfer facilities has been studied extensively. Building on this research, various scholars have developed their own conceptualizations of the different components that influence transfer penalties. There is no consensus about the factors affecting transfer penalties found in literature (Cascajo et al., 2019), so this section of the essay will cover a few examples of conceptualizations developed by various authors. Lois et al. (2018) employs the node-place model to conceptualize the quality of transfer in terms of transport interchange hub as a *node* and as a *place*. Transport hub as a node refers to users' perceptions of the efficiency of the transit infrastructure and covers aspects such as the reliability and frequency of service, provision and clarity of travel information and the accessibility of transfer. Transport hub as a place is concerned with the user experience of transfer facilities and incorporates aspects such as perceptions of safety and comfort. Additionally, the model by Lois et al. (2018) considers different user profiles and recognizes that the perceptions of transfer quality may vary between different groups.

Iseki and Taylor (2009) conducted a literature review on the influence of transfer facilities on travel behaviour and identified three broad categories that contribute to transfer penalties. These categories include (1) operational factors of the transport system, such as headways, reliability and punctuality of service and availability of information, (2) the physical attributes of the transfer facilities related to comfort, safety and convenience and (3) passenger factors, such as whether the passenger is familiar with the transfer system, a frequent user, forced to wait at the transfer facility and able to engage in something productive while waiting. The authors specify that transfer penalties can be lowered by addressing *actual* and *perceived* walking and waiting times, *perceived* transfer burdens, and the fares paid. Fare policies and the lack of ticket integration can increase the monetary cost of traveling with transfers, having an increasing effect on the generalized cost of public transit travel. When it comes to walking and waiting times, the authors explain that these are determined by actual times with additional weights assigned by passengers. These weights in turn are influenced by different attributes and conditions at the transfer facilities, meaning that even though the design transfer facilities will not change for instance actual waiting times (since these are determined by operational factors), the *perception* of the waiting burden can be influenced by design.

A review by Cascajo et al. (2019) identifies six themes influencing transfer penalty: personal characteristics, trip characteristics, time, built environment, transfer characteristics and pure transfer penalty. The four last themes can be at least to some extent influenced by facility design. In fact, the authors report that some studies revealed the pure transfer penalty to vary significantly between different stations, highlighting the importance of station-specific environmental factors. The summary by Guo and Wilson (2011) offers a more simplified approach in relation to policy implications. They identify that walking times are determined by transit network and station design, waiting times by the operation and management of transit service, and the transfer penalty by a wide range of facility-related factors, such as safety and security, ease of wayfinding, availability of escalators and seating, weather protection and lighting.

Despite the differences in these conceptualizations, reoccurring themes emerge. These include actual and perceived walking and waiting times, availability of information and factors related to comfort and safety. In terms of factors directly influencing transfer penalty, we summarize them into (1) waiting times, (2) walking times and (3) pure transfer penalty. Literature indicates that perceptions of transfer experiences are crucial, which implies that even when certain attributes of transfer cannot be changed with facility design, the effect they have on transfer penalties on a psychological level can be influenced by design. Essentially, a distinction can be made between factors that influence actual walking and waiting times and the factors that influence passengers' perceptions of these times. The above review of literature shows that these factors, as well as the pure transfer penalty, can be influenced by facility design, operation and management of transit service, network design and fare policies. In this context, facility design can be divided into three very broad categories: (1) terminal layout, (2) wayfinding and the provision of information, and (3) factors related comfort. These three categories can be related back to the concept of interchange as a node and as a place by Lois et al. (2018). The two first categories are mainly concerned with interchange as a node since they are concerned with the functioning of the transit space. The third factor is in turn associated with interchange as both a place and a node.

Furthermore, literature emphasizes passengers' personal factors, such as whether they are familiar with the transit system, various socio-economic factors, and attitudinal profiles, as well as trip characteristics, such as the purpose of the trip (Iseki & Taylor, 2009; Lois et al., 2018; Cascajo et al.,2019). Although these factors depend on the individual and are external to terminal design, principles of inclusive design can be implemented in terminal design to ensure that even extreme users (a user with very particular needs) can use the service with ease (Duca et al., 2022). This type of an approach is expected to lessen the transfer penalties of different user groups. It is also likely that there are context-specific differences in the experiences of different factors that influence transfer penalty. For instance, Raveau et al. (2014) studied transfer experiences in London and Santiago metro systems and discovered differences in the ways passengers value waiting and walking times. In Santiago, metro users tend to be more willing to wait than walk, whereas in London, metro the users are more willing to walk than wait. The authors explain these differences in preference with the differing levels of complexity in the metro systems, the London metro being a more complex system with more possibilities for transfer in a single node. The user of this metro system might be more used to required transfers when travelling.

Figure 1 represents our summary and conceptualization of the factors affecting transfer penalty, based on the researched literature. The bottom section of the chart contains various elements of the transit system, including terminal design. The review of literature revealed that even when we are concerned with the effect of terminal design on transfer penalty, we cannot omit the other components of the transit system, given the fact that the other components have major influence on the factors that affect transfer penalty. For instance, the operation of public transit (i.e., scheduling and headways) determine actual waiting times at transfer. Similarly, walking distances in transfer are not only determined by terminal layouts but also by the design of the wider transit network (Guo & Wilson, 2011). The section above the components of the transit system contains the aforementioned broad factors that influence transfer penalties. The arrows represent the connections and influences between the different components of the chart.

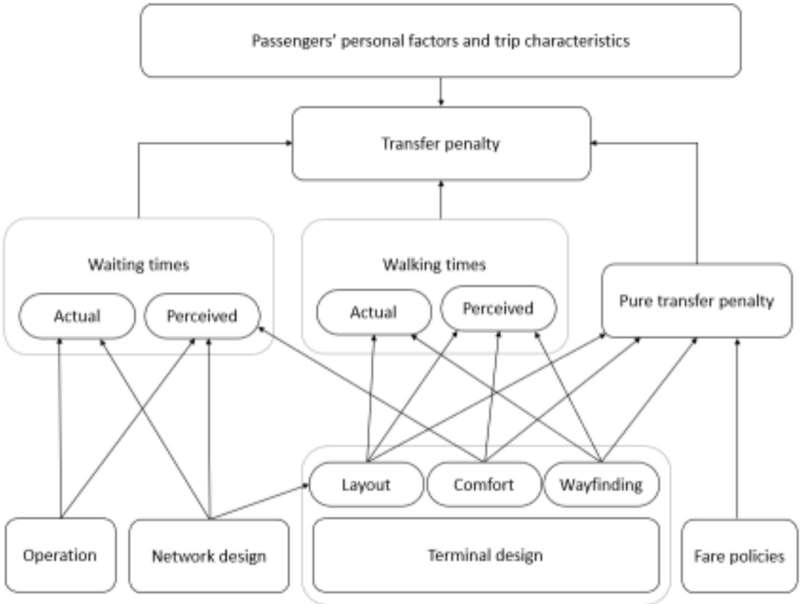

Figure 1. Conceptualization of the factors affecting transfer penalty, emphasis on terminal design. Source: authors

Towards passenger-oriented terminal design

Scientific literature is, on a general note, more concerned with conceptualizations of terminal design in relation to transfer penalties rather than practical design. Plenty of practical examples and for instance layout solutions are found in design manuals and best practice guides but not in scientific literature in the same volumes. Some practical insights are however found, and when it comes to the three identified categories in terminal design – layout, wayfinding, and comfort – and their relation to transfer penalties, scientific literature is mainly concerned with the first two. In terms of the third one, comfort, literature offers superficial and rather obvious suggestions that mainly have to do with the provision of amenities. For instance, Iseki and Taylor (2009) summarize that amenities, such as seating, restrooms, and weather protection, can increase passenger comfort and have a lowering effect on transfer penalties by affecting the perceptions of walking and waiting times.

In terms of wayfinding, Kalakou and Moura (2014) present that the importance of pedestrian wayfinding in indoor transportation facilities has been established in various studies and summarize that a high-quality wayfinding system can reduce actual walking times and uncertainty in navigation. In relation to the latter, easy-to-understand information can reduce the perceived burden of transferring (Iseki & Taylor, 2009). Li et al. (2021) studied the extent to which metro signs affect pedestrian wayfinding through short term memory and compiled practical recommendations for the design of transit signs and wayfinding. Based on their results on the changes in memory capacity over time, the authors recommend placing wayfinding signs with a maximum of 20-meter intervals to improve passenger efficiency. Similarly, the authors recommend reducing the amount of unnecessary information on the signs to ensure that passengers can remember the most crucial information on the signs.

As for terminal layout and walking routes, Raveau et al. (2014) conceptualize that transfers can be made between even, ascending, or descending levels. All these types of transfer can have varying levels of assistance that the authors classify into three categories: (1) assisted transfer that is made entirely with an escalator or a lift, (2) semi-assisted transfer which is partly made with an escalator or a lift and partly on foot and (3) non-assisted transfer that the user makes completely on foot. The authors studied user preferences and transfer experiences in relation to these factors in London and Santiago and discovered that an even-level transfer is the most preferred option. When transfer takes place between levels, ascending transfers are preferred since these are associated with less effort. In terms of assistance, the transfer experience tends to improve when the grade of assistance increases. As for reducing walking times and distances, Iseki and Taylor (2009) emphasize the importance of the physical distances between points of alighting and boarding as well as of the control of pedestrian flows, since the latter can influence walking speeds during rush hours. In fact, Molyneaux et al. (2021) points out that uncontrolled, bidirectional pedestrian traffic may increase travel times significantly, due to the 'slaloming' effect this type of flow has on pedestrian movement. The authors tested a simple control strategy – flow separators – in the context of railway stations and discovered that this type of pedestrian flow strategies can be very useful in transportation terminals. This is largely because demand for pedestrian space is induced by known timetables and that pedestrian flows egressing transit vehicles tend to happen in waves. In fact, crowded stations or platforms negatively affect the user's perception of the transfer, and Cascajo et al. (2017) even evaluate the level of crowding as being the biggest variable in transfer penalties.

Furthermore, station layouts and the positioning of platforms for different lines and modes has a significant effect on walking distances in transfer. As a positive examples of layout design, we would highlight the cross-platform design, as seen in Figure 2 1.). The literature cited throughout the essay emphasizes the importance of minimizing walking distances and thus times as well as the need to change levels in transfer, and these ambitions are successfully met in cross-platform transfer. This type of design solution is found for instance in Stockholm's Tunnelbana network. On the contrary, for instance perimeter oriented bus terminals, while offering more safety for passenger by reducing the number of conflict points pedestrians and vehicles, have been shown to increase walking distances (Iseki & Taylor, 2009).

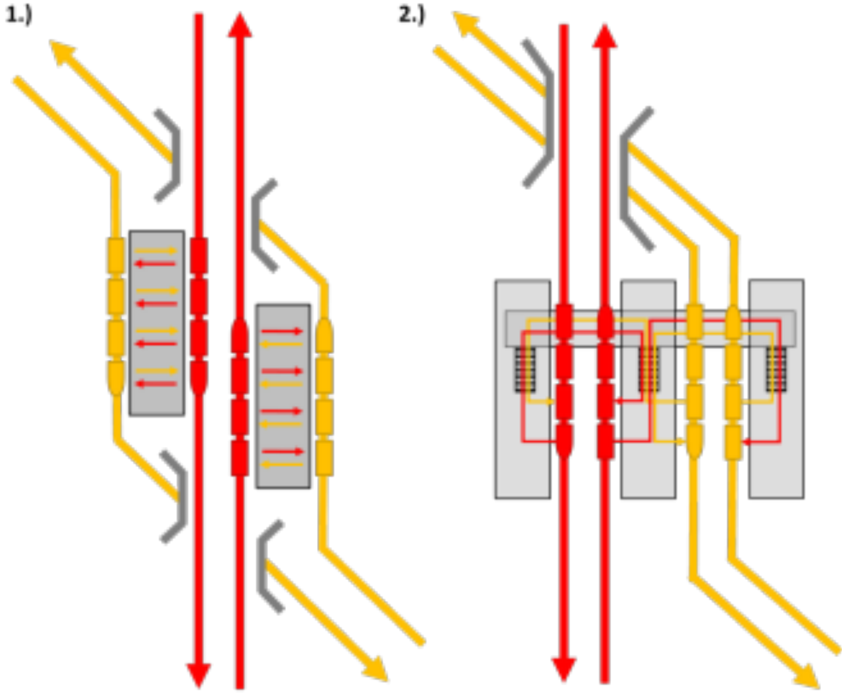

Figure 2. Two possible designs for the alignment of a two-line transfer, as 1.) cross-platform transfer and 2.) parallel indirect two-level transfer. Source: authors

Reflection

The operators and users of public transport networks often have opposing interests when it comes to network and terminal design. For example, a cross-platform transfer has complex requirements for infrastructure and operations, while a parallel alignment, as seen in Figure 2 2.), is much easier and cheaper. Good terminal design can reduce this contradiction by reducing transfer penalty (Allard & Moura, 2015). However, a general change in design mindset must occur. The perspective of the passenger and their perceptions of the transfer facility as end users must be taken into perspective (Duca et al., 2022). Therefore, research strives to understand these social psychological factors and implement design standards accordingly. To reduce the transfer penalty as much as possible the context of use of the hub must be understood and the tasks undertaken there acknowledged. Thus, the function of the hub as a node and as a place (Lois et al., 2018) must be considered, which contains not only its role as a transfer and transit facility, but also potential side roles, for example as shopping mall or exhibition centre. Exactly these competing interests have created many of the problems we perceive when looking at multimodal passenger terminals, not only between operators and customers but also between third party organizations, such as retail stores or restaurants. This implies that some of the stations valued as badly designed might not only have been the result of misled planning but a way to intentionally prolong walking and waiting to attract travellers as customers. Since every terminal is a point of access and egress, the factor of entrance and exit points has to be well considered, especially since some facilities important for the hub-function might be outside the actual station, for example, a bus stop or bicycle parking. Therefore, terminal design concerns not only the station building, but the whole functional transfer node which sometimes might even be multiple neighbouring stations. For this, street-level accessibility is fundamental keeping in mind the reduction of walking times, but also concerns like inclusivity, signing and information and the fusion with the built environment surrounding the terminal. To minimize transfer disutility, it must be intuitive for the passenger how to best get to the mode, line and direction they want.

The issue of transfer has been overlooked in public transit planning, and transportation planners and researchers have paid much more attention to the quality and quantity of the operation of public transit than on ensuring well-functioning transfers (Guo & Wilson, 2011; Iseki & Taylor, 2010). This seems logical, given the fact that operational factors of public transit most likely have larger effect on ridership than connectivity factors at transfer and that operators have much more control over their vehicles than stops and stations. Furthermore, multimodal terminals are crossing points of different modes that are often operated by different authorities, leading to situations where at the same time no one and everyone is responsible for the quality of the transfer environment. This becomes even more obvious when looking at the funding situation. Due to the unclarity of which mode a multimodal terminal belongs to, the monetary responsibility is equally vague, especially on intra-urban and regional level. Official promotion and intermodal budgets are often a very recent development, for example only since 2010 there is an EU fund pot to support the design of intermodal hubs (Allard & Moura, 2015). We believe that these types of institutional unclarities and the fuzziness of responsibilities are a major cause of many poor transfer solutions and facilities. Aesthetic and architectural values often override the functionality of transfer facilities in the design process (Guo & Wilson, 2011), which might lead to the neglecting of many of the functional and comfort-related aspects in design. However, the integration of responsibilities, planning and funding is incremental to create sustainable terminals.

What's more, as established earlier in the essay, the factors influencing transfer penalties are not only shaped by terminal design but also by the other components of the transit system, such as operation and network design. For instance, creating settings for cross-platform transfers requires a certain type of network with different lines meetings at certain stations and timetables with at least some degree of integration. If these conditions are not met, minimizing walking and waiting times with terminal design is very difficult, if not impossible. We argue that the elimination of any missing links in the network structure is indeed the key to creating possibilities for walking-distance transfers in the first place, meaning that high quality terminal design is much more difficult to create as an 'add-on' after the network has already been built. We conclude that creating efficient and positive transfer experiences starts from the design of the whole transit system and that terminal design should never be considered as a separate process from the design of the overall transit network. Consequently, we argue that this process requires a clearer institutional environment where the allocation of the responsibility of terminal design is unambiguous.

The typical analytical approach in evaluating transfers is the 'laundry list', consisting of positive and negative aspects of terminal design in relation to transfer penalties, which majorly fails to consider the relative importance of each aspect and other time and cost factors (Guo & Wilson, 2011). Additionally, Guo and Wilson (2011) argue that many aspects of transfer that passengers deem important are difficult to quantify and most likely have a small total effect on travel behaviour on individual level. Iseki and Taylor (2010) argue that most previous studies on this topic have been conducted from a design perspective and often result in rather obvious suggestions, such as providing adequate seating and lighting in waiting areas. However, the authors argue that research has clearly shown that passengers' evaluation of out-of-vehicle time is influenced by a wide range of factors that exceed factors related to the built environment and the design of stations. Although many of the findings of our essay are rather intuitive – increasing the comfort of transfer facilities and minimizing transfer times and distances – and indeed compose a type of 'laundry list', we argue that this type of work is necessary for simplifying the basic principles of high-quality terminal design in a chaotic institutional environment, as established above. Conceptual and design-oriented work in transfer planning could lead to the creation of minimum standards that might find their way into the design of future transfer terminals. However, Iseki and Taylor (2010) summarize that we have only little knowledge about which aspects of transfer facilities are actually the most important and in which combinations when trying to ease the burden of transferring. This means that more research is necessary before we should try to formulate any sort of best practice guidelines.

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E-Bus Scheduling

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Abstract

The following Review Articles aims at reviewing available literature regarding the introduction of E-Buses in urban public transport networks, with particular focus on the scheduling constraints of both vehicles and crews.

Battery Electric Buses (BEBs) are the type of E-Buses taken into consideration in this review through the lens of the Electric Vehicle Scheduling Problem (E-VSP).
By introducing the planning processes and scheduling objectives that the implementation of e-buses requires, covering then the most impactful constraints that emerge with their adoption (both complete and partial), and concluding with the illustration of the 5 solution approaches to the scheduling problem deemed more relevant by the authors on the basis of information availability and frequency of use, the article attempts to provide the reader with holistic level information regarding the topic.

Introduction

Public transportation plays a vital role in urban mobility, offering a more eco-friendly and efficient mode of transport for millions of individuals globally. In recent times, Battery Electric Buses (BEBs or electric buses in the article) have emerged as a potential solution to tackle the environmental and economic issues linked to conventional fossil-fuel-powered buses, despite the operational challenges arising from their limited driving range. The implementation of electric buses can substantially decrease greenhouse gas emissions, enhance air quality, and reduce operation expenses; these are making them a desirable choice for public transportation systems. Nevertheless, the seamless integration of electric buses into public transportation networks necessitates meticulous planning and optimization of their scheduling, a task that is both intricate and demanding.

According to Eurostat EU-27 data, transport emits about 23% of total GHG emissions in Europe, and road transport is responsible for 72% of GHG emissions from transportation. In this scope, public transportation assumes an important role in decreasing carbon emissions from road transportation. With the development of electric buses in the last decade, it has been seen that BEBs can play a crucial role to decrease carbon emissions from public transportation compared to diesel buses. In addition to this, BEBs are helpful to generate better air quality which improves health outcomes of citizens and reduce noise pollution improving passenger experience. Lastly, they offer advantages to secure country energy demands. (X. Tang et al, 2019)

Since passengers usually have varying socio-economic characteristics and expect a high level of service (i.e., transport systems should be safe, accessible, comfortable, affordable and provide the possibility of reaching destinations quickly (Perumal, R.M. Lusby and J. Larsen, 2019)), the objectives of good scheduling for electric buses include maximizing service reliability, minimizing operating costs, and reducing environmental impact. To achieve these objectives, electric bus scheduling models must consider various constraints, such as vehicle range, charging station availability, and crew availability.

The Electric Vehicle Scheduling Problem (E-VSP) is an optimization problem that involves scheduling electric vehicles, including electric buses, to minimize operating costs while satisfying various constraints.

The objective of the E-VSP is to minimize the total operating cost of the electric vehicle fleet, which includes the cost of energy consumption, vehicle maintenance and crew scheduling.

The scheduling of electric buses involves the allocation of resources, such as vehicles, drivers, and charging stations, to ensure reliable and efficient service. Furthermore, crew scheduling, which is integrated with scheduling of e-buses, involving assigning drivers to specific routes and shifts, is an integral part of electric bus scheduling. The integration of crew scheduling with electric bus scheduling presents additional challenges, such as ensuring that drivers have sufficient rest time and that their schedules comply with labour regulations, creating further constraints for the E-VSP.

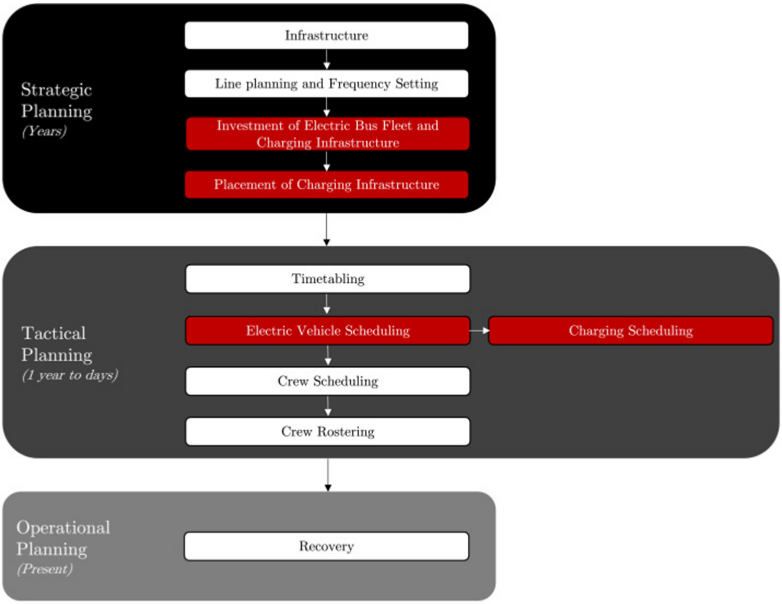
This review essay aims to provide a comprehensive overview of electric bus scheduling, focusing on the objectives of electric bus scheduling models, the constraints that must be considered, and the solution approaches that have been proposed to address these challenges. We will begin by discussing the importance of electric buses for public transportation and the challenges associated with their scheduling. Next, we will delve into the objectives of electric bus scheduling models, including service reliability, operating costs, and environmental impact. We will also discuss the various constraints that must be considered, such as vehicle range, charging station availability, and crew availability.

Furthermore, we will explore some of the solution approaches that have been proposed to address the E-VSP, including skip-stop methods, solutions related to battery charging and swapping problems and few other charging methods.

Electric Bus Planning Process and Scheduling Objectives

The adoption of electric buses needs holistic and complex planning from multiple perspectives, which include charging infrastructure implementation and operational strategies, among others. Tang et al., 2019 expresses that *bus scheduling is one key step in public transit operational planning, and it focuses on how to operate a bus fleet to fulfil the timetable of service trips.*

As stated by Perumal et al. (2019), the planning process for electric bus transportation spans several years and consists of three phases as shown by Figure 1. The strategic planning phase begins approximately three years prior to implementation and involves analysing infrastructure, planning routes and frequencies, investing in electric bus fleets and charging infrastructure, and determining the placement of charging stations. The tactical planning phase commences one year before the present day and focuses on timetabling, scheduling electric buses and charging infrastructure, as well as crew scheduling and rostering. Lastly, the operational planning phase addresses fleet recovery and is based on the current situation.



Through the second phase of the electric bus planning process, the scheduling of electric buses and charging infrastructure is handled and the E-VSP, its objectives, and the objectives of the electric buses scheduling models, are considered as the main drivers for scheduling.

As indicated, the Electric Vehicle Scheduling Problem (E-VSP) focuses on scheduling electric buses in a way that minimizes operating costs while satisfying various constraints. The E-VSP is essential for the successful integration of electric buses into public transportation systems, as it helps ensure reliable and efficient service. Moving beyond, the E-VSP has several objectives like energy optimization, charging infrastructure utilization, emission reduction, passenger satisfaction, cost efficiency, integration with existing systems, scalability, and adaptability.

In the scope of energy optimization, the E-VSP investigates methods to minimize energy consumption in electric bus operations, considering factors such as route length, traffic conditions, and passenger demand. The E-VSP then analyses the optimal placement and utilization of charging stations to ensure seamless operation of electric buses while minimizing downtime and infrastructure costs. According to Olsen et al. (2020) the E-VSP should look for new charging models that reflect the non-linearity of the charging process in a precise way, contrary to what constant and linear charging time models do, increasing the total costs; partial and opportunity charging are incorporated in said models (single/unique depot).

In addition, Chao et al. (2013) expresses that minimizing the capital investment (number of vehicles in the fleet and number of standby batteries in the case of a battery swapping strategy further discussed later in this essay) for the e-bus fleet and the total charging demand in stations, are objectives of the E-VSP.

Furthermore, emission reduction is another issue that the E-VSP considers by looking at the assessment of the environmental benefits provided by electric bus scheduling, focusing on the reduction of greenhouse gas emissions and air pollution in urban areas (Li et al, 2019).

When it comes to passenger satisfaction, the E-VSP aims to evaluate the impact of electric bus scheduling on passenger satisfaction, considering factors such as wait times, travel times, and service reliability. Tang et al. (2019) explains that the E-VSP should be able to minimize en-route breakdown, reduce delay cost to both passengers and operators, and enhance robustness against stochastic traffic conditions which, due to high variability, can be an issue for schedules based on fixed trip times, while at the same time optimizing vehicle schedules and electric fleet sizes. Li et al. (2019) also highlights the importance of passenger experience (waiting penalty – dependent on case-by-case operational strategy) and indicates that the external cost caused by emissions (if the fleet involves mixed type of vehicles) should also be considered.

Another issue for operational efficiency is cost. For a cost-efficient operation, the E-VSP examines the economic feasibility of implementing electric bus scheduling in public transportation systems, considering factors such as operational costs, electricity prices, maintenance costs, and initial investment. Rogge et al. (2018) indicates that minimising the total cost of ownership (TCO) should be targeted by the E-VSP as the main criterion in investment decisions between different alternatives. Required fleet size and type of e-buses, in-service costs unrelated to energy consumption like crew driving hours, bus specific costs related to energy consumption and investment in charging infrastructure, should all be considered.

E-Bus Scheduling Constraints

This section summarizes the constraints that are to be considered in the Electric-Vehicle Scheduling Problem (E-VSP), with the addition of conventional Vehicle Scheduling Problem (VSP) constraints that also apply to Battery Electric Buses (BEBs). When considering e-bus constraints, it can be argued that all constraints are derived from two limitations that BEB's present compared to diesel fuelled and more conventional vehicles: range and charging time.

Range, related to battery capacity, and charging time, are in fact the two central constraints to consider when considering an e-bus fleet. From these two constraints, all other constraints regarding planning and operations stem out, in a direct or indirect manner.

While some models these constraints come from differ in the way that they consider multiple or single bus depots, or mixed or uniform fleets, the constraints are here presented together independently of these aspects.

Each constraint has been generalized to the level that it allows for multiple references to be assigned to it, based on the different articles reviewed by this essay that it was found in; without voiding it of its significance through this generalization process.

General VSP constraints, applicable to the E-VSP are first presented, while E-VSP specific constraints are presented further in this section.

The timetables for trips are planned in advance and vehicles should run strictly on the basis set by them (Chao et al., 2013); since each depot has a given maximum capacity (Tang et al., 2019; Chao et al., 2013), the number of vehicles at a station cannot exceed the station capacity (Chao et al., 2013); each trip is assigned and performed exactly once (C. Tang et al., 2023; Josephine et al., 2015), and run by exactly one vehicle (Chao et al., 2013); every trip is connected by only one preceding and subsequent trip (C. Tang et al., 2023), and each vehicle block contains a feasible sequence of trips (Josephine et al., 2015); all available buses during a given period are assigned to a run type (Perumal et al., 2022).

Time-based constraints regarding the E-VSP include no time overlap between events (e.g. charging and service trips) assigned to one vehicle (Rogge et al., 2018; Olsen et al., 2020); charging done only within a pre-defined time window (Rogge et al., 2018); travel time feasibility (Wang et al., 2022); and route time feasibility (Perumal et al., 2022).

Battery capacity and e-bus driving range constraints are battery capacity limitations (Olsen et al., 2020; Josephine et al., 2015); State of Charge (SOC) check to determine whether or not a bus has sufficient remaining energy to complete a trip and the successive deadhead trip (Olsen et al., 2020; Chao et al., 2013; Rogge et al., 2018; C. Tang et al., 2023; Wang et al., 2022) taking into account a safe driving ratio variable (Li et al., 2019); unit distance energy consumption of a trip in relation with running speed and stop density (C. Tang et al., 2023); driving range and maximum distance without recharging (Wang et al., 2022; Perumal et al., 2021; Josephine et al., 2015) on all service arcs (Li et al., 2019); battery renewal constraints (Perumal et al., 2021); minimum SOC energy level threshold when traveling from one stop to another (Perumal et al., 2022); minimum vehicle battery capacity level (Josephine et al., 2015).

Charging process constraints include recharging can only happen at charging stations (Olsen et al., 2020); buses leave the depot after full charging (Rogge et al., 2018; (Tang et al., 2019); flow constraints of charging infrastructure network (Rogge et al., 2018); at any point the capacity of each refuelling station must be satisfied (Li et al., 2019); buses should not be charged between two trips (C. Tang et al., 2023); re-charging time and needs (Perumal et al., 2021; Wang et al., 2022; Josephine et al., 2015; Perumal et al. 2022); minimum recharging duration (Perumal et al., 2021); the energy provided from the charging station does not exceed the maximum battery capacity (Perumal et al., 2022); a vehicle can only be charged at defined stop points (Josephine et al., 2015); minimum proportion of chargers of each type with respect to the number of electric buses in the fleet (Perumal et al., 2022).

Crew scheduling and crew requirements constraints involve early, day and late work modes with time shift (Wang et al., 2022); work intensity constraints (Wang et al., 2022); (local) labour regulations (Wang et al., 2022; Perumal et al., 2021); daily driving trips (Wang et al., 2022); driver wages (Wang et al., 2022); maximum duration of a duty without break (Perumal et al., 2021); minimum break duration (breaks often allowed only at certain bus stops) (S.S.G. Perumal et al., 2021); maximum number of driver vehicle changes (Perumal et al., 2021); continuous attendance of vehicles, during idle time (Perumal et al., 2021); every trip is covered by exactly one block and one duty respectively (Perumal et al., 2021); duties are selected to cover deadheads (Perumal et al., 2021).

Furthermore, monetary constraints, externality constraints and other types of constraints should be taken into account: operation costs (Wang et al., 2022); Time of Use (TOU) power price policy and electricity prices (Wang et al., 2022); carbon emission constraints (Wang et al., 2022); total (vehicles plus chargers) procurement cost not exceeding allocated budget (Perumal et al., 2021; Perumal et al., 2022); a bus cannot be operated after a certain age and has to be salvaged (Perumal et al., 2022), and the End of Life (EOL) of an e-bus battery is conventionally defined as a remaining capacity of 80% to prevent operational complications (Rogge et al., 2018); and, the total power consumption during each time period cannot exceed the contracted capacity (Perumal et al., 2022).

Solution Approaches

The complexities of the VSP applied to BEBs require tailored approaches that should be applied on a case-by-case basis considering local characteristics of different kinds.

In this section, different solution approaches to solve the e-bus VSP will be covered. The list is not meant to be comprehensively exhaustive, but it aims to give an overview of the different strategies that can be adopted to overcome the limitations that e-buses present when compared to more conventionally fuelled vehicles; keeping in mind that no solution can be utilized to solve all criticalities and constraints at once, but instead as an approach in combination with others, hence the name "Solution Approaches"

The following are the solution approaches covered in this section. They range from charging process solutions to ones regarding daily service operations changes:

- Skip-stop;
- Battery swapping;
- Adoption of different charging time models;
- Static and dynamic rescheduling;
- Opportunity/Pantograph charging.

Skip-stop

The skip-stop method is a strategic method applied in the electric bus scheduling process for public transportation systems. This model aims to optimize the efficiency of electric bus operations by skipping stops along a route for route optimization purposes, thereby reducing travel time, energy consumption, and operational costs. The skip-stop method is particularly beneficial for electric buses, as it helps to conserve battery life and extend the range of the vehicles.

In the skip-stop method, bus stops are categorized into different groups, with buses only stopping at designated stops within each group. This approach allows for a more streamlined service, as buses can bypass certain stops, reducing dwell time and accelerating the overall journey. The skipped stops are still serviced by alternate buses, ensuring that passengers have access to transportation, albeit with slightly longer waiting times at certain stops. Tang et al. (2023) assesses the case study conducted in Dandong, China which tests the skip-stop approach. *The experimental results show that compared to using a full-stop strategy, the use of a skip-stop strategy can reduce the total system cost by 15.09% and improve the average energy utilization rate by 9.02%* comparing to full-stop methods by which electric buses need to stop at every stop along a route. The test consisted of 27 stops on a length of 13 km. In the case, the skip-stop method was utilized when the charging level of electric buses reached the minimum required battery state of charge (SOC) which is defined to avoid battery damage and lifespan reduction. In this case, 30% of battery capacity.

One of the key advantages of the skip-stop method is its potential to reduce energy consumption in electric buses. By skipping stops, buses can maintain a more consistent speed, which in turn reduces the energy required for acceleration and deceleration. This is particularly important for electric buses, as their battery capacity is a critical factor in determining their operational efficiency and range. According to the experiment results gathered in Dandong, China, Tang et al. (2023) shows that trip energy consumption cost was reduced by 4.97% compared to full-stop strategy.
Additionally, the skip-stop method can contribute to improved passenger satisfaction by reducing travel times for those on-board the bus. Passengers traveling longer distances can benefit from a faster journey, as the bus makes fewer stops along the route. However, it is essential to strike a balance between the benefits of the skip-stop method and the potential inconvenience to passengers who may experience longer waiting times at the kipped stops. Tang et al. (2023) expresses that passenger waiting time cost in stations which have not been served by electric buses, decreased by 10.07%, and passenger in-vehicle time cost dropped by 13.86% comparing to the full-stop method. On the other hand, passengers who have to wait at stops skipped by the first arrival buses feel more frustrated due to the extra waiting time.

As indicated by Tang et al. (2023), the skip-stop strategy has 2 specific constraints for operations along with other classified constraints in previous sections of the essay. These are: no two consecutive stops are both skipped in the same trip and the skip-stop strategy is not used by two consecutive trips.

In summary, the skip-stop method is a valuable tool for e-bus scheduling in public transportation systems. By selectively skipping stops, this approach can optimize energy consumption, reduce travel times, and improve overall operational efficiency. However, careful planning and consideration of passenger needs are crucial to ensure that the benefits of the skip-stop method are maximized while minimizing any potential drawbacks negatively impacting passenger travel experience.

Battery swapping

Battery swapping as a solution approach tries to directly tackle the charging time constraint that e-buses present when compared to more conventional diesel-powered buses. It is based on the exchange of batteries with a low State of Charge (SOC) for fully charged stand-by ones kept in a battery charging station.

The approach and case study presented by Chao et al. (2013) is based in Shanghai, China and considers fast battery chargers and an automated rapid battery exchanging system that can complete a battery exchange operation in 12 minutes, from the time the bus enters the station to the time it can return to service. Though a more conservative time of 15 total minutes is considered (Chao et al., 2013), this yields a nearly 72% charging time reduction compared to the 53,53-minute average charging time presented by Olsen et al. (2020) considering 5 bus types and 4 different charging time models.

Furthermore, in the Chao et al. (2013) model and case study, buses undergo a battery exchange in two separate instances: when the remaining energy in the battery is not sufficient to power the remaining service trips the bus is assigned to, and to preventively charge ahead of peak hour service trips.

While these clear charging time saving results seem to indicate that battery swapping would be the ideal solution for the E-VSP, some drawbacks are also evident.

Chao et at. (2013) present their vehicle scheduling model with battery exchanging with the objective of minimizing the capital investment, both in terms of number of vehicles and standby batteries, and the charging demand in stations for this type of strategy. This highlights the high capital investment required for this approach, primarily derived from the added number of batteries needed to be purchased to be kept on standby during daily operations. In the model developed by Chao et al. (2013), specific constraints are utilized in addition to the more conventional E-VSP ones. These are: vehicles change batteries either when the remaining energy is not enough to fuel the remaining trips, or to charge ahead of peak hours (Chao et al., 2013); battery exchange operation time constraints (15mins in the specific case examined in the article) (Chao et al., 2013; C. Tang et al., 2023); and, stand-by battery charging time constraints (Chao et al. 2013).

The model does not offer a single optimal solution but a set of Pareto optimal points instead. This is due to the conflict between the minimization of fleet requirements while at the same time minimizing the charging demand in stations; a decrease in vehicle fleet investment will in fact result in an increase of the total charging demand, while a decrease in the total charging demand will result in a required investment increase. Therefore, a solution with different levels of these two variables will be chosen according to different criteria depending on the case specific characteristics and the inevitable bias of different kinds of decision makers.

Adoption of different charging time models

With most E-VSP solution methods often over-simplifying electric battery powered vehicle charging procedures, Olsen et al. (2020) proposes charging time models that better reflect the non-linear nature of the charging process in a more precise way, compared to more conventionally utilized constant and/or linear charging time models. The presented models have the benefit of being able to be applied to different types of charging strategies such as: overnight charging, opportunity (commonly pantograph) charging, and battery swap.

Olsen et al. (2020) focuses their model on lithium-ion batteries, currently the most used type of battery, which present constant current/constant voltage (CC/CV) charging procedure characterized by two phases: the first being a linear battery charging phase, and the second one being a battery charging phase presenting a non-linear profile.

The simplification issue with most of current E-VSP solution models indeed lies in this second non-linear phase. More specifically, constant charging time models provide an overestimation of the time windows required to charge a BEB, therefore leading to unutilized waiting times at charging station for buses that could already be operating service routes. The main reason behind this overestimation is caused by the fact that constant charging times do not take battery SOC into consideration at the start of the charging process, which assumes the need for charging the entire battery capacity.

The direct effect of this overestimation is the higher demand for the vehicle fleet to cover for longer charging times than needed, increasing the total costs, through the bus procurement cost, without need.

Olsen et al. (2020) derives from this that the potential for partial battery charging remains unutilized. While constant charging time models mainly impact BEB operators by increasing their costs, while not necessarily impacting user experience and operations, this is not the case for linear charging time models.

According to Olsen et al. (2020), linear charging time models underestimate the time required to charge a BEB, leading to violations of vehicle range restrictions. Bus breakdowns during operation can therefore happen with more frequency due to the real SOC of a BEB being often lower than the planned one, having serious impacts on public transport users experiencing the effects of said breakdowns.

Instead of the constant and linear charging time models, Olsen et al. (2020) proposes two models that more precisely follow the second phase of the lithium-ion battery charging procedure. The first one being the logarithmic model and the second one being the exponential one.

The latter is more precise than the former, but both these models can yield better results in the actual charging time estimation, therefore overcoming the estimation flaws of the constant and linear charging time models, offering a possible solution to prevent the issues presented above.

Static and dynamic scheduling

Most E-VSP models and solutions consider trip times to be fixed and traffic conditions to be deterministic; two assumptions that simplify the vehicle scheduling problem but do not represent the real stochasticity of road traffic conditions.

Road traffic conditions in fact present a high degree of variability that can heavily impact trip times depending on different parameters, such as time of day and weather conditions. Considering the lower range that BEBs have and the effect that traffic conditions have on bus energy consumption, en-route breakdowns and increased costs derived from delays, are two direct impacts that these imprecise assumptions can have.

Tang et al. (2019) presents a robust scheduling model that takes the stochasticity of road traffic conditions into account, while also optimizing vehicle schedules and electric vehicle fleet sizes in a single-depot case. To do so, they introduce two separate VSP problems: the Static Vehicle Scheduling Problem (S-VSP) and the Dynamic Vehicle Scheduling Problem (D-VSP).

The S-VSP introduces a buffer-distance in the model, that hedges against the impacts of stochastic traffic conditions on energy consumptions, mainly caused by speed changes, ensuring that e-buses don't run out of charge en-route. The higher the value of said buffer-distance, the higher the scheduled cost, but this increase can be compensated through the cost savings derived from the increased robustness provided by this value compared to a lower one. The opposite is also true, where a lower buffer-distance value allows for a reduction in scheduled cost but at the expense of a higher breakdown rate.

The D-VSP on the other hand adopts a computationally more complex approach that yields better results in highly variable road traffic conditions, making it relatively insensitive to them.

By dividing a day's bus operation into a set amount of time periods, Tang et al. (2019) developed a model based on dynamic programming that considers Automatic Vehicle Location (AVL) traffic data and updated forecasts of future traffic conditions based on historic data. At the end of each time period, each bus's schedule is re-evaluated considering the remaining range based on the battery SOC, and the dynamic program is able to determine if a re-schedule is necessary or else if a bus can continue with the pre-determined schedule made at the start of operations; the option to deploy additional vehicles and commence a charging procedure for others is also evaluated at each time period change. The model developed by Tang et al. (2019) is also able to determine the impacts that each decision made at the end of each time period, will have on future periods in terms of deployed/available fleet and battery SOC; all to minimize the sum of operational costs in the considered period and the cost expectations of future ones.

While, as mentioned before, the D-VSP is computationally heavier than the S-VSP, it can yield the smallest realized total cost while being rather insensitive to traffic stochasticity compared to the S-VSP. Compared to the traditional VSP, Tang et al. (2019) introduces the buffer distance parameter to hedge against the stochasticity of energy consumption due to stochastic traffic conditions, as a specific constraint of the static scheduling model.

Opportunity/Pantograph charging

As indicated by Perumal et al. (2022), *the use of electric buses requires special charging facilities which have to be accommodated into the current infrastructure.*

In this section, we will mention pantograph charging which is one of the charging methods for electric buses into public transportation.

Pantograph charging is an innovative and efficient method of charging electric buses, which has gained significant traction in recent years due to its ability to minimize downtime and facilitate seamless integration into existing public transportation systems. This charging method utilizes a specialized overhead charging infrastructure, which connects to the electric bus via a retractable pantograph mounted on the roof of the vehicle. The pantograph, a conductive device, establishes an electrical connection between the bus and the charging station, allowing for the rapid transfer of energy to the vehicle's battery. Perumal et el. (2022) expresses that *a pantograph charger can be installed at intermediate bus stops and has a charging power of 300 kilowatt* in where *the optimal size of the electric bus fleet is determined as well as their battery capacity, which is measured in terms of kilowatt-hour (kWh).*

One of the key advantages of pantograph charging is its ability to provide high-power, fast charging capabilities however *pantograph chargers have a high installation cost* (Perumal et el., 2022). This enables electric buses to recharge their batteries in a matter of minutes during scheduled stops or layovers, reducing the need for extended charging periods and allowing for continuous operation throughout the day. As a result, pantograph charging can significantly improve the operational efficiency of electric bus fleets, making them a more viable and sustainable alternative to traditional fossil fuel-powered buses.

The charging infrastructure can be easily integrated into existing bus stops or depots, minimizing the need for additional land or construction. Moreover, the modular nature of pantograph charging systems allows for easy expansion as the number of electric buses in a fleet grows, ensuring that the charging infrastructure can keep pace with the increasing demand for clean and efficient public transportation.

In addition to its fast-charging capabilities, pantograph charging offers a high degree of flexibility and scalability, but at the same time requires a specific constraint for the scheduling process. This constraint is defined by Perumal et al. (2022) with the requirement of energy balancing at each bus stop along a specific line.

Conclusions

The incidence of electrified bus fleets in urban centres is projected to grow. Nonetheless, given the inherent limitations and challenges posed by electric bus technologies, it is essential to make further refinements to the present bus transportation planning concerns. Therefore, the planning process and scheduling of electric buses are recognised to be vital and fast-growing concern for cities.

In this essay, the objectives of the E-VSP, electric bus scheduling constraints and solution approaches for both electric buses scheduling strategies and charging problems, have been presented after reviewing 11 related publications.

Since the investment amount and production capacity of electric bus manufacturers, in the following short and mid-term time periods, the public transportation fleets will be mixed fleets with both electric and diesel buses.

According to findings, as suggested by Rogge et al. (2018) mixed fleets provide benefits, especially for peak hour flexibility because of some constraints for electric buses like range, battery capacity and electricity prices. In the long-term, if further technological revolution will be realised for battery technologies, fleets with only electric buses will be able to provide more benefits to society.

It has also been also noticed that the scheduling strategies, methods, decisions, and ways of introduction of electric buses into public transportation depend on fleet size, city charging infrastructure systems, and demand on the route. Case-by-case evaluation and decisions are therefore vital for electric buses scheduling since each case presents different requirements, specifications, and constraints, keeping in mind that integrating two or more planning problems into a case, add further computational complexity but further improvement in efficiency of electric bus transport systems.

As numerous technological constraints exist in relation to the scheduling of electric vehicles, the advancement of recovery techniques that facilitate the real-world implementation of electric vehicles is considered a prospective field of study.
This Review Article attempted to review articles that were available on the wide topic of e-bus scheduling and could be further integrated with articles concerning said technological advancements in the field.

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Travel barriers affecting subjective wellbeing in Tampere, Finland

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Abstract
Travel is an important activity enabling everyday life, as well as a recognized factor for the wellbeing of people. This study examined how experienced travel barriers and their effect on access to important destinations influenced subjective wellbeing (SWB). The study comprised a survey of 772 people living in two suburban areas of Tampere, Finland. The survey included questions about everyday travel, travel barriers, and their effect on access to destinations. SWB was measured using the Personal Wellbeing Index (PWI). Responses were analysed by comparing PWI scores with travel barriers and access to destinations using one way ANOVA. Results indicate a significant connection between several experienced barriers and SWB. Some travel barriers were associated with a worrying decline to critically low level of SWB, which raised questions about transport equity and connections between travel and wellbeing in the context of Finnish transport system.

Keywords: Subjective wellbeing, Personal Wellbeing Index, travel behaviour, travel barriers, Finland,

1. Introduction

Travel is an activity with intrinsic value that enables a person to participate in their desired activities (Choo et al., 2005; Mokhtarian and Salomon, 2001). The relationship between travel and subjective wellbeing (SWB) has been investigated extensively from a diverse range of perspectives including commuting (Chatterjee et al., 2020; Tao et al., 2022), social exclusion (Delbosc and Currie, 2011), transport poverty (Awaworyi Churchill and Smyth, 2019), mental health (Liu et al., 2022), residential location (De Vos et al., 2013), built environment (Mouratidis, 2021), travel modes and travel mode shift (Ettema et al., 2016), and mobility of older people (Nordbakke and Schwanen, 2014).

SWB describes the level of wellbeing an individual experiences by subjectively evaluating their life in that moment (Diener and Ryan, 2009). Diener (1984) defined SWB as an experience of the individual which consists of negative and positive matters. SWB measures typically include an extensive evaluation of aspects of a person’s life to emphasis an integrated judgement of the person's life.

The importance of wellbeing lies in the multifaceted effects it has on a person, which can in turn affect the whole society. As an example, wellbeing has been linked with various aspects of health such as, mortality (Chida and Steptoe, 2008), coronary heart diseases (Kubzansky and Kawachi, 2000), healthy behaviours (Lyubomirsky et al., 2005), and has been shown to be a protective factor for health (Ostir et al., 2001; Steptoe et al., 2015). Other relevant example of the importance of wellbeing can be found in the connection with working life, as wellbeing has been connected to productivity of the workers (Oswald et al., 2015), job satisfaction (Bowling et al., 2010), and income (De Neve and Oswald, 2012; Ferrer-i-Carbonell, 2005). The national economy is an important area that is affected by health (Suhrcke et al., 2006) and work life (Schaufeli, 2018), further highlighting the importance of wellbeing, in addition to its intrinsic value in people’s life. These benefits are of such significance and importance that wellbeing is noted within the Sustainable Development goals of the United Nations (2023). In this study we examined how different travel barriers and their effect on access to different important destinations affect SWB.

The Personal Wellbeing Index (PWI) is one of many ways of measuring SWB (International Wellbeing Group, 2013). PWI was developed by Cummins (1995) to find a "gold standard" for measuring SWB by surveying respondent's satisfaction in different areas of their lives. The PWI studies respondent's satisfaction with life with a validated set of questions regarding different aspects of their life (International Wellbeing Group, 2013).

It has been established that normative range of the PWI is from 49 (70%) to 56 (80%) in Northern European countries (Cummins, 1998; Cummins et al., 2003). Most people within the normative range can maintain their life satisfaction, however the ability to maintain life satisfaction has been predicted to change when the PWI scores fall below the normative range, indicating a shift of control in life satisfaction maintenance from internal mechanisms to external circumstances (Cummins, 2003). Cummins (2003) implies based on these finding that the relationship between objective life conditions and life satisfaction may be heavily influenced by the level of life satisfaction and therefore by the level of SWB. Furthermore, when compared to the Depression, Anxiety and Stress Scale, PWI scores below 44.2 (63.2%) are connected to moderate depression score, and scores below 41 (58.5%) to severe depression (Cummins et al., 2012). Although it is outside the scope of this study to speculate if respondents were suffering from depression, the connection with lowered PWI and depressive inclinations is a reinforcing factor to examine with importance the decreased SWB within respondents who experienced certain barriers to travel.

The survey was conducted in two suburbs of Tampere, Finland: Kaleva and Hervanta. Tampere is one of the fastest growing cities in Finland (Tilastokeskus, 2023) and in recent times has seen notable investments in infrastructure, such as the new tram system which improved the public transit system of Kaleva and Hervanta. Furthermore, the city of Tampere has included wellbeing as a measure in the city strategy (City of Tampere, 2023). Results from a recent survey of the well-being amongst Tampere's residents show that in general residents are satisfied with transport connections and routes (City of Tampere, 2023). However, the study did not consider the reasons behind these experiences.

This paper seeks to investigate: How experienced travel barriers are connected to SWB? and how are identified barriers related to access to destinations important to wellbeing? The gap in the knowledge that this study is contributing to is the connection of the travel barriers and SWB in an urban Finnish context. The findings of this study have the potential to demonstrate the connection between SWB and the travel barriers in Tampere. Furthermore, the findings have potential to guide similar reflection in comparable environments in Finland and other Nordic countries.

2. Method

2.1 Procedure

The analysis presented in this manuscript is derived from a survey conducted between March and September 2022 in the suburbs of Hervanta and Kaleva in Tampere, Finland (Sjögren and Tiikkaja, 2022). A representative sample of 4,000 persons, aged 18 or older, was drawn from the Finnish Digital and Population Data Services Agency's Population Information System. The sample was stratified by age and gender with only native Finnish speakers included in the sample. No persons with a marketing ban were included in the sample.

An invitation letter and accompanying documents were sent to respondents in mid-March 2022 (Sjögren and Tiikkaja, 2022). The letter included a cover letter, explanatory statement, instructions on how to answer the survey, a paper copy of the survey, a return envelope, and a privacy notice. Participants could answer the survey online or by returning the completed paper copy of the survey. No incentives were offered for participating the study. In total, 772 respondents completed sufficient questions to be included in the analysis. A summary of self-reported demographics for the participants are presented in Table 1. The institutional ethics committee deemed the project low risk, as such ethical approval was not required for the study.

Table 1: Demographic characteristics

Variable		n	%
Gender (n = 756)	Female	400	52.9
	Male	347	45.9
	Non-binary or do not want to answer	9	1.2
Age (n = 768)	18-29	209	27.1
	30-44	167	21.7
	45-64	172	22.3
	65-74	147	19.1
	75+	73	9.5
Employment (n = 771)	Full-time	272	35.3
	Part-time or work occasionally	47	6.1
	Unemployed, laid off or on sick leave	44	5.8
	Stay home parent	12	1.6
	Student	139	18.0
	Part-time pension or retired	244	31.7
	Other	13	1.7
Household size (n = 768)	1	343	44.5
	2	317	41.1
	3	50	6.5
	4 or more	58	7.5
Household income (n= 750)	Less than 10,000 euros	83	11.1
	10,000 - 20,000 euros	160	21.3
	20,001 – 40,000 euros	199	26.5
	40,001 – 60,000 euros	145	19.3
	60,001 – 80,000 euros	82	10.9
	Over 80,000 euros	81	10.8
Driver's licence (n = 768)	Yes	611	79.6
	No	157	20.4
Public transport ticket (n = 770)	Yes	700	90.9
	No	70	9.1

2.2 Materials

The survey comprised questions on demographic characteristics, travel barriers, difficulties reaching destinations due to barriers, and subjective wellbeing. Travel barriers were measured on a four-point scale (1 – not a barrier, 2 – a small barrier, 3 – a moderate barriers, 4

– a substantial barrier), while their effect on accessing destinations were measured on a three-point scale (1 – does not complicate, 2 – complicates a little, 3 – complicates a lot). SWB was measured using the Personal Wellbeing Index (PWI) (International Wellbeing Group, 2013). The PWI consists of seven items with total scores calculated by summing the seven items. Each item was measured on an 11-point scale from 0 to 10 (International Wellbeing Group, 2013). This results in an overall score with maximum of 70. Summary statistics for the PWI items are presented in Table 2.

Table 2: Personal Wellbeing Index item scores

Item Cronbach's Alpha (.905)	M	SD
Standard of living	7.57	1.86
Health	7.15	2.14
Achieving in life	7.47	2.03
Personal relationships	7.58	2.02
Safety	7.83	1.82
Community	7.03	2.00
Future security	7.03	2.13

2.3 Analysis

All analyses were conducted using IBM SPSS 28. Descriptive statistics are presented for survey questions including demographics, SWB, and travel barriers. Cronbach's alpha was used to assess the reliability of the PWI items. One way ANOVA was used to identify statistically significant differences between SWB, demographic, barriers to travel, and destinations with effect size measured using eta-squared ($\eta 2$). Tukey HSD was used to conduct post-hoc testing. Statistical significance was evaluated with alpha () set to 0.05.

3. Results

A comparison of SWB from the PWI by demographic characteristics is presented in Table 3. Statistically significant differences in self-reported SWB were identified based on employment, household size, household income, and having a driver licence. No significant differences were identified for SWB by age, gender and having access to public transport.

When considering employment, the highest levels of SWB were reported by stay-at-home parents, followed by those in full-time work. Unemployed respondents had significantly lower rates of SWB compared to other employment categories. Regarding household size, persons living in single person households had significantly lower rates of SWB compared to all other groups, with no significant differences in SWB reported amongst other household sizes. SWB was also found to increase with household income, with significant differences observed between households based on income level. Finally, having a driver's licence was associated with higher levels of SWB.

Variable		M	SD	F	p	η2
Gender (n = 756)	Female	51.50	10.78	1.175	.309	.003
	Male	51.85	11.80			
	Non-binary or do not want to answer	46.11	8.72			
Age (n = 768)	18-29	51.81	10.07	.969	.424	.005
	30-44	50.51	11.78			
	45-64	52.80	10.77			
	65-74	51.92	11.27			
	75+	51.16	12.27			
Employment (n = 771)	Full-time	53.87	9.00	11.70	<.001	.084
	Part-time or work occasionally	51.21	9.59			
	Unemployed, laid off or on sick leave	39.80	14.66			
	Stay home parent	57.08	5.79			
	Student	52.00	9.63			
	Part-time pension or retired	51.11	12.13			
	Other	48.23	18.52			
Household size (n = 768)	1	48.95	12.53	12.78	<.001	.048
	2	53.89	9.65			
	3	54.10	9.50			
	4 or more	53.47	8.30			
Household income (n= 750)	Less than 10,000 euros	48.05	14.15	9.91	<.001	.062
	10,000 - 20,000 euros	48.92	12.70			
	20,001 – 40,000 euros	50.50	11.50			
	40,001 – 60,000 euros	53.68	8.14			
	60,001 – 80,000 euros	55.00	8.23			
	Over 80,000 euros	56.37	7.66			
Driver's licence (n = 768)	Yes	52.55	10.26	19.78	<.001	.025
	No	48.14	13.85			
Public transport ticket (n = 770)	Yes	51.60	11.34	0.141	.708	.000
	No	52.13	9.81			

Table 3: Total PWI scores stratified by demographics.

Next, travel barriers were assessed, including analysing if there were significant differences in self-reported SWB by travel barrier (Table 4). The barriers were measured on 4-point scale evaluating if the item causes no-barrier (1), slight barrier (2), moderate barrier (3), or substantial barrier (4).

Participants identified insufficient options for car parking, and a lack of cycling infrastructure as the greatest travel barriers (mean scores of 2.19 and 2.10 respectively). These were followed by insufficient bicycle parking options, insufficient public transport, and long travel distances. However, overall participants reported low scores for each of the travel barrier items. For each item, participants' self-reported

SWB scores were assessed using one-way ANOVA. Significant differences in SWB were reported for most items except for insufficient options for car parking and insufficient options for storing and parking bicycles. This was an interesting finding as these items were identified as some of the greatest travel barriers. The largest differences were identified for cost, with significantly lower rates of SWB for those who felt cost was a travel barrier. Differences in SWB were also observed when considering distance to destinations, illness or disability and accessibility.

Items	Item scores		PWI		
	M	SD	F	p	η2
Cost (n= 763)	1.61	0.80	28.68	<.001	.102
Destinations are located far from my home (n=757)	1.75	0.87	19.44	<.001	.072
Travel time (n=759)	1.73	0.87	6.64	<.001	.026
Accessibility (n=750)	1.23	0.58	10.15	<.001	.039
Illness or disability (n=756)	1.29	0.69	15.99	<.001	.060
Insufficient public transport connections (n=752)	1.77	0.95	4.61	.003	.018
Finding information about public transport timetables and routes (n=759)	1.58	0.90	7.32	<.001	.028
Difficulty to order a taxi (n=745)	1.54	0.92	3.79	.010	.015
Taxi availability and certainty to get a taxi (n=741)	1.65	0.94	4.56	.004	.018
No car (n=373)	1.73	0.94	7.18	<.001	.055
No driving licence (n=245)	1.56	0.94	2.66	.049	.032
Insecurity in travel (n=754)	1.35	0.67	9.17	<.001	.035
Insufficient options for car parking (n=720)	2.19	1.10	1.61	.186	.007
Lack of pavements and bicycle ways or insufficient maintenance (n=754)	2.10	1.01	3.93	.008	.015
Insufficient options for storing and parking a bicycle (n=727)	1.75	0.95	0.86	.469	.004

Table 4: Travel barrier items and differences in total PWI

Figure 1 further explores the travel barriers, by showing mean PWI scores of the four barrier levels. The normative range of SWB as specified by Cummins is also shown as vertical lines (PWI scores 49 and 56) (Cummins, 1998; Cummins et al., 2003). It is noted that for some travel barrier items there are relatively low sample sizes in some groups within the item's answer. Nevertheless, notable decreases are important to consider, despite affecting only a small proportion of respondents.

As expected, the mean PWI score for the respondents who did not experience a barrier was in the normative range for each item. Similarly, mean PWI scores for the respondents who experienced slight barriers were in the normative range for all items except those related to accessibility, and illness or disability. For respondents who experienced moderate travel barriers, mean scores were below the normative range for cost, travel time, accessibility, illness or disability, finding information about public transport timetables and routes, not having a car, not having a driving licence, and insecurity in travel, with similar patterns found for respondents who experience substantial travel barriers. Post-hoc testing confirmed significant differences in PWI when comparing to respondents experiencing no barrier with the respondents experiencing moderate of sustainable barriers for cost, accessibility, illness or disability, not having a car, not having a driver's license, and insecurity in travel.

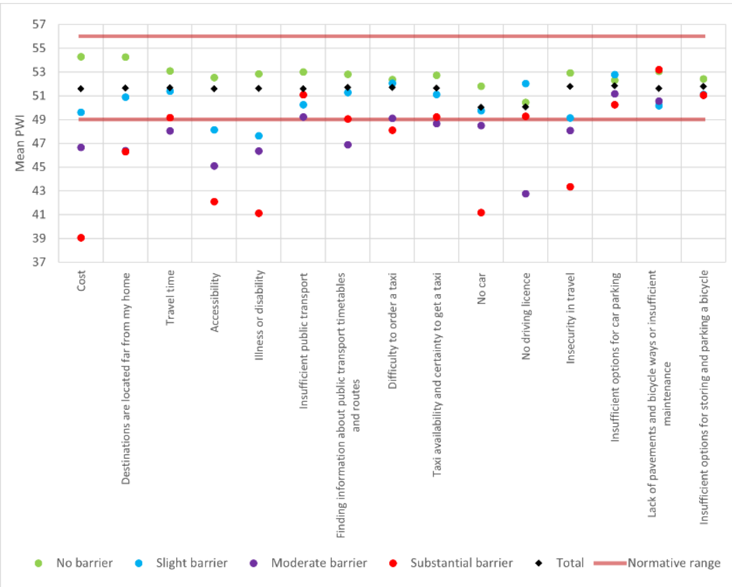

Figure 1 PWI means in the travel barrier items between different answer options.

Finally, participants were asked to identify if there were locations and activities that were more difficult to engage in due to the travel barriers. These items were evaluated on a scale of 1 to 3 evaluating if the respondent experienced no barrier (1), slight barrier (2), or moderate/substantial barrier (3) to access the destinations important for their wellbeing.

Overall, the majority of respondents noted that travel barriers do not cause them difficulties when accessing destinations. The greatest effects that barriers had to access destinations were associated with destinations related to recreational activities including visiting summer cottages or nature activities or visiting friends and relatives. However, there were also some respondents who reported difficulties in accepting jobs, commuting, and accessing retail and medical services. Considering wellbeing, again those who did not experienced difficulties tended to report higher levels of SWB, with statistically significant differences identified for most activities except for taking children to day care.

Items	Item scores		PWI		
	M	SD	F	p	η2
Accepting a job (n = 487)	1.35	0.60	10.73	<.001	.042
Work trips or travel to study place (n = 524)	1.37	0.61	6.40	.002	.024
Taking kids to day care (n = 281)	1.15	0.43	.006	.994	.000
Going to grocery store (n = 743)	1.17	0.44	8.32	<.001	.022
Going to other stores (n = 746)	1.35	0.59	15.19	<.001	.039
Using post services (n = 740)	1.19	0.47	9.73	<.001	.026
Going to pharmacy (n = 745)	1.14	0.41	12.88	<.001	.034
Going to health centre or child health centre (n = 737)	1.20	0.48	16.34	<.001	.043
Visiting friends and relatives (n = 735)	1.58	0.71	13.90	<.001	.037
Participating in interesting hobbies (n = 706)	1.45	0.64	11.60	<.001	.032
Going to the cinema, theatre, museums or concerts (n = 717)	1.33	0.59	11.93	<.001	.032
Visiting summer cottage or nature attractions (n = 683)	1.65	0.78	13.35	<.001	.039

Table 5: Item means evaluating access to destinations affected by travel barriers and PWI.

Figure 2 Item means evaluating access to destinations affected by travel barriers and personal wellbeing index

Figure 2 presents the mean PWI for each answer option within the items of Table 5. For each item, mean PWI was in the normative range among the respondents who did not experience travel barriers that affected their access to destinations. Those who experienced slight barriers with going to grocery store, usage of post services, and going to a health centre or a child health centre had a mean PWI below the normative range. For those experiencing moderate/substantial barriers to access their destinations, only the items Visiting summer cottage or nature attractions (M = 49.20, SD = 12.91, N = 129), and Taking kids to day care (M = 52.63, SD = 14.49, N = 8) had mean PWI within the normative range. The lowest mean PWIs within these items was among those who experienced moderate/substantial barrier for going to health centre or child health centre (M = 42.04, SD = 17.37, N = 25), going to pharmacy (M = 43.37, SD = 18.92, N = 19). Other notable low mean PWI results were connected to moderate/substantial barriers to accessing grocery store (M = 45.53, SD = 17.24, N = 19), going to other stores (M = 45.36, SD = 14.74, N = 45), and using post services (M = 45.74, SD = 16.31, N = 27). Post-hoc tests confirmed significant differences between every item, expect taking kids to day-care, when compared to those who reported no barriers.

4. Discussion

The transport system can influence SWB through access to important activities, physical mobility, and physical infrastructure (Delbosc, 2012). As personal characteristics will influence how people define their expectations for a good life, SWB can be impacted if barriers prevent people from meeting their expectations (Delbosc, 2012). Satisfaction with daily travel and daily activities has been shown to have an influence on SWB (Bergstad et al., 2011). Improving SWB can have an impact on individuals and society as a whole, as SWB can have an effect on health, social issues, employment, education, and environment (Maccagnan et al., 2019). Also, these issues are acknowledged in the Sustainable Growth Programme for Finland as a point of interest and national aim, with the programme's general objectives being productivity growth, raising the employment rate, faster access to care, and progress in equality (Finnish Government, 2021).

According to our study, employment, driver's licence, household size and household income are significantly connected with PWI results. According to the mean PWI scores within each category it can be interpreted that being unemployed, laid off, or on a sick leave may have a critical effect on SWB. The findings indicate that household income is also connected to SWB. This result may be connected to household size, as single person households had notably lower mean PWI compared to households with two or more residents. Because SWB is a complex subjective experience, it is important to be aware of the effects of demographic factors when interpreting the results, as they may affect or explain the connections with the PWI results of the other items.

Results of this study displayed the connections that travel barriers had on SWB. The only barriers that were non-significant were insufficient options for car parking and storing and parking a bicycle. Cost was the travel barrier with highest effect size, and the respondents experiencing cost as a substantial barrier had the lowest mean PWI of 39.08, which is a PWI score as low as people with severe depression (Cummins et al., 2012). Other notable findings were the considerable decline in mean PWI among the respondents who experienced accessibility, illness, or disability as a travel barrier. Insecurity in travel, and not owning a car had a connection with lower mean PWI as well.

Access to destinations affected by travel barriers had a significant connection to PWI results, with the exception of taking kids to day care not being significant. Respondents experiencing slight barriers towards going to grocery store, pharmacy, post services, or health centres reported mean PWI below the normative range, but the reported mean PWI was in the normative range for respondents experiencing slight barriers with other access to destination items. Results found that experiencing moderate or substantial barriers with access to different destinations decreases the mean PWI near to the lower limit of normative range, or considerably below it. Especially experiencing moderate or substantial barriers towards going to health centre or child health centre, pharmacy, grocery store, other stores, or post services had a relationship to the respondents reporting low PWI results. The common factor between the items that had the lowest mean PWI scores, may be the essential nature of the services and the lack of voluntariness to use them when in need.

PWI total of 44.2 has been connected to moderate depression scores (Cummins et al., 2012). However, it could be argued that it is not responsible to unambiguously reference the findings of Cummins et al. (2012) as a flawless instrumentation to identify depressed individuals, as the research is quite limited. Especially since the results of this study finding a connection between low mean PWI and the experienced barriers had a relatively low sample size and high standard deviation in many instances. Despite this limitation, the noteworthy decreases in SWB as an effect of travel barriers or other travel related circumstances is a topic of great importance and deserves more attention and further research in the future.

This study highlights connections between experienced travel barriers and how they affect access to important destinations, which may lead to issues with transport equity (Litman, 2022) and fluctuation in SWB. Barriers that could be connected to these conditions are for example not having a car, destinations being located far from home, cost, travel time, insecurity in travel, accessibility, illness or disability, and the barriers to access destination presented in the study. These connections may imply that people who experience substantial or moderate barriers from certain travel barriers, or for accessing important destinations, may be exposed to the risk of declining SWB. Stanley et al. (2011) had a similar finding by presenting the indirect association of improved mobility as a mean to improve wellbeing by reducing the risk of social exclusion. Also, Currie et al. (2010) presented strong links between wellbeing and social exclusion, and a link between transport disadvantage and the travel poverty construct which led to lower ratings of SWB.

Measures to affect equity and wellbeing in transport are varied. Measures can be aimed towards spatial planning (Church et al., 2000), public transit (Stanley and Lucas, 2008), and fiscal factors (Litman, 2022). Although, the decline of SWB affected only a fraction of respondents, it is important to acknowledge the consequences, as they may cause serious negative outcomes to the person themselves and to the society in multiple different ways. Nevertheless, the study contributes important information about the transport related declining of SWB among the citizens of Tampere, Finland.

Potential limitations of the study include having the sample framed to two areas without notable shortages in services, and all respondents being Finnish speakers. When interpreting the decline of PWI results of those who experienced barriers, potential limitations can be noted as some of the sample sizes within independent answer options were relatively low in comparison to the rest of the sample, and the standard deviation is relatively high within some cases.

As a conclusion, this study demonstrated a connection between SWB and travel barriers and how they affect access to destinations. Connections between certain experienced travel barriers and access to destinations affected by travel barriers with the decline of SWB were significant, and therefore answers the research question by demonstrating this connection among the residents of Hervanta and Kaleva, which may also be applicable to other similar areas, such as Finland in general, Nordic countries, or other high-income countries.

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7. Appendix

Appendix 1: Responses by the level of barrier with sample size, mean, and standard deviation.

Item	Response	N	Mean	SD
Cost	No barrier	432	54,29	9,44
	Slight barrier	224	49,62	10,44
	Moderate barrier	83	46,67	13,61
	Substantial barrier	24	39,08	19,00
	Total	763	51,61	11,22
Destinations are located far from my home	No barrier	371	54,26	9,73
	Slight barrier	236	50,89	10,54
	Moderate barrier	118	46,40	12,46
	Substantial barrier	32	46,31	16,93
	Total	757	51,65	11,21
Travel time	No barrier	382	53,11	10,32
	Slight barrier	233	51,40	11,07
	Moderate barrier	109	48,06	12,21
	Substantial barrier	35	49,17	14,85
	Total	759	51,68	11,20
Accessibility	No barrier	627	52,53	10,39
	Slight barrier	81	48,16	11,60
	Moderate barrier	33	45,12	14,65
	Substantial barrier	9	42,11	26,07
	Total	750	51,61	11,23
Ilness or disability	No barrier	617	52,84	10,17
	Slight barrier	81	47,65	11,93
	Moderate barrier	35	46,37	11,85
	Substantial barrier	23	41,13	20,60
	Total	756	51,63	11,21
Insufficient public transport	No barrier	387	53,01	10,19
	Slight barrier	205	50,27	11,53
	Moderate barrier	104	49,24	13,67
	Substantial barrier	56	51,11	11,13
	Total	752	51,60	11,25
Finding information about public transport timetables and routes	No barrier	483	52,83	10,28
	Slight barrier	157	51,29	11,10
	Moderate barrier	72	46,90	12,00
	Substantial barrier	47	49,06	14,85
	Total	759	51,72	11,08
Difficulty to order a taxi	No barrier	515	52,37	10,67
	Slight barrier	99	52,08	9,50
	Moderate barrier	86	49,12	11,33
	Substantial barrier	45	48,11	17,22
	Total	745	51,70	11,16
Taxi availability and certainty to get a taxi	No barrier	451	52,73	10,34
	Slight barrier	146	51,12	11,08
	Moderate barrier	93	48,68	11,89
	Substantial barrier	51	49,24	15,40
	Total	741	51,66	11,17
No car	No barrier	198	51,83	10,76
	Slight barrier	108	49,77	11,22
	Moderate barrier	36	48,50	13,27
	Substantial barrier	31	41,19	19,70
	Total	373	50,03	12,41
No driving licence	No barrier	166	50,47	12,05
	Slight barrier	41	52,05	9,27
	Moderate barrier	18	42,78	14,56
	Substantial barrier	20	49,30	14,31
	Total	245	50,07	12,15
Insecurity in travel	No barrier	559	52,94	10,52
	Slight barrier	138	49,15	11,12
	Moderate barrier	43	48,09	10,43
	Substantial barrier	14	43,36	21,94
	Total	754	51,79	11,10
Insufficient options for car parking	No barrier	261	52,33	10,75
	Slight barrier	178	52,80	10,99
	Moderate barrier	161	51,19	9,93
	Substantial barrier	120	50,25	13,34
	Total	720	51,84	11,12
Lack of pavements and bicycle ways or insufficient maintenance	No barrier	262	53,07	10,95
	Slight barrier	245	50,19	11,42
	Moderate barrier	156	50,58	11,74
	Substantial barrier	91	53,22	9,60
	Total	754	51,64	11,19
Insufficient options for storing and parking a bicycle	No barrier	385	52,43	11,49
	Slight barrier	200	51,12	10,23
	Moderate barrier	82	51,07	8,58
	Substantial barrier	60	51,07	14,12
	Total	727	51,80	11,11

Item	Response	N	Mean	SD
Accepting a job	No barrier	347	53,62	9,41
	Slight barrier	108	49,90	10,12
	Moderate/substantial barrier	32	47,06	13,69
	Total	487	52,36	10,10
Work trips or travel to study place	No barrier	366	53,43	9,63
	Slight barrier	121	50,63	9,61
	Moderate/substantial barrier	37	48,78	12,96
	Total	524	52,46	9,99
Taking kids to day care	No barrier	247	52,95	9,89
	Slight barrier	26	53,08	10,87
	Moderate/substantial barrier	8	52,63	14,49
	Total	281	52,95	10,09
Going to grocery store	No barrier	636	52,59	10,26
	Slight barrier	88	48,83	12,27
	Moderate/substantial barrier	19	45,53	17,24
	Total	743	51,96	10,84
Going to other stores	No barrier	531	53,11	10,42
	Slight barrier	170	49,77	10,30
	Moderate/substantial barrier	45	45,36	14,74
	Total	746	51,88	10,90
Using post services	No barrier	630	52,60	10,35
	Slight barrier	83	48,55	11,85
	Moderate/substantial barrier	27	45,74	16,31
	Total	740	51,90	10,91
Going to pharmacy	No barrier	663	52,53	10,29
	Slight barrier	63	47,24	12,25
	Moderate/substantial barrier	19	43,47	18,92
	Total	745	51,85	10,92
Going to health centre or child health centre	No barrier	616	52,67	10,22
	Slight barrier	96	48,74	11,59
	Moderate/substantial barrier	25	42,04	17,37
	Total	737	51,80	10,93
Visiting friends and relatives	No barrier	402	53,55	10,06
	Slight barrier	237	51,35	10,29
	Moderate/substantial barrier	96	47,40	13,06
	Total	735	52,04	10,75
Participating in interesting hobbies	No barrier	447	53,40	10,36
	Slight barrier	203	51,00	9,37
	Moderate/substantial barrier	56	46,82	14,82
	Total	706	52,19	10,67
Going to the cinema, theatre, museums or concerts	No barrier	526	53,19	10,08
	Slight barrier	146	48,84	10,32
	Moderate/substantial barrier	45	48,82	15,73
	Total	717	52,03	10,72
Visiting summer cottage or nature attractions	No barrier	358	54,22	9,40
	Slight barrier	176	51,15	9,51
	Moderate/substantial barrier	129	49,20	12,91
	Total	663	52,43	10,39

Efficient bicycle networks and expansion strategies

Talvitie, Joel, tekniikan kandidaatti, Kuivalainen, Veeti, tekniikan kandidaatti, Aalto-yliopisto, rakennetun ympäristön laitos:

Abstract

This article explains some of the key attributes and factors relating to efficient bicycle networks and their expansion strategies. Varying from a network scale to brief discussion about the streetscape design, many scientific publications are referenced to explain the crucial aspects which must be taken into consideration when planning an attractive cycling network. Modal switch from other transport modes, especially from cars is one of the goals of this cycling promotion. Various methods such as building new bicycle facilities, improving the quality of existing ones and increasing the comfort and safety of the connections were found to improve the attractiveness of cycling in urban context. Additionally, this article analyses the reasons behind cyclists' route choice as well as the metrics such as connectedness, directedness and coverage which can be used to measure the level of network functionality. Lastly, network growth under limited resources is considered and an equitable distribution of cycleways across the city is found to be important in preventing neighbourhood segregation while not being too far from a utilitarian kind of distribution in terms of return to investment.

1. Introduction

Cycling has been a part of urban mobility for a long time, but it has been seen differently through the times. In the 21st century, however, cycling is largely connected to climate-friendly modes of transport and therefore the political push for the increase of the share of cyclists in cities can be seen especially in some European countries. Many methods have been tried to encourage people into cycling. According to Buehler, R & Dill, J. (2016.), almost all cities that have attempted to do so have expanded bike networks, including bicycle lanes, cycle tracks and traffic calming of neighbourhood streets. Therefore, the analysis of bicycle network efficiency and expansion plays a key role in this large context of cycling promotion. As one of the key methods has been the construction of bike-specific lanes and roads, the effect of these should be evaluated as precisely as possible.

This essay will cover some of the key concepts relating to bicycle network's functionalities both from street level and network level, concentrating more on the network level. At first, we will introduce the context in which cycle networks play a key role, secondly, we will introduce one type of theory which presents the maturity of cycle networks in each city as well as discuss the improvements which should be done first to promote cycling on each level. After those, we analyse more deeply the reasons behinds cyclists' route-choice and which attributes of cycle networks are most crucial in terms of cycling promotion. On the fourth chapter we discuss the evaluation methods of existing bicycle networks and critically analyse their effectiveness from a given viewpoint. Finally, the distribution of limited resources invested in bicycle networks is considered ending with conclusion.

1.1 The role of network expansion in attracting cyclists

Buehler, R & Dill, J. (2016.) analysed numerous publications relating to cycling networks especially in the United States. Even though some studies did not find correlation between the length of the bicycle network, none of them argue that constructing more bike lanes would decrease the popularity of cycling. On the other hand, Dill, J & Carr, T. (2003) found from their study of 42 large US cities that each additional linear mile of bike lanes per square mile land area was associated with a roughly 1% increase in share of bike commuters. From this result, some connections were missing in the bike networks of these cities. Cities in the United States mostly are not built solely for prioritizing cycling and therefore would put them at most to the level 3 of bicycle cultural maturity which is explained in more detail later. One percent increase in the share of bike commuters obviously cannot be infinite as there would be a point where constructing a new bike lane would not benefit large numbers of commuters to change from a car e.g., to a bike. However, in cities where coherent bike networks are lacking, this could very well be one of the first steps towards a more bike-friendly city.

2. Bicycle maturity and bicycle network needs

Different cities are at different maturity levels regarding their bicycle culture and infrastructure. Thus, the next logical step for a network expansion depends on what maturity level the city is at. As an example, connecting missing links works well for cities that have some kind of bicycle network but are lacking connectivity, whereas those cities that already have a well-connected network can focus on improving travel comfort and speed, e.g., by investing into cycling superhighways. Building high-speed and high-capacity links is not always optimal for cities that are at low stages of bicycle maturity. These cities should instead focus on providing adequate connections between main locations and residential areas, which will allow the bicycle culture to develop and the user base of cyclists to grow.

The bicycle network needs follow some kind of hierarchy, where a limited budget should be first allocated to building basic components of the network, and at later stages of maturity emerged needs, such as the need for mitigating congestion, can be tackled. Reggiani et al. (2022) have proposed a theoretical need-driven framework that draws inspiration from Maslow's (1943) hierarchy of human needs, often represented as a pyramid. Just as the bottom layers of the Maslow pyramid, the bottom layers of the proposed bicycle network needs pyramid must be adequately satisfied before higher-order needs become relevant. Reggiani et al. (2022) defines five levels of bicycle culture, and their corresponding hierarchical bicycle network needs as follows (figure 1.):

- 5. Bike dominant – Mitigate congestion
- 4. Bike friendly – Comfort
- 3. Bike emerging – Connectivity
- 2. Bike ignorant – Safety and accessibility
- 1. Bike hostile – Basic and direct paths

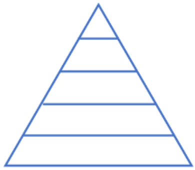

Figure 1. Reggiani et al. (2022) defines five levels of bicycle culture, and their corresponding hierarchical bicycle network needs.

A bike hostile city is mainly focused on car mobility, and it is lacking in the very basics of bicycle infrastructure. According to Reggiani et al. (2022), bike hostile cities require direct and well-known bike connections between the most important parts of the city. The way to move away from the lowest tier of bicycle culture is to build fast and build cheap: to redistribute the existing road space instead of building segregated bike paths. Bike sharing fleets may already be established at this stage.

A bike ignorant city already has an interest in developing bicycle culture but is lacking in coherent network planning. This kind of city should simultaneously look at increasing safety and accessibility of the network. Safety in this case means reducing the chances of crashes by, e.g., limiting the speed of cars, investing in lighting, and setting up separate traffic signals for cyclists. Increasing accessibility means building infrastructure to locations where it has the best chances of offering communities a basic level of bicycle accessibility.

A bike emerging city has some plans for cycling mobility but has a network that is not yet well connected. Emerging bicycle cities have many possible paths for expansion, but only through careful analysis and planning can they choose the most effective way forward. The key things they should understand are the latent cycling demand and the weak links of the infrastructure. By understanding latent demand, it is possible to maximize the number of new users with minimal investments, and by identifying weak links (or missing components), it is possible to increase overall connectivity in the city.

A bike friendly city has already a well-connected network, and relatively comfortable and safe cycling. It can focus on further increasing the bicycle modal share by improving route guidance, improving traffic control, and further prioritizing the bicycle mode in traffic. It can also integrate cycling better to public transport to encourage multi-modal trips.

A bike dominant city has a very mature cycling culture, even to the point that there are new kinds of problems. The volumes of cyclists start to exceed the capacity of the cycleways, which decreases the perceived safety and comfort. In these cities, congestion mitigation and rethinking of road space are necessary to facilitate the high volumes. Network expansions in new locations are rarely needed at this stage.

3. Cyclists' route choice and its effects on modal split

One of the main features of cycling is that moving a bike requires muscular force excluding bikes that are fully electric. This feature itself sets many requirements for a well-balanced and tempting bicycle network. In addition, the speed and vulnerability of a cyclist are attributes that ultimately affect many different factors relating to the attractiveness and comfort of cycling. Broach, J, et al., (2012) and Dill, J (2009) in their papers concretize the attractiveness of bicycle facilities with the number of cycled kilometres in Portland, Oregon in the United States. According to them, using a GPS device to track cyclists, it was found that 50% of the cycled kilometres occurred on roadways whereas the other half occurred on bicycle facilities even though they only accounted for 8% of the bikeable road network. This results itself presents the fact that cyclists appreciate paths specifically designed for bikes. Examples of factors which could be analysed relating to bike networks to evaluate the quality of a given network are presented in more detail later. However, some attributes that affect the route choice of cyclists are the number and type of intersections, grade of the road, number of lanes, condition of the road, length of the connection and perceived feeling of safety.

Analysing the whole bicycle network instead of just single links is important when trying to improve the share of cyclists in urban areas. This relates to the route choice options and differences between the available routes. Intersections for instance usually have a negative effect on cycling experience (Buehler, R & Dill, J., 2016). As mentioned earlier, muscular force is required to move a bicycle which means that all stops on a cycle route increase the physical workload required. This includes intersections with traffic lights and stop signs but also nodes where cyclists must decrease speed to travel safely. These interruptions to a cycling trip negatively affect the attractiveness of a given route and may cause some deviations for a cyclist and ultimately distort the modelled cycling routes if these attributes are not considered thoroughly. Crane et al., (2017) explain that according to reveal preference of cyclists, they are willing to deviate from the most efficient routes to commute on safer roads. This claim, however, works only to an extent. The problem of having a safe but also an efficient cycle route could be solved by separation of traffic modes, especially cyclists from other modes. However, the separation of traffic modes should not be done with the expense of a dramatic travel time increase and decrease in efficiency. For example, a study done in Vancouver, Canada found that 90% of non-recreational cyclists' trips were withing 25% of the shortest route distance (Winters, M et al., 2010). This percentage would obviously vary between cities regarding their network capabilities but the fact that only 10% of these cyclists were willing to deviate more than 25% is prominent information for cycling network planners.

4. Network metrics

Evaluation of a cycling network is a critical part of building a coherent and well-balanced part of infrastructure which ultimately promotes cycling. As the effects of such an infrastructure are long-lasting, evaluation of the existing network should be done already in the early stages of its lifespan. This way the future construction can be done iteratively so that the future cycle network projects are getting increasingly better than before. The biggest problem in this evaluation, however, is that there are many types of cyclists who all have different preferences relating to cycling. This results in a situation where compromises must be made. In academic literature some, methods of evaluating the networks include for example trying to formulate coefficients to various preferences or by measuring attributes that are found to affect the attractiveness of cycling. This section will qualitatively introduce some metrics used to measure the performance of specific bicycle network attributes. Based on these metrics and research on cyclist preferences, bicycle facility investments can be allocated in a data-driven manner, and in some sense, most efficiently.

4.1 The main types of metrics and related network improvements

Much of the contemporary research on network-wide scale is computational, which has produced quite an abundance of mathematical expressions. Naturally, it is not simple to mathematically represent some of the ultimately experiential features. Furthermore, it is hard to say which exact metrics should be used, because they might fit different purposes: some of them could be computationally simple, some of them could fit the purpose of multi-modal transport planning than others, and ultimately the context of the city determines the most applicable measure. By researching the literature, we have identified some of the main groups of metrics that could be incorporated in planning processes in some form or another.

Orozco et al. (2020) use connectedness and directness as the main metrics in their algorithmic study that aims to suggest optimal investment strategies. Boisjoly et al. (2020) use route deviations, network connectivity, and the proportion of route travelled on bicycle facilities. Szell et al. (2022) use the following quality metrics in their algorithmic growth models: length, length of the largest connected component, coverage, directness, number of connected components, and local and global efficiency (related to directness). Vybornova et al. (2022) use gaps, gap clusters, and detour-based measures to identify missing links in networks.

It seems that the most common measures are related either to connectedness (which is the opposite of gaps), coverage, or directness (which is the opposite of route deviations). However, the studies mentioned above use algorithms that don't discriminate between low-quality and high-quality links, so an apt critique is whether they measure the quality of the infrastructure itself enough. Therefore, in addition to the previously mentioned, we would suggest including a quality metric that includes the safety, comfort, and speed of the individual links. Next, the main groups of metrics are introduced in more detail.

4.2 Connectedness

Connectedness is the measure of how continuous the bicycle infrastructure is, or in other words, how little fragmentation there is. Connectedness is related to the question of can one go to their destination safely and on dedicated infrastructure (Orozco et al. 2020), with no particular concern about travel time or distance travelled. As discussed in section 2 about bicycle network needs, the first steps a city takes in developing its bicycle network are not, and perhaps shouldn't be, about increasing connectedness. Rather, the low maturity cities should be somewhat opportunistic in taking inexpensive steps at expanding their network and/or building facilities between high-demand locations. This leads to a fragmented network with smaller and larger components but not necessarily interconnected with one another. After the main network pieces are built, the cities should aim to connect the components to enable more trips on dedicated infrastructure. The following illustration by

Vybornova et al. (2022) supports this idea, where the undeveloped cycling cities need not worry about connectedness, bike-emerging cities can increase connectedness by tying fragmented pieces together, and beyond bike-emerging cities can focus on directness-improving connections that fill in missing links, simultaneously building redundancy and resiliency in the network. They mention Los Angeles as an example of an undeveloped city (on the left in Figure 2), Budapest as a city with a fragmented network (middle), and Copenhagen as a city with an already well-connected network (right).

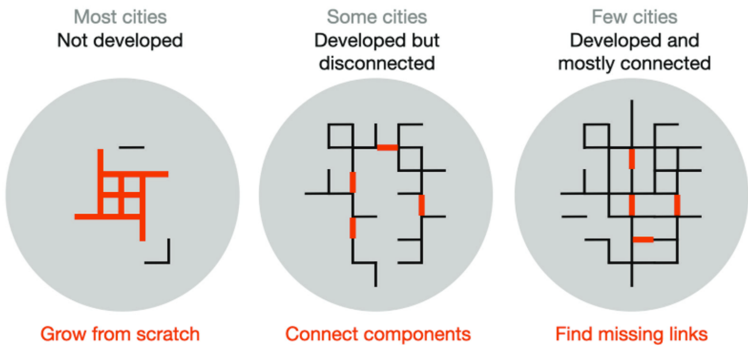

Figure 2. The role of connecting fragmented components and filling in missing links in different cities (Vybornova et al. 2022).

Vybornova et al. (2022) approach the problem of increasing connectivity in Copenhagen by identifying gaps at streets (a street that has no protected infrastructure but connects two parts of protected infrastructure), intersections, right-turn lanes, bridges, and roundabouts. The common factor in these gaps seems to be that there is an underlying idea to connect two parts of the city, but due to construction difficulties or high costs, the gap part did not get protected bicycle lanes.

4.3 Coverage

Coverage measures the percentage of either the area or the population of the city that has accessibility to the bicycle network, for example in a 200-meter radius. Coverage is related to connectedness in the sense that coverage of a fully connected network is better for the residents than coverage of any random segments. Whether or not to increase coverage, is somewhat a value-based decision and is related to land-use planning and distributive considerations, as will be discussed in section 5.2.

4.4 Directness

Directness is in its simplest form, the ratio between Euclidean distance and shortest path distance between two points (Szell et al. 2022). Directness is one of the most important attributes of the network, because if the route is not direct, cyclists may opt for a more direct but unsafe route with mixed traffic. In a stated preference survey, Stinson & Bhat (2003) found that commuter cyclists strongly prefer directness on route to their workplace, however, they are also willing to make slight detours to use bicycle facilities.

Directness can be measured not only for bicycle networks in isolation, but as bicycle-to-car directness. This measure controls for the unavoidable low directness in special geographical cases, such as hilliness and water bodies. The directness along bicycle network is compared to the directness along the network allowed for cars. For example, Orozco et al. (2020) define bicycle-to-car directness as the ratio between average car route distance and the average length of the shortest bike route.

4.5 Quality of the path

Connectedness, coverage, and directness are not enough to explain travel behaviour, because the quality of the path for which these attributes are calculated, can vary a lot. For example, the algorithmic approaches introduced before, often do not consider the safety, comfort, and speed of individual links. Furthermore, the choice of a particular route often depends on the next-best option, so one needs to evaluate what is the difference between taking a detour on bicycle-dedicated bike lane and going straight on a mixed traffic street.

Some of the quality attributes that could most easily be included in computational models include inclines, number of intersections, number of traffic lights, car traffic volume, and the maximal speed that the path allows. As an example of the possibilities, in estimating the adequacy of a particular route for daily commuters, one could incorporate a perceived exertion model that uses elevation data along routes to calculate the perceived physical effort (Carl et al. 2013).

4.6 User preferences between the metrics

There is no one metric or criterion that clearly dominates the others in all possible senses. For example, it depends on the trip purpose, the physical health, safety preferences, among other things, whether directness is preferred over continuous protected infrastructure. Furthermore, many things, such as the coverage of the network, is also a matter of local politics and spatial planning. Some idea of the ranking of route attributes for commuter cyclists was found in a stated preference survey by Stinson & Bhat (2003). They found that commuters prefer, in order of importance: lower travel times (perhaps most closely linked to directness), residential roads over major and minor arterials (indicating that traffic calming is effective), bicycles facilities over non-bicycle facilities (emphasizing connectedness), bridges having protection for cyclists, smooth pavement, streets with no parallel parking, fewer major cross streets, flat ground, continuity of bicycle facility over an interrupted one, fewer stop signs, and finally fewer red lights.

5. Bicycle network growth under limited resources and distributional considerations

Realistically, bicycle lanes cannot be built on any of the streets. The volume of motorized traffic, available space for widening the road, the number of intersections, among other things, place constraints on which streets are the most suitable for placing a bicycle lane in. For a moment, however, let's assume that such constraints don't exist, and the optimal growth is only based on how the network topology at large creates welfare by connecting locations and how much it costs. Analysing the costs and benefits on a more generalized level allows to later add to the equation the specific constraints of each location and justify decisions based on a comprehensive analysis of network-wide effects as well as local effects in addition to investment costs. In this section, we will consider how the general shape and structure of the network affects the distribution of benefits among different stakeholders and communities.

5.1 Trade-offs associated with the general shape of the network

The following illustration (Figure 3) by Szell et al. (2022) shows not only how different network shapes are desirable from the points of views of the investor and the traveller, but how there is a trade-off between economizing and building resilience. The solution that connects the most locations with minimum path length, is called the minimum spanning tree. This arrangement provides the maximal cost-efficiency if the only goal is to connect the main points of interest with a bicycle path. While this arrangement could in some circumstances minimize the cost per travelled kilometre, it has some significant downsides. It provides less direct routes, which compromises the competitiveness of the bicycle mode, and thus reduces some of the user attraction, which is not desired if the city plans to increase the number of cyclists. The minimum spanning tree could also prioritize already developed areas while ignoring under-developed ones (Mahfouz et al. 2021; Szell et al. 2022), which could reinforce the socioeconomic inequalities among these neighbourhoods and contribute to segregation. The resiliency of this network is low because an interruption, such as a roadwork, cuts the entire network into disconnected pieces (Szell et al. 2022). If the goal is to make a city bikeable around the year, this kind of network requires a large effort into planning and establishing alternative cycling routes in case of interruptions. Based on these arguments, Szell et al. (2022; p. 2) criticize the fact that a large share of current computational research is geared towards connecting missing links in bicycle infrastructure, which often leads to suboptimal minimum spanning tree-like solutions.

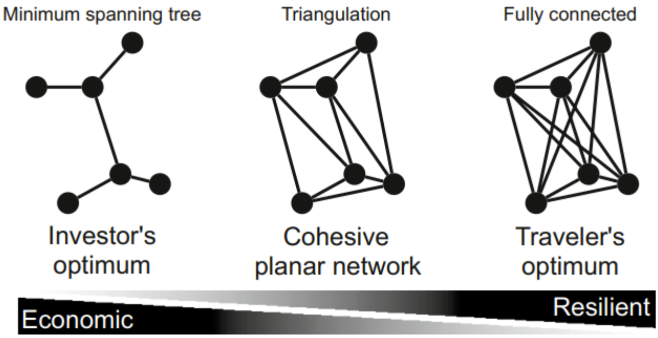

Figure 3. Illustration of the trade-off between economizing and building resilience in different network topologies (Szell et al. 2022).

On the other end of the spectrum, there is the traveller's optimal network. This network provides maximal directness, so it is the best we can do in terms of attracting people to the cycling mode. It is also maximally resilient and provides access to even some of those underserved neighbourhoods that don't have any regional points of interest. However, this network in all its redundancy, could have the highest cost per travelled kilometre because the utilization rate of any single path is smaller. In between the investor's and traveller's optimal networks, there exists an array of intermediate solutions, including the triangulation approach used by Szell et al. (2022) in their computational bicycle network growth algorithms. The intermediate solutions provide a fair amount of directness, and a fair amount of resiliency by offering at least two routes between any two points, while still being reasonably inexpensive to build.

5.2 Utilitarian and egalitarian expansion

It is not only the shape of the network, but also the location of it, that has consequences on bicycle accessibility throughout the city. It is tempting to concentrate new bicycle infrastructure in locations that are already bike-emerging, as there are still a lot of potential cyclists to attract in these locations, and enhancements greatly improve the comfort for existing cyclists. However, prioritizing always the highest-demand routes could eventually lead to an uneven distribution of investments across neighbourhoods. For instance, an expansion strategy that aims to connect missing links in bicycle infrastructure could be effective in enhancing the existing network, but it is mostly the already affluent neighbourhoods that gain from this expansion. Communities that have few or none bicycle paths, would get neglected in this utilitarian expansion regime, because it is more costly to start building the network from scratch than to improve existing ones. An egalitarian strategy, on the other hand, would aim to distribute either the investment or the outcome fairly in space. This strategy could imply more immediate costs and friction in establishing a bicycle culture in the city, but perhaps it would be a more sustainable growth option that reduces long-term inequalities and segregations between different parts of the city.

As with other network attributes, also the spatial distribution of infrastructure requires deliberation of trade-offs between utilitarianism and egalitarianism. In the long-term, it is obviously good to pursue spatial equity, but under uncertain financial outlook in the future and the near-future climate crisis, it is tempting to just maximize the modal shift to cycling. Mahfouz et al. (2021) developed a road segment prioritization algorithm for cycling infrastructure, which can be applied either city-wide (utilitarian expansion) or at a community level such that the investment gets distributed proportionally (egalitarian expansion). They found that the egalitarian algorithm, while equalizing the distribution of investment, did not come at any noticeable cost of less connectivity or less city-wide gains.

This result suggests that maybe it is not so "anti-utilitarian" to be egalitarian after all.

6. Conclusion

The current bicycle networks in cities differ significantly, however, there are many strategies to improve these existing networks as well as expand them to provide larger coverage of bicycle facilities. Analysis and evaluation of cyclists' route choices and various preferences are an essential for planners to understand this complex problem of cycle networks. Methods for such a planning require a deep understanding of individuals and their revealed preferences as well as hopes for the future.

Whichever is the city's desired shape and coverage of the network and the associated outcomes, it is evident that to reach certain objectives, one must plan on a network level. This planning is a multi-objective problem, where each city has its own constraints and prospects. First, the bicycle network does not exist in isolation from the other transport system, so developing it efficiently could require making changes also in car traffic (traffic calming, street space reallocation) and public transport (integration to cycling in terminals and vehicles). Second, the bicycle network itself has multiple attributes and metrics which influence the attractiveness of cycling. These include, e.g., directness, coverage, connectivity, safety, low physical and mental stress, and allowed travel speed. Third, the performance of the network can also be measured from multiple non-traveller points of view, including resiliency, equitability, and cost-effectiveness.

Our readings have provided articles on computational methods to assess performance by some particular network metrics (Boisjoly et al. 2020; Carl et al. 2013; Mahfouz et al. 2021; Szell et al. 2022; Vybornova et al. 2022), articles that explore empirical cyclist preferences between network qualities (Broach et al. 2012; Buehler & Dill 2012; Crane et al. 2017; Dill 2009; Dill & Carr 2003; Nello-Deakin 2020; Stinson & Bhat 2003; Winters et al. 2010), as well as one article providing strategic guidelines for network expansion in different cities (Reggiani et al. 2022). The common finding across most of these articles is that all the previously mentioned network attributes matter, but directness is ultimately the most dominant one due to its effect on travel speed. A cyclist is willing to accept less safe and comfortable cycling environment if it makes the route significantly shorter. However, other attributes such as coverage, connectivity, and protected infrastructure, can be influential in attracting new bicycle users (matching latent demand in the city).

We found that the order of improvements matters when making a shift from a car-friendly city to a bicycle-friendly city. According to Reggiani et al. (2022), going from low level of bicycle-maturity to high bicycle-maturity, the preferred order of infrastructure expansion is building direct facilities between most important locations first, then increasing the spatial coverage of the network, then increasing connectivity by bridging missing links, and finally when most of the expansion is done, making capacity and comfort improvements to the existing facilities. According to results of Mahfouz et al. (2021), it is plausible that equitable spatial distribution of facilities is not always in conflict with "utilitarian expansion", indicating that could be room for incorporating egalitarian principles in network growth strategies. However, there is possibly a trade-off between cost-effective expansion and an expansion that builds resilience (Szell et al. 2022).

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Relationships Between Weather and Cycling

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Abstract

As cycling gains more traction and attention as a beneficial mode of urban transportation, different factors have emerged in different regions of the world to influence its adoption and promotion. One of the most wide-spread and colloquial of these factors is that of the weather or climate of the region, and how it may facilitate or, more often, dissuade cycling practices. Although it may appear intuitive that "poor" weather shall negatively impact the amount of cycling that occurs in a region, the reliability of this intuition is challenged by example locations where cycling in "poor" winter conditions is the norm rather than the exception, or where cyclists are relatively indifferent towards rainy weather. As such, the aim of this literature review is to identify the real effects of weather on cycling behaviour in different locations and uncover relationships between secondary covariates and responses to weather. Rainfall, temperature, and wind are identified as the three most important measurable weather parameters that affect cycling behaviour. In most locations, cycling rates drop significantly when it starts to rain, temperature thresholds vary between locations, and the effect of wind is only significant when above 5 Beaufort. Several studies also reveal factors that interact with measurable weather parameters to influence behaviour in significant and seemingly complex ways. These include the trip purpose, traveller sociodemographic, the characteristics of the built environment, and perceptions of normality. The identification of these covariates and a discussion about interrelations amongst them contributes to an explanation of why weather seems to affect cyclists in some places more than in others, while also highlighting directions for future research.

Introduction

We were interested in looking at the effects of weather on cycling behaviour. One of the challenges we faced while searching for suitable research papers was the fact that most of the research is from Europe or North America. However, we wanted to look at the effects of weather in different locations, because our assumption was that these effects would be different in different parts of the world, given the differences between climates, cultures, and habits. We managed to find a good and comprehensive literature review article, which led us to a few other good articles from there.

An interesting overall finding from the literature review is that many of the studies cite climate change and its potential effects on our cities as the main reason for carrying out this research and being interested in looking into the effects of weather on cycling behaviour or active mobility in general. It is understood that weather will keep getting more unpredictable in the years and decades ahead, and more extreme weather is likely, while rising temperatures will be evident in many parts of the world. Therefore, many of these researchers are interested in finding how these changes may affect behaviours, as well as what steps we may be able to take to adapt our behaviours to the changing climate.

In this essay, we will first present our findings on the direct effects of weather on cycling behaviour, and then we will discuss some related factors and covariates that seem to be at an interplay with the weather effects. Following this, we provide a synthetical discussion of the research area, identify gaps, and finally reflect on the research process as related to the Integrated Urban Transport course.

Direct Weather Effects

The journal articles we reviewed studied a few different weather factors, either on their own or in conjunction. Generally, what we found from the review is that a handful of factors are cited as the most prominent ones in affecting cycling behaviours, namely rainfall or precipitation, temperature, wind, and humidity.

Most of the papers we studied identify rainfall as the single biggest deterrent of cycling. This is the case for most of the locations. Some studies found that there is a large drop in cycling rates with even the smallest hint of rain, after which the decline slows down (Liu et al., 2017, Böcker et al., 2013). Another study concluded that rainfall not only affects cycling rates, but also cycling distances as well (Hong et al., 2020). Böcker et al (2013) mention studies in Canada and the UK that show lower total cycling trips in places with traditionally higher amounts of precipitation than other places. One study mentioned in the literature review article (Böcker et al., 2013) found that light rain mostly has an impact on the clothing worn by cyclists, and only heavier rain impacts cycling rates. We should note here that, even though some studies explicitly identify and mention rainfall as the specific factor, other studies resort to talking about precipitation in more general terms, which may contain different forms of precipitation like rain, snow, etc.

Temperature seems to be the second major factor affecting cycling behaviour. A study conducted in Rotterdam actually found that temperature is more significant than any other factors like rainfall and wind (Helbich et al., 2014). According to Liu et al. (2017), temperature has a strong effect on cycling. Several studies in Europe and Canada showed that cycling rates are positively correlated with temperatures up to 25 degrees Celsius, after which the relationship becomes negative (Liu et al., 2017). This pattern has been observed in many places and from different studies as well. Generally, there seems to be a “bell-curved” relationship of temperature with cycling. The cycling rate generally increases gradually towards a peak before declining relatively sharply thereafter. The peak and slope(s) of that curve seem to be location-specific, meaning that it is different in different parts of the world. For example, a study in Singapore questioned cyclists and identified that temperatures between 29.5C and 31.5C are the most comfortable ones and are in fact seen as “lower temperatures” (Meng et al., 2016) as opposed to some places in Europe or Canada where 25C to 28C were the peak level comfort temperatures identified (Liu et al., 2017; Bean et al., 2021). This is also validated by Böcker et al (2013) who mention several studies that found a positive relationship with temperature up to a certain degree; but especially in hotter climates, temperatures above a certain context-specific threshold had a negative effect on cycling. Another effect of temperature we can spot in different parts of the world is the seasonality. As discovered by a study about bikeshare use in different cities across different climates, the use of bikeshare in temperate climates like that of Paris or Brussels peaked in the summer and dropped in the winter, while in more tropical climates, like that of Brisbane, it remained fairly consistent (Bean et al., 2021).

Additionally, Böcker et al (2013) cite a study looking at mode choice for going to school in a few different cities which found that the cycling rates triple in the summer over the winter.

Another factor that came up in different studies is wind. As mentioned by Böcker et al (2013), most studies find that there is a negative relationship of wind with cycling. Liu et al. (2017) found that wind speed has a moderate effect on cycling behaviour, and Saneinejad et al. (2012) found that wind affects cyclists in Toronto, even more than pedestrians. As we can see from Böcker et al. (2013) again, the range with which wind is negatively associated with cycling varies from study to study and from place to place, from a weak negative relationship to a strong one. Only a few studies seem to have investigated the wind speed specifically, and they generally find that stronger winds are more strongly associated negatively with cycling

than lighter winds. For example, Böcker et al (2013) cite a study that found that only winds of 5 on the scale of Beaufort and up see a decrease in cycling rates. Studies that found weak relationships with wind may be consistent with this finding, as those studies did not observe/record wind speeds above 5bft.
Finally, humidity was mentioned as a factor that may affect cycling use, but this one was not studied by most of the research studies. In fact, only two of the articles we found mention and talk about humidity (Meng et al., 2016; Lee & Pojani, 2019), and they are both from Singapore, which may lead us to believe that humidity might not be a huge factor in a central or northern European context, or a North American one.

Covariates Affecting Cycling Responses

The findings presented in the previous section show that the effects of weather on cycling behaviour exhibit some generally consistent and strong relationships in most locations (i.e., a bell-shaped response to a range of temperatures, thresholder responses to wind & rain, etc.). However, observations that the specific parameters and intensities of these relationships change between contexts prompts questions about what covariates and mediating factors may help to explain the different responses to weather in different places. The authors of the two literature reviews to date on the subject (Böcker et al., 2013; Liu et al., 2017) argue that responses to weather cannot be detached from subjective interpretations of weather, which will be related to a variety of factors beyond objective measurements of individual weather parameters (i.e., temperature). Böcker et al. (2013) note that such parameters always co-occur, forming more holistic weather categories that are interpreted differently by individuals of different sociodemographic, inducing reactions to the weather that are embedded within a cultural context. Echoing the importance of cultural-contextual covariates, Hudde (2023) measures the difference between German and Dutch cyclists' responses to weather, showing that the average German cyclist is much more sensitive to weather parameters despite the climates of both countries being quite similar. These findings are demonstrated in Figure 1. Not only do German cyclists stop cycling sooner as temperatures and daylight decrease, but relatively more of them do so. Meanwhile, the 'raininess' of the city seems to affect the German modal split, but not the Dutch modal split. These different responses tacitly reflect those that can be observed between cities in North America, Europe, Australia, and Singapore, but our ability to explain them solely as an effect of differences in objective weather measurements is much more dubious. Hudde speculates that the different responses must be due to cultural differences expressed either directly, through general subjective perceptions about cycling and weather, or indirectly, through the way spaces are planned and what infrastructure/maintenance activities go on. In all, Böcker et al. (2013), Liu et al., (2017), and Hudde (2023) suggest that factors affecting the way a cyclist views the weather as relevant to their life will covary with their observed responses to it. The section hereunder surveys available evidence that relates such factors to cycling-weather responses including trip purpose, demographics & personal factors, built environment characteristics, and the perception of normality.

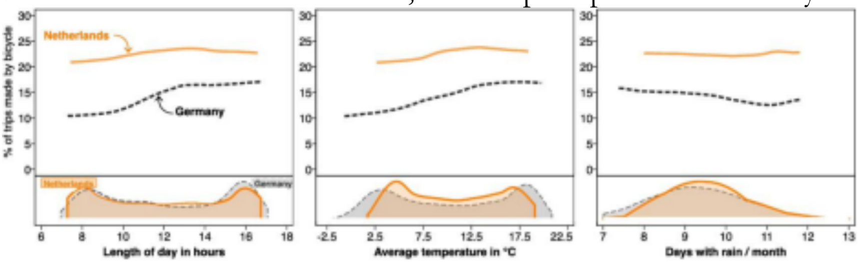


Figure 1. Cycling responses to weather in Germany vs Netherlands, including relative number of observed cities at each weather measurement. Reprinted from Hudde (2023).

Trip Purpose

Indeed, trip purpose appears to affect the response to weather for cycling trips. Several studies have found that leisure trips are affected by weather much more than work trips. For example, Helbich et al (2014) found that wind and rainfall are not significant factors when it comes to work cycling trips, but they are for leisure cycling trips. They also found that temperature plays a role in both trip types but is more significant for leisure trips. Similar findings are mentioned in Böcker et al (2013), where studies have shown differences between weekdays and weekends, as well as peak hours and off-peak hours denoting a larger effect of precipitation on leisure trips. Liu et al (2017) have concluded that even though rainfall and temperature can account for a large portion of the daily fluctuations in bike usage, there is a clear distinction between weekday flows and weekend flows, which goes to show the difference between leisure trips and utilitarian trips, as they call them. Bean et al (2021) looked at data for bikeshare use from forty different cities in the world and saw that most models place the hour of the day as the most significant factor, for both weekday and weekend trips. For example, they mention that usually weekend cycling trips peak around 2 to 3 in the afternoon in most locations, whereas in a more tropical location the peak was around 5pm. Equivalent results can be inferred for weekdays, with peaks around the morning and afternoon rush hours, or maybe in the middle of the day if the specific location has a cultural tradition like a siesta. We should note here that these weekday effects are only hinted at in this study, and they unfortunately do not provide a specific result on the weekday cycling peaks.

As mentioned above, most studies find that leisure trips are affected more than work trips in most of the locations. The only notable exception we found through our review was in Singapore. Meng et al (2016) found that work trips are more affected by weather than leisure trips. Of course, the weather in Singapore is different than most of the other locations studied in other papers, like in Europe and North America. Singapore has a more tropical climate. But the authors of the study provide a potential explanation for this phenomenon in the work culture of the country. It may be the case that the effect of adverse weather on people's ability to show up to work on time is preventing them from choosing to cycle to work when the weather is not ideal for them. Also, we assume that in Singapore it may be less acceptable to show up at work wet or sweaty, and if the workplace does not have any showers or changing rooms, this makes it almost impossible for people to choose to cycle to work under these conditions (Lee & Pojani, 2019).

Demographics & Personal Factors

There is a sub discourse in the literature which explores how the personal characteristics of individual travellers may affect observed sensitivities to changing weather. As Böcker et al. (2013) note, sociodemographic variables are usually included in studies as control variables rather than as mediating variables, but there is still some descriptive evidence on these. Exhibiting one of the most prevalent and consistent relationships among the studied factors is gender. It seems that in most cases where cycling responses to weather are measured, either through trip-making observations or stated-preference surveys, authors find a more sensitive response from female cyclists to 'adverse' weather. Most of the studies measure responses to precipitation, but some also demonstrate relationships with temperature or weather more generally. In Sweden, precipitation was more often cited by females as a barrier for cycling (Böcker et al., 2013; citing Bergström & Magnusson, 2003) - a result replicated in Victoria, Australia, where 47% of female cyclists cited "weather" as a barrier compared to 35% of males (Ahmed et al., 2013). In Australia and Canada, actual reductions in cycling due to precipitation were also observed to be more frequent amongst females (Böcker et al., 2013; citing Keay, 1992 & Chan et al., 2006). Significant differences in trip-making sensitivity to precipitation were also replicated in Chicago and New York but, notably, only on weekdays in New York and weekends in Chicago (Bean et al., 2021). For temperature, one study observed that, in cold weather in Toronto, female cyclists' tendency to cycle was ~1.5 times more sensitive than males (Saneinejad et al., 2012). Finally, a study in Singapore demonstrates a potential exception to the prevalent relationships found elsewhere. Taking random samples of cyclists on dry and rainy days, authors found a negligible difference in the composition of cyclists - roughly 70% of cyclists were male on each day (Meng et al., 2016). Most authors providing the primary evidence for the above relationships do not attempt to explain them, though other authors have speculated about the potential reasons underlying them. Some have made connections between physical fitness and gender (Motoaki & Daziano, 2015); between gender, differences in the modal split in general, and perceptions of safety and risk (Böcker et al., 2013; Hong et al., 2020; citing Emond et al., 2009); and between gender and "needs" for unique end-of-trip facilities such as change rooms in which to redo makeup or change into skirts for work (Lee & Pojani, 2019).

Another demographic factor that is speculated to be of significance for weather-cycling responses is age. In absence of direct, conclusive evidence, but in acknowledgement that in many locations cycling is generally more prevalent among younger age groups, authors often indicate that age is *likely* to covary alongside weather-cycling sensitivity (Böcker et al., 2013; Liu et al., 2017; Amiri & Sadeghpour, 2015). Liu et al. (ibid) treat advanced ageing as synonymous with disability, indicating a deteriorating ability to "cope" with adverse weather. Moreso related to cycling in general, Liu et al. (2020) note that, for example, elderly people may require more rest after conducting physical activities on a previous day, and that perhaps this need could intersect with weather-related experiences. Amiri & Sadeghpour speculate not in terms of ability, but rather in terms of age "affecting" things like thermal comfort, trip distances, and safety concerns. Meanwhile, Böcker et al. merely regard age as one of many sociodemographic aspects of cultural context that are likely to mediate the experience of weather and cycling. The available evidence that could substantiate these speculations is conflicting and appears inconclusive. The expected relationship was tangentially observed in Stockholm. There, stated weather perceptions amongst adults aged 51-65+ were much more sensitive to changes in actual temperature conditions than those amongst younger people (Liu et al., 2020). In the same study, stronger weather perceptions were shown to correlate well with more/less outdoor leisure-related travel (not cycling, specifically). Conversely, an opposite relationship was indicated by evidence gathered in Toronto, where authors found that younger cyclists' behaviour was more sensitive to colder temperatures than that of older cyclists (Saneinejad et al., 2012).

Other studies that attempted to find such evidence failed to demonstrate a significant relationship between age and weather-cycling sensitivity. Amiri & Sadeghpour (2015), while demonstrating that older age is indeed related to a reduced inclination towards multimodal cycling trips, and an increased likelihood to use cycling for commuting over other purposes, found that cold weather in Calgary did not seem to impede cyclists in the 44+ age group more than those in younger groups. Meng et al. (2016) likewise found no significant difference in cyclists' age composition on wet days vs dry days in Singapore.

Experience level with cycling, as a personal factor mediating responses to weather, has more consistent evidence supporting it than age. This evidence is, however, often less direct than the evidence associated with gender. The most direct and clear evidence comes from New York state, where Motoaki & Daziano (2015) utilized a hybrid-choice latent-class model to demonstrate that less-skilled (and less-experienced) cyclists consider rain to be 2.5 times more bothersome than more-skilled cyclists, and snow to be 4 times more bothersome. They also showed that colder temperatures were significant for negatively impacting attitudes of more skilled cyclists, while warmer temperatures were more significant for positively impacting attitudes of less-skilled cyclists. Similarly, Ahmed et al. (2013) found that "casual" cyclists (cycling < 3 days per week) were twice as likely to mention weather as an influence on their decision to cycle compared to "committed" cyclists in Victoria, Australia. This more direct evidence is also supported by findings that are somewhat more tangential, but perhaps still quite indicative. Hong et al. (2020)

found that, shortly following the construction of Glasgow's first modern cycling infrastructure projects, which generated a substantial number of new cyclists, rainy weather reduced cycling on the new cycling paths more so than on any other type of road/path. They speculate that this is likely due to the new paths attracting a relatively high volume of newer/casual cyclists, who are perhaps more sensitive to the rain. On the other hand, Amiri & Sadeghpour (2015) found that frequent, more-experienced cyclists in Calgary did not mind cycling in temperatures as low as -20C. Lee & Pojani (2019) provide potential reasons behind observed relationships between experience level and weather-cycling sensitivity. They report anecdotes from planners in Singapore, stating that experienced cyclists "employ various mechanisms to cope with the less desirable aspects of the local climate. For example, when there is rain, they may delay their departure time or use protective clothing" (Lee & Pojani, 2019).

Other sociodemographic factors are also likely important. For example, one study from Canada relates higher bodyweights of cyclists to higher sensitivity to snow and lesser sensitivity to wind (Böcker et al., 2013; citing Chan et al., 2006). Another study from the USA relates "ethnic diversity" and inner-city areas to a lesser likelihood to perceive weather as a barrier compared to people in rural areas, who are less "ethnically diverse" (ibid; citing Wilcox et al., 2000). As indicated by the latter findings, it may be difficult to disentangle certain sociodemographic groups from specific locations, and therefore also from what modal habits they may already be inclined to build. Location may extend to the formation of certain health factors and experience levels. Indeed, it seems important to examine the mediating effects of the built environment upon cyclists' sensitivity to weather, while keeping in mind also its potential entanglement with sociodemographic.

Built Environment Characteristics

Urban form and location have some direct evidence highlighting its substantial effects. Helbich et al. (2014) provide a clear demonstration through their observations of travel behaviour in the Greater Rotterdam area. They show that the effects of temperature, wind, and precipitation on cycling in less-dense peripheral areas are much more significant than in denser urban areas - with the exception of wind in the densest high-rise areas of downtown Rotterdam (Figures 2 & 3). The authors speculate that the microclimate created by denser urban forms functions to alleviate the negative effects of colder temperatures by providing heat, of hotter temperatures by providing shade, and of wind by providing shelter. To explain the mediating effect on precipitation, as well as on all other weather parameters, they propose that the denser urban form also enables shorter trip distances and, therefore, lesser time exposed to the elements. The larger negative effect of wind in high-rise areas is explained by the wind-turbulence effect associated with skyscraper buildings. The results from Rotterdam are consistent with earlier findings from Australia, which indicated that cycling volumes were much more sensitive to wind and rain in suburban, "exposed" areas compared to inner-city, "sheltered" areas (Böcker et al., 2013; citing Phung & Rose, 2008). Alongside these findings it should be noted that modal choice more generally can be very insensitive to the weather in suburban areas if those areas are car-dependent, as was demonstrated in Bergen, Norway (ibid, citing Aaheim & Hauge, 2005).

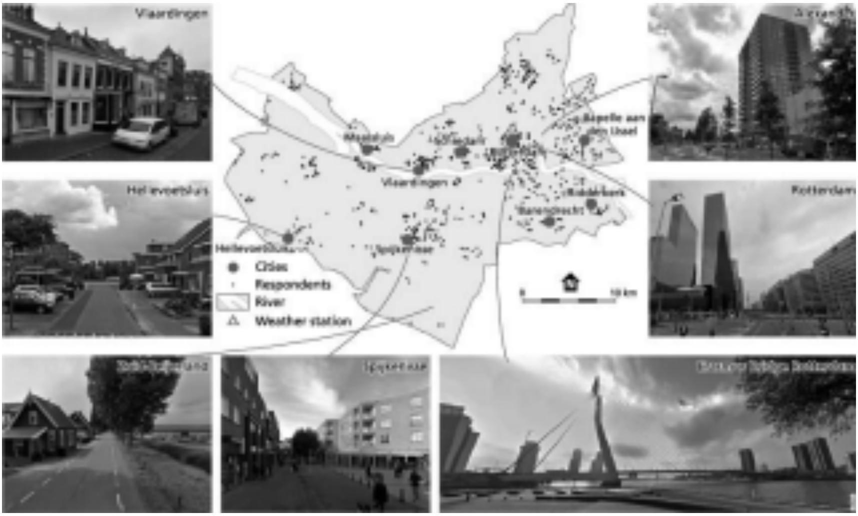
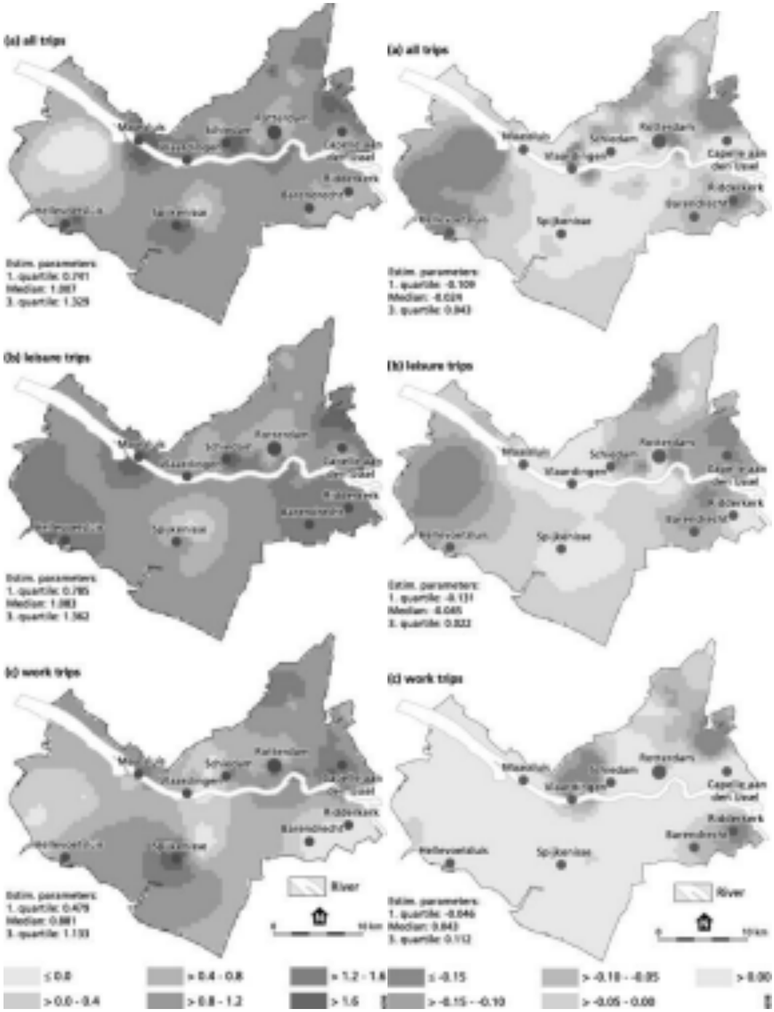


Figure 2. Legend of Greater Rotterdam locations. Reprinted from Helbich et al. (2014).


(a) all trips
(b) leisure trips
(c) work trips
Maassluis
Vlaardingen
Schiedam
Rotterdam
Capelle aan den IJssel
Ridderkerk
Barendrecht
Spijkenisse
Hellevoetsluis
River
≤ 0.0
> 0.0 - 0.4
> 0.4 - 0.8
> 0.8 - 1.2
> 1.2 - 1.6
> 1.6
≤ -0.15
> -0.15 - -0.10
> -0.10 - -0.05
> -0.05 - 0.00
> 0.00

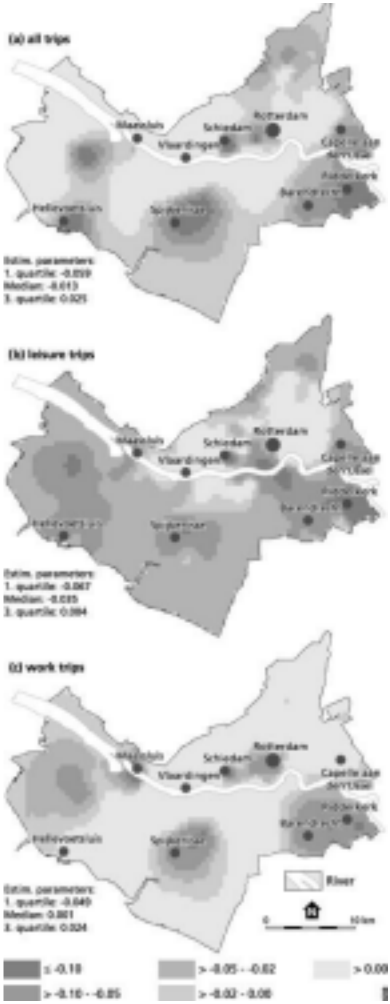


Figure 3. Significance of weather effects on cycling for air temperature (left), wind (middle), and precipitation (right). Reprinted from Helbich et al. (2014).

Where urban form and location may be considered one side of the built-environment coin, cycling infrastructure can be considered the other. Indeed, one of the limitations of the available evidence on

urban form is that it cannot be disentangled from the potential effect of the cycling infrastructure in the denser study areas simply being better. This was not controlled for in the referenced studies. Only some limited, tangential evidence regarding the effect of improved cycling infrastructure on weather sensitivity, per se, is available. There is consistent evidence that improved cycling infrastructure, including separated bike paths or lanes, more generally increases the rate of cycling (Böcker et al., 2013; Amiri & Sadeghpour, 2015; citing several authors), and that some absolute increase in cycling persists even in adverse weather (Amiri & Sadeghpour, 2015). Maintenance seems an important component of infrastructure; cyclists in cold climates, when asked about barriers to cycling, often cite snow removal as the most important aspect of winter maintenance (ibid). Evidence from elsewhere suggests that end-of trip facilities are another important component; cyclists in Australia state that facilities such as secure parking, showers, changing rooms, and lockers encourage them to cycle more in adverse weather conditions (Ahmed et al., 2013). This is echoed by the speculations of
planners in Singapore when they were asked how to improve cycling in adverse weather conditions (Lee & Pojani, 2019). These planners mentioned other infrastructural components as equally important, including shaded cycling paths, traffic calming at intersections, path connectivity at residential neighbourhoods, and softer policies such as cycling education. For them, improving weather sensitivity directly was not as important as improving infrastructure and safety more generally. Finally, the findings of Hong et al. (2020) in Glasgow indicate that improved infrastructure initially attracts newer and more casual cyclists who are more sensitive to the rain. This makes the entire composition of cyclists relatively more sensitive to certain aspects of the weather - perhaps only temporarily. Thus, while it may seem like a truism that improved infrastructure will, over time, improve cycling both within and regardless of adverse weather, it is obvious that the effects of infrastructure will be mediated by those of experience, trip purpose, and habit.

Perception of Normality

Perhaps intersecting with built environment conditions and aspects of sociodemographic identity are culturally embedded perceptions of what cycling behaviour is "normal". Limited evidence seems to suggest that "normal" weather corresponds to travel behaviours that individuals are already habituated to performing. Perceptions that weather is normal, or close to the historical mean for a given time (month) and geographic location, were shown to correspond to feelings of indifference in individuals in Stockholm (Liu et al., 2020). Such feelings were also shown to not significantly affect outdoor leisure travel behaviour; that is, people continued doing what they normally did - regardless of what it was - when they felt that the weather was normal for the time/place. This included winter conditions that may be considered harsh when compared to, for example, summer. Only relatively extreme feelings about the weather, which corresponded to relatively extreme deviations from the historically average weather for the time/place, were shown to affect travel behaviour (ibid). Meanwhile, conceptions about what weather conditions are normal for outdoor travel have also been shown to vary between cultural contexts. For a set of similar objective weather measurements, surveys inquiring "how do you experience the current weather today… good or bad for outdoor activity?" yielded clear cultural differences in weather perception between Japanese and Swedish populations (Liu et al., 2017; citing Thorsson et al., 2007). Hudde (2023) likewise points out that Dutch people do not seem to conceive of or talk about cycling as a seasonal activity as pervasively as German people do, and that this may contribute to the differences observed in Figure 1. This author also speculates that the way society and individuals conceive of themselves in terms of their sociodemographic identities (age, gender, class, etc.), and how they perceive these characteristics as related to cycling, may also affect their propensity to cycle in different weather conditions. The above findings and conjecture, together, may be taken to indicate that the normality of cycling in certain weather or seasons may also be a cause of cycling in that weather or season, rather than merely an effect of it, and that this normality is somehow flexible between contexts.

Discussion & Conclusion

Synthesis

This survey of the available literature on the relationships between cycling and weather has provided answers to several questions, but it has also prompted new ones. New questions, to be addressed by further research, can be identified through both synthetical discussion of available evidence as well as methodological discussion of existing studies. We will start with the former.

Available evidence makes a few things relatively clear. It is evident, for example, that precipitation categorically induces a decreased rate of cycling on a given day and, in each place, doing so at the first hint of it and having a lessened effect for further precipitation thereafter. It is also apparent that winds may only become significantly negative for the general cyclist when they are aptly strong (above 5bft). There is further evidence to support yet another intuitive relationship - that a comfortable range of temperatures exist above or below which some segment of the population begins to prefer other modes, perhaps believing it too hot or cold to cycle. The basic nature of these relationships between measurable weather parameters and cycling behaviour is clear and relatively consistent. Complicating the matter, it is also clear that the intensity and detail of them crucially vary between study locations, and that this is at least partly because they are mediated by the numerous covariates identified in this essay. Some covariates are more easily grasped than others; that a denser, sheltered urban form and smaller trip length will reduce the perceived severity of weather for a cyclist is, perhaps, obvious. What is not so obvious is precisely how or why a given sociodemographic segment reacts and behaves differently with respect to weather and cycling, or why the magnitude and direction of the relationships can vary between locations. Nor is it obvious how these segments, their built environment, their existing work/leisure habits, and their broader cultural context interact to sustain a general sense of normality or abnormality towards certain weather/cycling practices.

The entanglement of these covariates will be explored to identify gaps in the existing literature and outline the trajectory of this research area.

Which covariates seem related to each other? To start, it is difficult to separate trip purposes from frequency/regularity of cycling, and therefore also from personal experience with cycling. Evidence shows that in nearly all study locations commutes were much less sensitive to the weather than other trip types. Presumably, this is because such trips are on a strict schedule and are likely not optional - if there is no alternative mode immediately available, I must cycle to work regardless of the weather. However, it is also true that if a person is on such a regular cycling schedule, they are bound to gain more experience than a person who only cycles for leisure (sometimes) on weekends. As such, the evidence regarding higher experience seems to be in some part interchangeable with the evidence regarding commutes; commuters may be less sensitive because they are more experienced, or those with more experience are less sensitive because they are often commuters. It is plausible that both are true to some extent. It is also plausible that the infamously difficult-to-observe phenomenon called "habit" is partly responsible. If an experienced commuter-cyclist happens to own a public-transport ticket - can
access an alternative - that they may choose to cycle in the rain anyway is perhaps not entirely explained by a conventional understanding of "experience". A more precise characterization of the mechanism by which "experience" affects travel behaviour may be warranted. Referring to
the previous example, perhaps the cyclist decides to continue cycling in the rain rather than switch modes because they are *comfortable* cycling. This comfort is likely related to knowing how to cycle in the rain effectively, but also with the idea that it is *uncomfortable* to break a habit they are used to practicing. Thus, investigation into relationships between trip purpose, experience, habit, and the contextual factors that shape them may prove productive.

Next, gender, age, and social identity can be related to cultural perceptions of normality. We have gathered evidence in this essay which suggests that cyclists' reactions to the weather can and do vary along sociodemographic lines. For example, female cyclists are often quicker to change their cycling behaviour with the weather and older cyclists are *sometimes* more sensitive than younger ones. Although it may be tempting to look at this evidence and attempt to explain it in terms of biological necessity, this should not be done without first reflecting on how society can affect the way a specific group of people regards themselves, others, and the built environment, or how their feelings may translate into complex behaviours. For example, authors have attempted to explain gender-related evidence enumerated in this essay in terms of women's' and men's relative physical fitness and risk/safety perceptions (Motoaki & Daziano, 2015; Hong et al., 2020; citing Emond et al., 2009). These explanations are plausible, and there is ample evidence to suggest they should be taken seriously. However, the notion that observed differences in physical fitness or risk perception are simply caused by a difference of physiology is highly suspicious; it is not because of mere biology that women exercise less than men, or that women have more reasons to feel unsafe cycling down the street to the store. These things are contributed to in part by the organization and perception of identities within society. This is at least more flexible than genetic endowment. By the same token, not even mentioning the conflicting evidence surrounding it, the mechanism by which age affects cycling behaviour and weather sensitivity should not be accepted as a self-evident matter of physical necessity. While it may be true that age increases the risk of developing physical disabilities, age *itself* need not be regarded as one. What a person thinks when they regard themselves as "old", and how they think "oldness" relates to transportation, are neither biologically caused nor random. As Hudde (2023) suggests, cycling in the Netherlands is not apparently spoken or thought of as associated with a particular age group or gender, and it is perhaps for this reason that relatively more women and elderly people cycle there. This could also partially explain Dutch cyclists' distinctly low sensitivities to adverse weather - in the Netherlands, cycling is less conditional in general. All of this is to argue that the *meaning* of "woman" and "old" are contingent upon social systems in addition to physical ones, that these meanings may be flexible, and that they may affect cycling and weather sensitivity observations.

Finally, we can speculate about the relationship between infrastructure, the built environment, and normality. Infrastructure, as a specific and often identifiable component of the built environment, may palpably communicate to the population that cycling is a "normal" mode of transportation. This is perhaps related to and offset by the normality of car-transport communicated by nearby car infrastructure; even if cycling infrastructure is strong, I am unlikely to view it as a normal thing to use on rainy days if I am constantly comparing it to 3 lanes of car traffic nearby. So, while evidence shows that infrastructure can serve to increase cycling rates, its configuration may also serve to change perceptions about the role of cycling as a mode of transportation, solidify its status, and change the way cycling is practiced in different weather conditions.
In all, as speculated by Böcker et al. (2013) and Hudde (2023), culturally contingent perceptions surrounding weather, seasonality, cycling, and travelling may contribute to how cyclists tend to respond to weather. The way in which the built environment, sociodemographic identities, and trip purposes intersect to manifest behaviour and normality can be speculated upon as above, but it is not well accounted for by current evidence.

Gaps in the methodology

Beyond the gaps generated by the discussion above, we noticed a methodological pattern in many of these articles and in how they conducted their research. This pattern creates gaps of its own. Many of the articles used objective measurements, like the observed exact temperature at a specific location or the exact amount of precipitation at a given time, to try and explain some subjective human behaviours, even if these behaviours were observable in a way. This has led us to think about the methodology of using objective indicators to explain subjective behaviours. As we know, humans don't always behave in an expected or rational way, so we believe that studying the effects of weather from a subjective perspective might be an important opportunity to uncover effects that were not clear before. One such example could be the effect of forecasts on people's behaviour. We know that many times what is forecasted is not really what ends up happening. So, by taking the observable measurements to explain people's behaviour, might be misguided if the people had different information before starting their trips or before making their decisions as to which modes they will use.

Another related issue is the study of individual weather parameters. Many of the studies we reviewed were focused on the effect of single parameters on their own. While this might be important to understand the effects of each individual factor, we saw that there is a gap in studying many of these factors together. None of these phenomena occur on their own or in isolation. They always co-occur with other factors, and they all together make up the weather experienced by people. Even though there was mention of this in some of the studies we reviewed, we found that it hasn't been researched in detail. For example Böcker et al (2013) mention the researched effects of wind, and how one study showed that wind combined with specific temperatures can be perceived either as good or as bad, depending on the temperature. We would like to see further research on similar topics on the effects of weather factors combined.

We were also interested in finding how media representations affect attitudes towards cycling in different weather conditions and in turn behaviours. This is another gap we identified, even though it's slightly different than the direct or indirect effects of weather on cycling. But we do believe that the media and other cultural institutions have the power to influence perceptions.

For example Hudde (2023) mentions that in Germany there is a term, "Fahrradsaison", which means "cycling season" and it is portrayed in different media, government communications, and so on. But the existence of a cycling season, subconsciously denotes the existence of a season that is not for cycling. Another example is looking up cycling images on Google. Depending on the country you're in, you may get very different results. In the Netherlands you may get more images with average people cycling in the city, whereas in the UK you may get more images with professional or competitive cyclists. All these nuances have a subconscious effect on the development of a cycling culture and the attitudes and perceptions surrounding it.

A gap we identified that is related to how data is grouped and categorized, is regarding the grouping of different forms of precipitation. We noticed that many times this is researched under the general term of "precipitation", which usually includes rain and snow, when these types are very different from each other, and when not all snow is the same. The findings of Motoaki & Daziano (2015) highlight why this is important: "less-skilled cyclists consider rain to be 2.5 times more bothersome than more-skilled cyclists, and snow to be 4 times more bothersome". Perhaps it would be useful to start separating the forms of precipitation, and even the types of snow as well. This would provide researchers a much clearer picture as to how each of these types of precipitation impacts human behaviour.
Finally, an obvious gap we have identified and already mentioned before, is the location of the studies done so far. Most research studies are overwhelmingly based in North-Western Europe, North America, and Australia. These places cover but a small sample of the different climates and weather conditions on this planet. So we hope that in the future we can get a richer diversity of locations when studying the effects of weather on cycling or transportation in general.

The way forward & policy recommendations

Based on our findings and the gaps we identified, we believe that there is room to grow and develop the field of weather research on cycling and transportation behaviours. Having studied some of the effects of weather on cycling and how it influences behaviours and habits, we have come to understand and recognize some solutions to certain weather-related problems associated with cycling. Some policy recommendations we have identified and would like to see implemented include:

- *Trees for hotter climates*

  Planting trees and creating tree canopies above cycling paths is a great way to provide natural shading and cover for cyclists, especially in hotter climates where hot temperatures and scorching sunlight can discourage people from cycling. Obviously this does not only help to improve cycling rates, but it has an overall positive effect in the environment of the city and the aesthetics as well.
- *Safe cycling infrastructure*

  As we've seen from Hudde (2023), safe cycling infrastructure is the main way we can encourage more cycling and help everyone regardless of skills or background to get on a bike and travel around. This does not only include separate cycle paths, but it requires a holistic approach in terms of land use and transportation policy, where walking and cycling are placed as top priorities. Hong et al (2020) also provide recommendations in the direction of facilities at work like bike parking and showers. Or increasing the safety with regulations, speed limits and so on, can have a great impact on groups who are more affected by the perceived safety like women. In their words: "Interestingly, we can see that safe cycle paths are more sensitive to the seasonality effects. This implies that less-skilled people or casual cyclists use these paths more when weather is better."

- *Urban density*

  We have also recognized density as an important factor that may contribute to more cycling rates, as distances become shorter and therefore people need to be exposed to the elements for a shorter amount of time when cycling. This goes back to the 15- minute-city concept as well.
- *Employer support*

  Employers can utilize schemes or other incentives to encourage their employees to cycle to work. They can achieve this by providing bike parking and other facilities on site, and utilizing discount schemes for bikeshare systems or for purchasing bikes.

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Zero Emission Freight Transport and Impact on Last Mile Delivery

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1 Abstract

This literature review explores mainly the challenges and potential solutions in urban freight transportation, for last-mile logistics. The growing number of delivery vehicles in urban areas has led to problems such as traffic congestion, competition for parking spaces, noise, and air pollution. To address these issues, the paper focuses on the last mile problem in transportation logistics and the potential of disruptive innovations, a potential of disruptive innovations such as Unmanned Aerial Vehicles (UAVs) and Autonomous Delivery Robots (ADRs) as alternatives to traditional Internal Combustion Engine (ICE) vehicles. It highlights the drastic operational differences between aerial drones and ADRs and the need for changes in operational procedures to fully leverage these technologies. The study also discusses routing strategies and delivery routes, emphasizing the shift from one-route delivery to a point-to-point model with the advent of autonomous vehicle technologies. The paper concludes that while these technologies can reduce costs and emissions, their effectiveness depends on the specific urban setting and operational factors.

2 Introduction

The rise of eCommerce, increase urbanization, and demographic growth have created an increased demand for urban freight transportation. The COVID-19 pandemic has accelerated the increase of eCommerce as shops closed and the reduction of contracts was warranted due to government restrictions and the increase is projected to continue. According to the Pitney Bowes Parcel Shipping Index, parcel sipping per capita has grown from 12 parcels per person in 2014 to 34 parcels per person in 2020 and is estimated to double in the next five years. (Pitney Bowes, 2022) To meet this demand, logistic companies will need to employ more delivery vehicles to meet existing and future demands to deliver parcels to increasingly larger urban areas.

However, the growing number of delivery vehicles within urban areas can result in numerous problems, traffic congestion, competition with parking spaces and public spaces, noise, and air pollution are some of the externalities induced by the growing numbers of delivery vehicles. Economics, environment, and social, the three pillars of sustainability are linked to urban logistics. Within the economics side, the last mile problem is often the least efficient in terms of costs, and shipping cost is linked to the price of the good, and minimizing cost is one priority of an efficient logistic system. In the realm of the environment, heavy vehicles disproportionally contribute to air pollutants and emissions in terms of per-vehicle emissions. With high logistics demand, tailpipe emissions from delivery vehicles pollute within city boundaries directly exposing residents to air pollutants and negatively affecting their health and social well-being. In addition, the EU has set climate goals of a reduction of at least 60% GHGs by 2030 concerning 1990 levels. Therefore, there is a consensus to increase the sustainability of urban logistics while accommodating future growth.

One method to reduce the impact of urban logistics is to utilize and replace traditional delivery methods with greener modes of delivery. Within this paper, a focus will be researching the last mile problem in transportation logistics and the use of potentially disruptive innovations that can disrupt the traditional internal combustion engine (ICE) technologies currently employed by existing freight companies. The method of evaluation, certain advantages, and disadvantages of the disruptive technologies over existing ICE will be explored.

3 Literature review

According to the article, Smart urban logistics: Literature Review and future directions, cities must become' smart' to overcome the challenge of limited resources in the urban environment. Integrating emerging technologies such as machine learning, artificial intelligence, and/or big data analysis into the urban fabric is required to become a 'smart' city. Therefore, we choose to focus on emerging, "smart" urban logistics to cope with the challenge of increasing urban freight demand. (Gülçin Büyük¨ozkan, 2022).

The literature review breaks the search of relevant articles into distinct phases, keywords that are related to urban logistics (i.e., Last Miles Logistics, Urban Goods, City Logistics, etc.) and Smartness Related (i.e., Autonomous Vehicles, Drones, Robotics, Block Chain, etc.). The research article examined must state both an urban logistic and smartness keyword within its abstract or title to be included within the literature review. The article must also be published between the years 2000 – 2020. A total of 71 articles and 59 conference papers were filtered and examined by the authors. Each is further classified under main topics and applications and discussed technologies and smart solutions.

The authors found that a total of 17 main topics and applications, which discuss which topic is being covered within the realm of urban freight transport, emerged. The top 3 topics that were discussed are last-mile delivery, vehicle routing problem, and solutions assessment and comparison. The author noted and we can confirm that many of the papers listed cover more than one topic and it was difficult to categorize each one as its distinct category. The author of the review categorizes them based on the most frequently mentioned issue. However, we didn't feel it was correct to categorize each article into one category as urban logistics has many different distinct pieces that work together to deliver goods. For example, the article we review, Potentialities of drones and ground autonomous delivery devices for last-mile logistics, covered the topic of last-mile delivery, placement of Urban Consolidation Centres (UCCs), optimization of vehicle routing, and solution assessment and comparison of technology. A comparison will not be relevant if it fails to consider all the relevant parts. Therefore, we concluded the term last mile delivery is an umbrella term that covers most urban logistic requirements and operations.

Within technologies and smart solutions, the articles reviewed are more clear-cut than their topics and applications. 15 solutions were categorized by the authors and the top 3 topics were unmanned aerial vehicles, intelligent transportation systems (ITS), and GPS/GIS technology. Upon review of ITS, the topic is broad and can include studies related to traffic information systems, vehicle networks, and commercial vehicle operations. We have decided not to include ITS within our paper as it eclipses multiple different technologies. Reviewing GPS/GIS technology mostly pertains to the real time tracking of products and goods. As this technology focuses on the good and does not directly affect cities, it was decided that this technology will not be reviewed. Looking at the next highest ranked technologies, Autonomous Vehicles and Electric Vehicles/Cargo Bikes for fourth and fifth ranked respectively, we observed there were more articles within autonomous vehicles than electric vehicles/cargo bikes. In addition, unmanned aerial vehicles can be both remote-controlled and autonomous. We, therefore, decided to research unmanned aerial vehicles and autonomous vehicles as they both can be grouped with new modes of autonomous transportation.

4 Technology Description

The following section describes traditional delivery vehicles and introduces UAVs and ADRs, with a brief description of their characteristics, limitations, and use cases.

4.1 Traditional Delivery Vehicles Characteristics

Within the European Union, which follows the United Nations Economic Commission for Europe classification of vehicles defined as any power-driven vehicles having at least four-wheel and used for the carriage of goods fits within the category N. The smallest category of said vehicles category is N1 which is defined as ‘‘motor vehicles used for the carriage of goods having a maximum mass not exceeding 3.5 tonnes" (Economic and Social Council UN, 2005). These vehicles are shorter than heavier freight transportation which makes them ideal for urban logistics and last-mile delivery. Currently, these vehicles are powered by internal combustion engines (ICE) but industry trends are pushing for the electrification of these vehicles. Most articles, if considering the incorporation of the electrification of delivery vans, assumed even with the electrification of the fleet, operational behaviour would not change. It is assumed there will be a significant range and capacity compared to traditional ICE-powered vehicles.

4.2 Drones / UAVs Characteristics

The enhancement and capability of individual processes and the capacity of the system can be achieved in multiple ways, with remote technology and automation being among the most prominent. Historically UAVs have seen use as military vehicles, but their versatility allows them to transform logistics services (Joshuah K. Stolaroff, 2018). They can fly packages from a retailer's warehouse to the customer, providing point-to-point deliveries. Drones are quicker, more responsive, and faster to steer as they are not affected by congestion and can fly over buildings in a straight line. Drone delivery options include direct flights from the retailer's storeroom to the shopper, cargo transport by multiple drones via so-called waypoint stations, or UAVs carrying packages from a truck to the consumer and returning while the truck moves around delivery sites

(Joshuah K. Stolaroff, 2018). However, they usually deliver one parcel on a round-trip (Clement Lemardel´ea, 2021). Various sensors are installed inside these vehicles for detection and guidance to improve and optimize the efficiency of parcel delivery (Gülçin Büyük¨ozkan, 2022)

Aerial drones, powered exclusively by batteries, have similar characteristics to ADRs (Clément Lemardel´ea., 2021). Electric-powered drones' specifications are less clear than ADRs due to their developing technology and limited applications. Characteristics assumed in Lemardel´e et al.'s modelling exercise include travelling speeds of 80 km/h, landing and take-off speeds of 30 km/h, and a storage volume of 2 cubic meters. The range is highly uncertain, as it depends on numerous factors, such as battery chemistry, battery mass, payload, weather conditions, flight altitude, aerial dynamics of the drone (Quadcopter or Octocopter), acceleration frequency, and safety buffer. Theoretical maximum ranges of 5 km and 8 km for existing and future battery technology for quadcopters were calculated (Stolaroff, 2018). However, these numbers do not consider package weight or take-off and drop-off, which will decrease the range. A key advantage of drones over ADRs is the ability to swap batteries between trips, allowing constant operation, whereas ADRs have integrated batteries (Clément Lemardel´ea., 2021).

Small, electric battery-operated UAVs can be more efficient than the fossil-fueled vehicles they replace (Joshuah K. Stolaroff, 2018). During the COVID-19 crisis, drones were used to deliver face masks to remote islands in Korea and treatment pills and medicines from pharmacies to retirement villages in Florida (Rico Merkert, 2020). In remote African areas, drones have been used for medical supply deliveries, which could preview their role in an urban parcel or small package delivery. In commercial applications, drones have reduced costs and enhanced capabilities in industries like mining, logistics, engineering, transport network management, and agricultural scanning (Rico Merkert, 2020). Several companies, including

Amazon, Google, UPS, and Deutsche Post DHL, are developing commercial package delivery using drones (Joshuah K. Stolaroff, 2018). However, potential issues include congestion, traffic management safety, privacy and security concerns, and implementation in urban areas.

4.3 Autonomous Delivery Robots Characteristics

Autonomous delivery robots (ADRs) or automated micro-vehicles (AMVs) (Strubelt, 2019), sometimes referred to as Ground Autonomous Delivery Devices (GADDs) or Ground Autonomous Vehicles (GAVs) (Clément Lemardel´ea., 2021), are electric-powered, motorized, self-driving (with automation levels 3 and 4) vehicles designed to deliver items or packages without human intervention. ADRs fall under the European vehicle category L (2-4 wheels, up to 45 km/h speed, and 400 kg tare weight) and can be monitored or remote-controlled by people without a driving license. Two types exist - Sidewalk Autonomous Delivery Robots (SADRs) and Road Autonomous Delivery Robots (RADRs). These robots can deliver several parcels in one tour, optimizing route length and reducing operation costs despite potential congestion or reduced speed (Clément Lemardel´ea., 2021), having a vast range of operational characteristics due to their different development stages. ADRs are typically found in retailers-to customers' home settings, such as food delivery services (Doordash and UberEATS) and grocery delivery services (Instacart), which have seen a rise in popularity over the years. Within these markets, ADRs are used for delivering groceries, prepared meals, or medication from retailers or restaurants directly to customers' doorsteps. Domino's Pizza has partnered with Skydrop to test delivery of its pizza from the local Domino's store to the customer's home in New Zealand. While one for-one routes are more efficient using autonomous vehicle technologies than traditional delivery methods (Figliozzi M. A., 2018), it is unclear if the arrival of the delivery service induced an increase in orders. A review of these routing strategies was not covered in the cited studies.

Most ADRs use LIDAR as their primary means of sense, while some use cameras, computer vision, artificial neuronal networks, and LASERs for obstacle detection. Many ADRs are equipped with microphones and speakers for communication with people, and most use GPS for localization, often combined with other sensors and map services for better accuracy. Most ADRs feature communication technology such as WiFi or 4G, enabling remote control from a control centre, which enhances security and enables economic operation, as a single supervisor can manage 50-100 delivery robots without human assistance (Strubelt, 2019)

4.3.1 Main Types of ADRs

SADRs are pedestrian-sized robots that use sidewalks or pedestrian paths. They are relatively slow and lightweight, often limited by city and state regulations. Companies like Starship Technologies, Robby, and KiwiBot are prominent names in the SADR space (Rico Merkert, 2020). ADRs operating on sidewalks typically have a speed of 5 kph and a capacity of up to 100 kg depending on the type (Engesser, Rombaut, Vanhaverbeke, & Lebeau, 2023), but popular models like Starship can only carry up to 10kg, with a range of around 20 km but can be artificially limited by operators (Baum, Assmann, & Strubelt, 2019). In comparison to a van, the capacity of the vehicle is limited, so more vehicles need to be dispatched to yield the same maximum capacity. However, ADRs are more flexible as the number of dispatches can be adjusted to the daily fluctuation of parcel levels.

RADRs travel on roadways shared with conventional motorized vehicles. Designs like NURO are smaller and lighter than typical delivery vehicles, while others like uDelv and AutoX are based on existing vehicles that have been automated or modified for autonomous deliveries. RADRs can be accompanied by specialized "mothership" vans, which can drop off and pick up several RADRs for delivery (Figliozzi & Jenningsa, 2020). Operating on roads and away from sidewalks typically has higher speeds and capacities than SADRs. However, they are less developed, with only three operational AMVs out of 39 GAVs examined (Figliozzi & Jenningsa, 2020). Nuro, a true AMV, had a capacity of 113.4 kg a speed of 40 kph, and a range of 16 km. These ADRs operate closely to traditional vans as they are built to operate along routes with multiple stops. However, as range and capacity increase, so do battery size and vehicle weight, potentially disqualifying them as ADRs due to weight.

5 Different Approaches for UAVs and ADRs Assessment

Comparison of technology only includes ADRs, aerial drones, and traditional trucks to help determine which mode is better. A focus on economics, emissions, and energy use will help pinpoint the advantages and disadvantages of each technology. Emissions and energy use are combined as ICE trucks are typically used as a baseline unless otherwise stated. However, the inclusion of electric trucks will shift emissions to the grid, and a comparison of energy use is warranted.

5.1 Optimization and Scheduling

5.1.1 Routing Strategies

The operation of either aerial drones or ADRs is drastically different between the two as one operates on a three-dimensional plane while the latter operates on two dimensions. Compared to traditional urban logistics where a human drives from a distribution centre on a small diesel truck and deliveries multiple packages along a particular route, it has even further differentiation. (Lemardel´e, Estrada, Pages, & Bachofner, 2021) Different speeds, capacities, and ranges further change operational requirements and not to mention the autonomous nature of the two new technologies creating differences in economic costs. Expecting either technology to compete or even fully replace the existing technology without changes to the operational procedure will result in a futile attempt. Within this section, an explanation of differences in routing, technical characteristics, and their impact will be examined.

5.1.2 Delivery Routes

The emerging autonomous vehicle technologies within transportation logistics are emerging to compete with the traditional methodology of one-route delivery to a point-to-point model. The routing of packages should also adapt to this technology to optimize their costs to fairly compete with traditional delivery routes.

5.1.3 Traditional Delivery Route

A typical route for a courier delivering packages would start from a distribution centre (DC) where the packages would be assigned and loaded to a particular route. Trucks will drive to a particular service area which will then make multiple stops for delivery and return to the DC. Sometimes, if the option is available, parcel lockers are available, and some deliveries are routed to those lockers for customer pick up at a later point. This option decreases the distance travelled instead of traveling to all customer locations, the carrier travels to the lockers and delivers multiple parcels at once. An example of a traditional route can be seen in **Figure 1a.** (Lemardel´e, Estrada, Pages, & Bachofner, 2021)

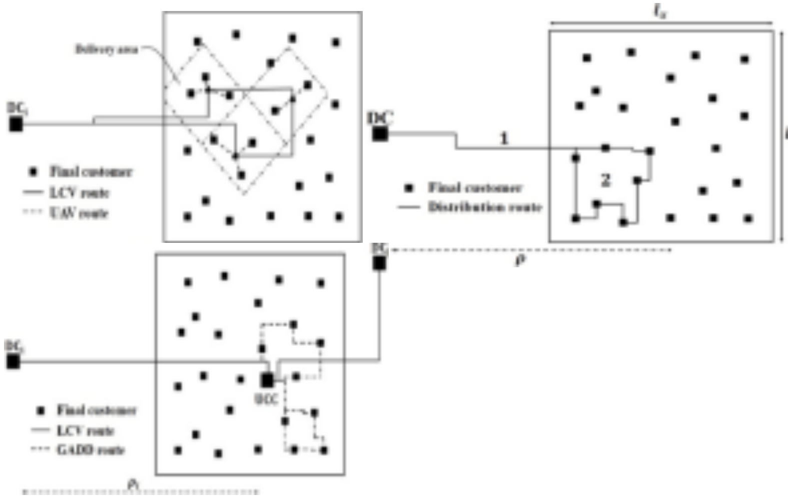


Figure 1: Various Delivery Routes a) Traditional Route, b) GAVs + UCC, c) Drone + Van (Lemardel´e, Estrada, Pages, & Bachofner, 2021)

5.1.4 GAVs Delivery Route

Typically, DC is located far from residential centers and exclusive use of autonomous vehicles delivery cannot fully replace couriers due to its limited range. A method to overcome the range limitation is to create urban consolidation centres (UCCs) within the city and use the ADRs as the last mile delivery as shown in **Figure 1b**. A traditional truck would drive from the DC to the UCC and offload parcels. Workers within the UCC will deconsolidate the package and place each delivery within the ADRs which would then be sent out to the customer. The UCC will store, charge, and maintain the ADRs. It is unknown if each competing carrier will co-manage the UCCs and ADRs together or will have competing networks. There are strong economic incentives to work collaboratively to achieve economies of scale as last-mile deliveries are common to all couriers. (Lemardel´e, Estrada, Pages, & Bachofner, 2021)

Another method to increase the range is the use of "mothership", specialized vans to drop off and pick up several ADRs at once. Parcels are assigned a route within the DC and placed in mothership and driven to some service area. There, the mothership will offload ADRs to complete multiple last mile deliveries and return to the mothership. Multiple stops by the mothership can be made to reduce operational costs. Charging of the ADRs by the mothership (wherever from the van's battery pack or ICE) is a possibility to increase the number of deliveries. However, as the mothership must carry ADRs and battery packs, the space within the van dedicated to parcels will decrease. Trade-offs between the number of ADRs against the additional parcels will need to be considered. (Lemardel´e, Estrada, Pages, & Bachofner, 2021)

ADRs also can serve multiple customers on each trip if the model selected has significant capacity and compartments. Generally, these are more limited to AMVs as they are designed to conduct multiple stops but ADRs can in theory be coupled. Within this paper, it is assumed ADRs can only serve one customer per trip. (Engesser, Rombaut, Vanhaverbeke, & Lebeau, 2023)

5.1.5 Aerial Drones Delivery Routes

Like ADRs, drones can operate in UCC or using motherships. Figure 1c for ex (Engesser, Rombaut, Vanhaverbeke, & Lebeau, 2023) ample, shows how the "mothership' concept works to deploy aerial drones. Drones require significant clearance such as a front yard to drop off parcels. It is unclear how the drone will be able to operate in dense urban environments. Would drones deliver parcels to rooftops, balconies, or the front door? These conditions remain unsolved. (Lemardel´e, Estrada, Pages, & Bachofner, 2021)

5.2 Acceptance of Technology

Adaption of the ADRs and aerial drones varied greatly with ADRs being able to penetrate many delivery markets with success.

We assumed that ADRs are generally accepted by the public due to their popularity and clear definition as defined within the EU. This is not the case for aerial drones as there are few applications. In a study conducted by (Schaarschmidt, Bertram, & Knobloch, 2021), they survey participants about their concerns and find barriers to the adoption of drone deliveries. Of the participants of the surveys, there was a clear consensus of physical (chance of injury), financial (cost of delivery), and data/privacy risks (giving up personal information) as barriers to the adoption of drone technology. We have not reviewed physical and privacy risks within this report, but the papers reviewed show a potential reduction of operational cost as will be discussed in Section 5.4. The study concludes to increase the adoption of drone technology, all three risk perceptions need to be addressed to enhance the perception of drone technology's usefulness in the application of logistics.

5.3 Sustainability, lifecycle assessment- Emissions and Energy Usage

ADRs show significant reductions in emissions and energy consumption in urban areas, while UAVs demonstrate greater efficiency in specific scenarios. Both technologies depend on the urban setting and parcel density, with each technology potentially reducing costs and outperforming traditional delivery methods in specific scenarios. However, the superiority of either technology over the other remains unclear, as both cost and energy efficiency is influenced by operational factors and assumptions.

5.3.1 ADRs Lifecycle Assessment:

The study by (Cl´ement Lemardel´ea, 2021) calculated whether ADRs have the potential to be utilized in two European cities, specifically Barcelona's historical centre and Paris suburbs. They chose 4 different strategies to assess the potential use case, accounting for externalities associated with vehicles, including WTT (well-to-tank) and TTW (tank-to-wheel) emissions (mostly fumes and GHG), vehicle production externalities (only GHG from battery production), and the impact on urban infrastructure. The paper neglects end-of-life treatment externalities, which account for less than 5% of total externalities, as well as congestion, noise, and safety issues. They assumed the energy consumption rate of 0.03 kWh/km, WTT efficiency rate of 0.7, range to be 100km, and speed of 5km/h for ADRs. The results show that ADRs generate the lowest number of externalities, reducing emissions by 60% to 80% compared to the traditional, standard practise Strategy A0 with the widespread adoption of combustion engine delivery vans. Truck-launched delivery drones achieve around a 55% reduction in externalities, while Strategy A1 (where drivers do not transport the packages to the final clients but drop them in distribution bays, that concentrate the demand of an entire neighbourhood) offers a 20% reduction to ICE vans or 40% with EVs. They also conclude that in the Paris suburb use case, externalities decrease by roughly 70% compared to traditional delivery methods, given a demand density of 100 parcels/km2. In the Barcelona historical centre, using GADDs can reduce externalities by nearly 80% compared to conventional methods, with a demand density of about 300 parcels/km2.

Miguel Figliozzia, 2020 concludes that ADRs have the potential to reduce last-mile travel, energy consumption, and CO2 emissions compared to conventional delivery methods. This case study quantified the energy needed to deliver to 48 customers using various vehicle types. It was found that the energy consumption of eight SADRs is a small fraction of the energy consumption of the mothership van. In high-density urban areas with heavy traffic and limited parking, the small NURO vehicle may be the most efficient option. ADRs several times (although the study doesn't specify by how much) are more energy-efficient than conventional diesel vans and drones but have similar energy efficiency as electric vans like the Renault Kangoo. In terms of safety, the NURO is slower, smaller, and lighter than conventional vans, reducing the likelihood of severe crashes with pedestrians or cyclists. The adoption of smaller, driverless, and more economical ADRs could lead to higher utilization of electric commercial vehicles in urban areas, concludes the study.

5.3.2 UAVs Lifecycle Assessment:

A detailed review by Figliozzi assesses the potential effectiveness of drones to lower CO2e lifecycle emissions, comparing them to alternatives on the market. A similar study by Goodchild and Toy 2017 concluded that drones emit less than conventional substitutes, only when businesses are located close to the depot, suggesting that EV trucks and drones should complement each other. When CO2e was analysed, the authors considered the emission generation to charge the battery, as well as a battery to propeller emissions, and an analogous approach for conventional vehicles. They concluded that energy consumption for a drone MD4-3000 was 21.6 Wh/km compared to 1016 Wh/km ICE RAM Promaster 2500 pick-up truck. When assuming a payload of 5 kg the drone proved to be 47 times more efficient (energy consumed per unit distance), with the same energy consumed when the pickup travels one time delivering 47 packages. The overall efficiency of the drone (to deliver power to the battery and consequently to the propellers) is assumed to be 67% while in the case of an ICE truck is 25%. The emissions produced by the UAV are 22 times cleaner than the van on a per unit energy consumed basis. Taking into account the difference in the payload as a van can carry 378 times more cargo than one UAV trip, emissions produced by the UAVs are still 2.8 times cleaner even though at consumed 8 times more energy than the ICE truck.

Completely different results are achieved when drone emissions per delivery with the vehicle phase are calculated. The vehicle phase includes the emission produced as a result of manufacturing and disposal of the said drone itself and its batteries. Considering the emissions per unit of payload mass in the vehicle phase, UAVs produced 70 kg CO2e per kg compared to 5 kg CO2e per kg for the diesel van. Electric trucks and vans are more efficient than typical US vans, making UAVs less efficient than electric vans for delivery scenarios with over 10 customers per route (Figliozzi M. A., 2018).

In a study by Kirschstein, 2020, energy utilization models were employed to evaluate the energy requirements of UAVs, EV trucks, and traditional pick-ups for distributing packages to clients from a central distribution centre. The corresponding CO2e emissions were calculated and compared based on energy needs. Under low and moderate traffic congestion, diesel trucks necessitate approximately 40-50% more energy than EVs and 80-90% more energy in situations with high congestion.UAVs often require more energy than diesel trucks in most situations with medium wind conditions. In very specific cases such as a low number of customers per stop, low to moderate wind speeds, medium traffic congestion, and a customer area radius of 8km, UAVs consume less energy compared to EVs. Kirschsetistein`s study also concluded that UAVs, in many scenarios show no environmental benefit over the use of diesel vehicles, as UAVs emit less CO2 only if the CO2 emission coefficient is lesser than 0.3 kg CO2e/kWh in rural situations, having an 8 km customer area of coverage and 2 destinations per stop. What needs to be noted though is this was a theoretical study in contrast to the real-world case of the Goodchild and Toy, 2017 study.

Another study by Joshuah K. Stolaroff, 2018 in a real-world test found test standard configuration was not advised for package delivery at longer ranges; however, increasing battery size can increase range, with a maximum range of around 5 km for both quadcopter and octocopter. With a chosen battery sizes of 1 kg for quadcopter (range of about 3.5 km) and 10 kg for octocopter (range of about 4.2 km) and an average energy density of 150 Wh/kg study pointed out the necessity of additional warehouses close to customers, increasing energy use. Based on calculations a small quadrotor drone (delivery of 0.5 kg package) has lower impacts than diesel truck delivery, ranging from a 54% GHG reduction in California to a 23% reduction in Missouri, however, a continued reduction in carbon intensity and energy efficiency improvements in associated commercial buildings are essential for realizing the potential environmental benefits of drone delivery. Unfortunately, the article is of an older date, received in Nature in October 2015 and published in February 2018, so the results may be different in upcoming years.

5.4 Operation Costs

Although ADRs can reduce the number of trucks and drivers, the difference in the technical specification and operational setting will influence the operational costs in determining if there is a clear advantage of either technology over the other. Referring back to the study by (Clément Lemardel´ea., 2021) who modelled three delivery scenarios shown in Figure 1, within Barcelonas historical centre and a Paris suburb. Within the Paris suburb scenario, the model showed which used a parcel density between 40 – 200 parcels per km2 bounded to a service area of 9km by 20 km grid. The low end of parcel density showed there was a 15% difference in cost between the worst performing routing, traditional route + storage lockers (2.1 euros), and the best-performing routing truck-launched UAVs. (1.8 euros) Interestingly if compared to a scenario of a higher density of 200 parcels per km2 or higher, the traditional delivery route + storage lockers achieved the lowest operational cost per package. Meanwhile, ADRs perform better than traditional routes but were unable to achieve better operation savings than UAVs or traditional routes and storage lockers in any density. Cost and energy optimal did not align within this scenario as the ADRs were the most optimal in terms of energy usage.

Within the Barcelona city centre scenario which has a high density of parcels (150 – 600 parcels per km2) bounded by a small service region of 2km by 1.5 km grid, different results emerged. All traditional routing methods are not competitive in any density scenario with either ADRs or UAVs at least halving per delivery cost. ADRs are more cost competitive in a higher-density scenario than UAVs with cost curves intersecting around 225 – 250 parcels per km2. Cost and energy optimal results were identical in this scenario.

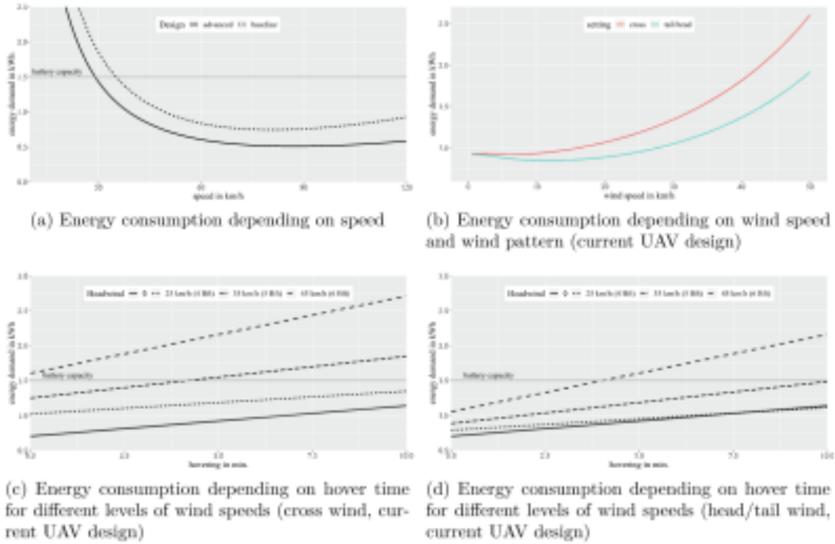
It can be concluded that either autonomous technology can reduce costs but the advantage of either technology over the other is not clear. However, the results show the most optimal technology is dependent on the urban settings in which the technology is operated, and even traditional routing can exceed either technology. The author of the study, however, acknowledges the uncertainty of assumptions used for the inputs within the study and showed many of the inputs, technical or setting related, are sensitive.

6 Technology and Limitations

Drones and ADRs can be negatively affected by difficult weather, such as rain, snow, and high winds, which could impact their reliability and efficiency. While drones and ADRs can potentially reduce energy consumption and emissions, their actual performance depends on factors like traffic conditions, payload, and operational settings. Their deployment may require additional infrastructure, such as warehouses, charging stations, and maintenance facilities, which could increase costs and environmental impacts.

6.1 UAV Sensitivity to Weather Conditions:

Wen-Chyuan Chiang, 2019 considered an emission-lowering Vehicle Routing Problem with Drones (VRPD) and found that using drones offers up to 30% of the total CO_2e emissions reduction compared to ICE diesel-powered trucks, as seen in Figure 2. The benefits reported, are based on comparing ICE vehicles against drones, not acknowledging EV trucks can also be considered as environmentally friendly parcel deliveries. Moreover, environmental factors such as wind and transport conditions, nor delivery delays have not been studied much in comparative studies.



(a) Energy consumption depending on speed

(b) Energy consumption depending on wind speed and wind pattern (current UAV design)

(c) Energy consumption depending on hover time for different levels of wind speeds (cross wind, current UAV design)

(d) Energy consumption depending on hover time for different levels of wind speeds (head/tail wind, current UAV design)

Figure 2 Energy usage of UAV at different speeds (Kirschstein, 2020)

A study by Kirschstein, 2020, a detailed energy consumption model for drones, considers weather and hovering patterns, where in crosswind conditions, aerial vehicles need to counterbalance air drag to maintain direction, to stay on course, which in return increases power needed, lowering efficiency. In head/tailwind settings, tailwind reduces energy demand on one leg while headwind increases it on the other. An energy-optimal travelling speed exists and hovering for up to 5 minutes requires significant energy demands. Lithium-ion polymer battery capacity lasts only for 4 minutes of hovering in moderate breeze conditions, resulting in a much lower radius of operation for UAVs (Wen Chyuan Chiang, 2019).

6.2 Future UAVs Developments:

As drones are becoming more prevalent in cities ensuring safety and productivity is essential. The development of low altitude airspace management systems (LAAM) is a key topic, with industry operators looking to create multifaceted management systems tailored to their needs, from both government organisations such as NASA or private entities such as Amazon and Google, potentially be used to regulate drones, facilitate flight planning, and ensure safety (Rico Merkert, 2020). Additional technological factors to consider in logistics-oriented UAV purposes include the take-off and landing concepts, and likewise autonomous control capabilities. Most commercial UAV models offer fully automated stations (Scott et al., 2017). However, for Business-to-Customer (B2C) concepts, the UAV should have the capability to come back and land on uneven surfaces or use detachment technologies like ropes (as seen with Flirty and Google) or parachutes (as used by Zipline in Africa) or the newest Zipline Detachments Unit. A study in Lancet found that delivery of health supplies in remote areas of low and middle-income countries (LMICs) was effective, cut delivery times, and reduced blood wastage. In Rwanda, drone delivery resulted in products arriving 79-98 minutes earlier than by road, with a 67% decrease in blood termination date. Only a small percentage (<1%) of units were damaged during delivery. This study supports the idea that drones can consolidate and ensure timely deliveries to hospitals, potentially improving patient outcomes (Swaibu et al., 2022). In B2C circumstances, it is logical to expect that drones (or their base) must hover until the cargo is entirely lowered, and conditions for detaching the cargo are met, such as waiting for a clear detachment area or the receiving customer's authorization, either by visual cues or app.

7 Limitations of the Research Reviewed

After reviewing various papers, it is unclear if the adoption of autonomous vehicles will have a positive impact on the typical measurable key measurable indicator like cost and environmental impacts. Most points towards ADRs and drone autonomous technology will bring a positive impact when compared to traditional ICE technologies. But if the trend of electrification in transportation continues, it becomes less clear if a positive impact will result.

There were some significant limitations and assumptions assumed if either technology is fully adopted. There is an explicit assumption there will be sufficient urban space for drones or ADRs to operate. Existing parking spaces may not provide significant space for loading and unloading for motherships but are assumed to be available. (Figliozzi & Jenningsa, 2020) Public concerns and impacts to other users, sidewalk users for ADRs, and air space users for aerial drones are not considered as well as safety and employment impacts. The increased use of ADRs can negatively impact pedestrians and cyclists on sidewalks, and autonomous navigation, collision avoidance, and communication systems still need improvements to ensure the safe and reliable operation of drones and ADRs in complex urban environments. The interaction of drones with other aircraft and aerial animals is not clear. As mentioned previously, drop-off zones designed for drones in urban areas are unknown.

ADRs also have a problem with the last 50 m problem. ADRs cannot climb stairs, ring doorbells, or physically hand off packages. A person must be present to pick up the package. ADRs also assume the delivery window, the time a delivery can take place, is 24/7. Customers must be home to receive parcels and homes creating restricted delivery windows. Homes are also more likely to be occupied during the evenings creating uneven demand which can affect the total ADRs required.

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Dynamic Parking Pricing: Implementation in North America

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Introduction

Dynamic parking prices, which adjust in response to changes in demand, can be a useful tool for managing parking availability and encouraging turnover. However, there are some limitations to this approach. First, it can be difficult to implement and administer, requiring complex pricing algorithms and systems to collect and process data in real-time. Additionally, dynamic pricing may not be well-received by drivers, who may perceive it as unfair or unpredictable. Parking as it stands is a relatively 'dumb' system, and introducing any smartness into the system will include a number of added complications that can limit the uptake and the success of the system. This paper will look into the parking problem overall, introduce dynamic parking as a potential solution, and then delve into the example of SF Park. Finally further considerations and alternate solutions will be considered in the context of dynamic parking pricing to provide context and consider further research.

The Parking Problem

There are three aspects of the parking problem that are essential to understand before exploring possible solutions, the issue of space, of pricing, and of cruising. It must be noted that because most trips in most North American cities start and end with a parked car, that parking is one of the most important intermediary goods in the market; however, since cars spend about 95% of their time parked it can be safely assumed that market lacks in efficiency (Inci, 2015)

(Shoup, 2005). Cars take up large amounts of space relative to the number of passengers they transport even when moving, but considering they are parked most of the time the efficiency of the method is reduced even further. Not only do parked cars take up a lot of space, but they also require a parking spot at every place they travel, be it workplaces, shopping centres, or at home; in the US there are an estimated ten parking spaces for every car, and on a typical day space equal to the state of Massachusetts is taken up by parked cars (Fabusuyi & Hampshire, 2018). While there is so much space devoted to parking, many drivers will insist that there isn't enough parking available; however, as Donald Shoup observed in his seminal book The High Cost of Free Parking, this is almost universally untrue, and rather drivers are saying there is a limited amount of free parking not parking overall. Herein lies another problem with parking: it is rarely priced correctly (according to the cost of its provision) and often the cost of parking is not directly levied on the parker (Shoup, 2005). This means that parkers are shielded from the true cost of parking and feel entitled to free or near free parking wherever they go, leading to drivers cruising through cities to find parking once they have already reached their destination. In cities across the US it is observed that between 50-30% of downtown traffic is caused directly from cruising (Chen et al., 2015). Drivers are not cruising looking for parking, rather they are looking for free parking, often on street parking provided at substantially lower rates than the true cost of parking charged by private parking garages (Shoup, 2005).

A Dynamic Solution

To tackle this parking problem, municipalities have considered changing parking fares dynamically on streets and in lots based on demand. It has been observed through many studies that the ideal occupancy for parking spaces in urban environments is between 60% and 80%, because at this level there is limited need cruising (as 20% of spots should be free) but still most of the spots are being used so the use of space is more efficient (Maternini et al., 2017). Parking price can be a strong driver of behaviour for drivers who, as Shoup observed, tend to value the money spent at the parking meter as of much higher value than the time-cost of cruising around in their car (Shoup, 2005). So, in the case of dynamic parking, municipalities can price the spots located in high demand locations at a higher price than low demand locations, incentivising the most cost-sensitive drivers to park in the less popular places, reducing demand for parking in the busier areas and increasing it in the less busy areas. This is only the first layer of dynamic parking pricing, and in order to take into account changing driver habits, and other trends in a city's transportation space, cities can also make the pricing of these spots dynamic, so has demand for spots in a certain location goes up cities can adjust the price higher, thus ensuring a similar level of demand for parking spots across the city and maintaining that ideal window of 60-80% occupancy overtime.

Of course, parking demand changes not only over the weeks but also throughout the day: downtown parking near job centres will likely be higher when people are at work, and then parking demand might be higher near retail centres later in day, etc, thus cities can also dynamically change the price of a parking space throughout the day, having an even finer layer of control over demand. The speed and sensitivity of price fluctuations relative to demand can be tailored to a municipalities' needs along with a program's scope will have a major impact on the effect of the intervention.

SF Park: A Case Study

Overview

SF Park was launched as a pilot program in April 2011 and initially covered 7000 on- street spots and 12,250 off street spots (SFMTA). The program allows for meters to be priced differently depending on the time of day, pricing zones are from 9am to 12pm, 12pm to 3pm, and 3pm to 6pm; between 6pm and 9am the meters were off, so parking is free. Every six weeks the hourly rate would either increase or decrease depending on occupancy. If occupancy was over 80% then the rate went up by 25 cents and if it was below 60% the rate would decrease by 50cents. The aim of the program was to keep occupancy between the ideal levels of 60-80% and ran in several districts throughout the city.

Results

The program was seen as a success by the city, and in subsequent reviews the results have been carefully analysed. The price increased in 32% of the zones, decreased in 31% of the zones, and didn't change in 37% of the zones (Pierce & Shoup, 2013). This result is quite interesting, because while it shows that the parking demand was certainly elastic relative to the price, it also indicates that the average price of parking throughout the city didn't change. From this it can be inferred that there are enough spots in the city, despite popular conception. It is unclear whether people shifted to other modalities during this time, if they parked in different zones, or if they carpooled. The results also showed that demand for parking is less elastic in the morning, than around midday and in the afternoon. Also, that demand is less elastic in residential areas than commercial areas (Pierce & Shoup, 2013). This isn't necessarily surprising, as it follows logically that when people need to go home, and park in residential areas, they do not have a lot of leeway in where they park, they are simply going to park as close to their home as possible. Also, the same follows for the morning demand, many people need to be at work at the same time every morning, and work in the same place, so they also will need to park wherever they can in the morning that is closest to their work. Finally, it is important to look at the changes to occupancy rates following the implementation of the program. For blocks that had an initial occupancy rate of <30%, it was found that 67% of them increased occupancy, and for those at above 90% occupancy, it was found that 68% reduced occupancy (Pierce & Shoup, 2013). From these initial results it seems as though the plan was a success, but it remains important to look at the bigger picture and note potential confounding factors.

Figure One: Parking prices on a weekday at Fisherman's Wharf in May 2012. (Pierce & Shoup, 2013)

Figure is on next page.

Before Noon

Noon to 3 pm

After 3 pm

Takeaways

Park SF was not the only parking reform that took place during this period in San Francisco, and thus there might have been some confounding factors when measuring the success of the program. It was noted that workplaces may have begun offering parking at work considering the changes, and since the pilot program didn't cover these spots, it is unclear whether workers just started parking at work instead (Fabusuyi & Hampshire, 2018). Also, since the program did not apply to every single spot within each zone, nor did it study or apply to spots outside the zones, demand could simply have just shifted between and from these un-studied spots, a more holistic study would have needed to consider these additional spots, particularly those at the edges of the zones (Fabusuyi & Hampshire, 2018). Two other changes in parking rules took place at the same time as the pilot was launched; an easier payment system was introduced and the duration which people were allowed to park for was relaxed (Fabusuyi & Hampshire, 2018). Unfortunately, it is impossible to separate the effect of these rule changes on parking demand from the SF Park program which makes it hard to identify which reform had the most effect. Further studies have noted some improvements to the program that SF Park could have undertaken; firstly, that the time periods could have been refined. Since the parking meters turned off at 6pm, people who came to the spot at 5pm could park overnight and only must pay for one hour of parking, it certainly would have been interesting to study the effects on overnight parking in the different districts and how the changing rates shifted the overnight parking trends (Pierce & Shoup, 2013). Finally, it was suggested that SF Park could have done more to predict the occupancy of different zones to pre-emptively change the rates, rather than just responding after each six-week period (Pierce & Shoup, 2013). While this certainly would have helped each zone reach the optimal price and therefore occupancy faster, it may have come under more public scrutiny; one of the strengths of the plan in terms of public opinion was that the price changes were based on real time occupancy which seems ‘fairer’ than predicted occupancy.

Other Considerations

Pricing Change

The major limitation or risk of an intervention like dynamic parking pricing is that there needs to be a balance between the speed at which the prices are changing to the speed at which drivers can observe and act upon the different prices. Some argue that: “these existing programs nevertheless share a common feature: the parking prices are updated once per several weeks or even several months, which is not sensitive enough to deal with the highly dynamic parking demand in realistic daily operations” (Lei & Ouyang, 2017). However, the faster the prices are updated, the more frequently drivers will need to be checking the pricing landscape. Since the point of dynamic parking pricing programs is to shift demand away from popular areas at popular times, drivers need to have a general idea of the cost of parking where and when they are looking to park. A program like SF park, updated the cost of parking every six weeks, allowing drivers plenty of time to be aware of and change their behaviour in accordance to the current price (Fabusuyi & Hampshire, 2018). Perhaps a three-week cycle would have been more effective in allowing spots to reach their optimal price faster while still allowing drivers plenty of time to be made aware of the changes; however, this leads to a discussion of the ‘smartness’ of the system, and the method by which drivers can check the prices and find spots.

Parking Reservations

A method that had been considered for reducing cruising in downtown areas is allowing drivers to make reservations on specific spots either on the street or in lots, which would allow them to drive directly to an open spot without the worry that it might be taken. While extremely promising, a program like this would also have some limitations, two being the way in which spots are reserved, and the number of spots which are allocated for reservation only (Chen et al., 2015). While a reservation system would reduce bottlenecks in high demand parking areas due to a reduction in cruising, visitors or tourists who are unaware of the system might find an extremely limited number of non-reservation spots, which could in turn lead to increase cruising for some, eliminating the benefits of decreased cruising for others. If too many spots are allocated for reservations, people might get quite frustrated cruising around looking at all the empty spots. Therefore, a reservation system would need to be easy to access, and unreserved spots should be able to be reserved on the spot by those who weren't aware they had to book ahead of time.

"Smartness of System"

Dynamic parking pricing, parking reservations, and other parking interventions often increase the 'smartness' of the parking system, and for faster response times and a higher ability to make reservations there will be a clear reliance on smartphone apps or even smart systems within cars. While trends towards 'smarter' systems are accelerating in almost all sectors it is important to note that not everyone is able to use these 'smarter' systems, and thus the benefits of these programs could be distributed unequally throughout the population. Another consideration is the safety of these systems. While it might see a good idea to allow drivers to reserve a spot with their phone, or even check out the block by block pricing with their phone, an increase in phone usage while driving either on the freeway into a downtown area, or while driving around downtown would be dangerous (Qian & Rajagopal, 2014). Decreasing cruising and optimizing parking need not come at the expense of driver and pedestrian safety which is another major problem in downtown systems. There needs to be a balance between the smartness of a system and its accessibility to allow usage without being on one's phone constantly.

Conclusion

As can be seen, dynamic parking pricing is an exciting method by which cities can manage the problems associated with downtown parking, and while the SF park program was successful in several measures, there are improvements and further considerations that should be taken into account when expanding the program or if it is taken up in other cities. Other cities such as Los Angeles have explored the possibility of dynamic parking pricing and as more cities do so, more data will be made available for study allowing for the constant improvement and expansion of these programs. It is important to bear in mind the end goal of these programs and make sure they are aligned with that of the city. While reducing cruising by smoothing out parking demand is essential, a reduction in car dependency in American cities should of course be the end goal, and whether these programs have achieved that is still unclear. An extremely interesting finding from both SF Park and the program in LA, is that overall parking prices did not increase, showing that the number of parking spots in these cities is sufficient to meet demand, but also that the cost of parking is still lower than the cost of provision (Qian & Rajagopal, 2014). A holistic increase in parking prices city wide could be a major step in reducing car dependency, however this seems unlikely due to a lack of political will, so perhaps these limited market/demand solutions remain the best option for now.

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