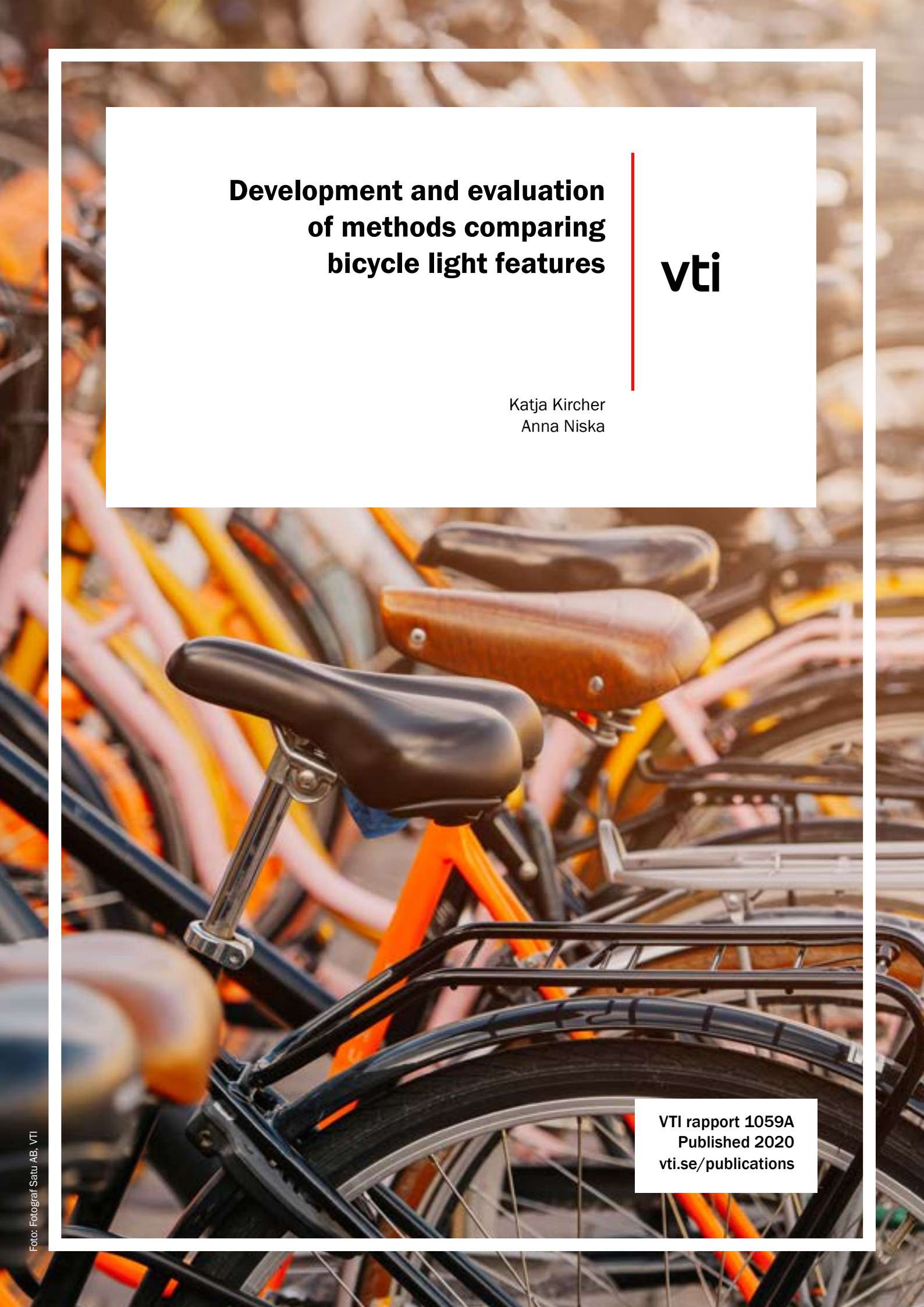




Development and evaluation of methods comparing bicycle light features

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Development and evaluation of methods comparing bicycle light features

Test av cykellysen - Metodutveckling och utvärdering

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Abstract

In this report, we present the results from a study commissioned by the research foundation of Länsförsäkringar (Länsförsäkringsbolagens forskningsfond). The aim was to develop and evaluate methods for testing how well-suited different bicycle lights are as vision aid, while at the same time making the cyclist visible and recognisable. Rather than comparing specific brands, the goal has been to evaluate generic features like brightness, beam shape, blinking versus steady beams, mounting position and so on.

Nine front and nine rear lamps from a wide price and design range have been selected from the bicycle lights available on the market. Brightness and beam shape were documented with lux measurements and via photographs. Six participants were asked whether they could, from a distance of 300 metres, identify front and rear lights and whether they showed a blinking, steady or rolling beam, and to rate the light setup for subjective preference. Gap acceptance and estimated ease of speed and distance judgements depending on beam type, mounting position and cyclist speed was investigated in a dynamic setting in an urban environment. Additional lighting features were demonstrated with films and photographs.

A combination of the test results showed that the methods used in the study complemented each other and were able to identify differences between the light features. It turned out that bicycle lights vary greatly in brightness and beam shape. However, all tested lights fulfilled the legal requirement of being visible from 300 metres. Bright front lights with a steady beam – preferably with a sharp cut-off of the beam on the upper edge while illuminating the sides of the road close to the bicycle – provides the best preconditions for the cyclist to see well. The light should be mounted on the handlebars for best recognition and be pointed slightly downwards to avoid glare. Also, for rear lights a steady beam is preferable.

Keywords

Bicycle lights, cycling, darkness, visibility, gap acceptance, method development

Referat

I den här rapporten redovisas ett uppdrag från Länsförsäkringsbolagens forskningsfond att utveckla metoder för och utvärdera hur väl olika cykellys hjälper en cyklist att se, bidrar till cyklistens synbarhet, till en bra igenkänning och en reliabel avståndsbedömning. Snarare än att jämföra cykellyse av olika tillverkare, har syftet varit att utvärdera olika generiska egenskaper såsom ljusstyrka och -spridning, blinkande kontra fast sken, monteringsposition på cykeln etc. Ett urval om 9 framlysen och 9 baklysen, i ett så brett spektrum som möjligt med avseende på pris och design, har ingått i studien. Ljusstyrka och ljusspridning har studerats genom luxmätning och fotografering av ljuskäglornas form. Hur väl lysena uppfyller lagkraven har utvärderats genom att försökspersoner från 300 meters håll fått avgöra om de ser ett framlyse, ett baklyse, med fast, blinkande eller rinnande ljus samt subjektivt bedöma respektive ljusuppsättning.

För att undersöka hur cykellyse med olika placering och inställning påverkar andra trafikanter möjlighet att avgöra avstånd och hastighet hos en cyklist i rörelse gjordes en fältstudie i verklig trafikmiljö. Några belysningstekniska egenskaper har också illustrerats genom demonstrationer med hjälp av fotografering och filmning. Sammantaget visar resultaten att de metoder som utvecklats har kompletterat varandra på ett bra sätt och kunnat visa på skillnader mellan de testade cykellysena. Studierna visar på en stor variation i ljusstyrka (lux) och ljuskäglans form för olika lysen. Alla cykellysena oavsett inställning uppfyllde dock gällande lagkrav om att tydligt kunna ses på 300 meters avstånd. Starka framlysen med fast sken – helst med en ljuskägla med skarp avgränsning uppåt och vidare spridning vid marknivå – ger bäst förutsättningar för en cyklist att synas och att kunna se. De ska monteras på styret för bästa möjliga igenkänning och riktas någon nedåt för att undvika bländning. Även för baklysena är ett fast sken att föredra.

Nyckelord

Cykellyse, cykling, mörker, synbarhet, metodutveckling

Förord

Under åren 2015 till 2018 genomförde vi ett större forskningsprogram ”Hjulburna oskyddade trafikanter” finansierat av Länsförsäkringsbolagens forskningsfond. Programmet som innefattade nio olika delprojekt hade framförallt cyklisters säkerhet i fokus även om också mopedister och motorcyklister berördes. I en sammanfattande slutrapport ”modell för säker cykling”, VTI rapport 979 (Wallén Warner et al., 2018) beskrevs en mängd olika aspekter relaterade till cyklisters säkerhet, utifrån de olika delprojekten och tidigare forskning. Baserat på den kunskapen föreslog vi slutligen en mängd olika åtgärder kopplade till cyklisten, cykeln och trafikmiljön för att öka cyklisters säkerhet. Bland annat föreslogs objektiva tester av cykeldäck och cykellyse som underlag till förbättrad konsumentinformation. Länsförsäkringsbolagens forskningsfond finansierade därför under 2018 en ”bäst i test-studie” av cykeldäck för vinterväglag (Hjort, 2018). På liknande sätt har vi nu fått i uppdrag från forskningsfonden att ta fram metoder för att objektivt beskriva en cykellyses egenskaper och använda dessa för att genomföra tester av ett antal cykellysen. Tanken är att den kunskapen ska användas som underlag för informationskampanjer riktade mot cyklister. Rapporten är skriven på engelska men, enligt önskemål från uppdragsgivaren, med en längre sammanfattning på svenska än vad som är brukligt i våra VTI rapporter.

Anna Niska har varit projektledare men Katja Kircher har ansvarat för planering, genomförande och analys och gjort större delen av arbetet i projektet. I övrigt har Carina Fors, Jonas Ihlström och Pia Brink medverkat vid planering och genomförande av laboratorie- och fältstudierna i projektet.

Ett stort tack till Mari Sparr och Maria Wedin på Länsförsäkringsbolagens forskningsfond för gott samarbete! Tack också till de försökspersoner som medverkat vid genomförda fältstudier. Resultaten har, i samband med ett granskningsseminarium, diskuterats med en referensgrupp med representanter från Länsförsäkringar, Transportstyrelsen och cykelbranschen. Vi är tacksamma för de värdefulla inspel till diskussion och slutsatser som referensgruppen och övriga medverkande vid seminariet bidragit med - ett särskilt tack till Jones Karlström som granskat rapporten.

Linköping, september 2020

Anna Niska
Projektledare

Quality review

A review seminar was held on 28 August 2020, with Jones Karlström as the reviewer. The authors have made adjustments to the final report. Research Director Maria Mäkitalo has thereafter reviewed and approved the report for publication on 6 September 2020. The conclusions and recommendations in the report are those of the authors and do not necessarily reflect the views of VTI as a government agency.

Kvalitetsgranskning

Granskningsseminarium har genomförts 28 augusti 2020 där Jones Karlström var lektor. Författarna har genomfört justeringar av slutligt rapportmanus. Forskningschef Maria Mäkitalo har därefter granskat och godkänt publikationen för publicering 16 september 2020. De slutsatser och rekommendationer som uttrycks är författarnas egna och speglar inte nödvändigtvis myndigheten VTI:s uppfattning.

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Summary

Development and evaluation of methods comparing bicycle light features

by Katja Kircher (VTI) and Anna Niska (VTI)

Lighting a vehicle in darkness serves two purposes – to see and to be seen. Depending on the vehicle type, various regulations apply. In Sweden, bicycles have to be equipped with a white light directed forward and a red light to the rear. Both must be clearly visible from a distance of 300 m. The rear light is allowed to flash, but then with a frequency of at least 200 flashes per minute, and it must be possible to dim the front light quickly if it risks blinding other road users.

On the whole, the rather small amount of previous studies could neither establish a clear link between darkness and the crash rate involving bicycles, nor between crash rate in darkness and the presence of bicycle lighting. Similarly, scientific studies could not yet show conclusively what type of light is most recommendable from a visibility standpoint. Consumer testing of bicycle lights is not done in a systematic way, and often specific lamps are investigated instead of their generic features.

This project aimed at investigating to which extent the breadth and variation of bicycle lights on the Swedish market fulfil the legal requirements, while at the same time developing methods that allow a scientific comparison of generic features of bicycle lights. Specifically, brightness, beam shape, flashing versus steady beam and mounting position were investigated, based on a selection of available lamps.

Three test methods of different complexity were used, with the results of one partially feeding into the next method. In a laboratory test, the brightness of front and rear lights was measured in nine spots and the beam shape as cast against a white wall was photographed. In a static field test with six participants, the same lamps were tested for whether they fulfilled the requirement of being visible from 300 metres distance, at the same time as they were rated for their perceived quality as bicycle light. The test was conducted on a gravel road in complete darkness. In this location, the beam of the front lights was photographed as well. The combined results of the two tests showed that all lamps fulfilled the visibility requirement, even though their level of brightness varied with a factor of more than 1:7 500 from the weakest to the brightest lamp included in the test. For front lights, the participants preferred bright lights with a steady beam before flashing beams, followed by weak, steady lights. For rear lights, flashing lights were preferred when seen from 300 m. The photographs of beams against a wall and directed at a road illustrate how the reflector shape of the lamp influences how well the lamp is suited for illuminating the road, and how the light field on the wall can be “translated” to reality.

The three differently rated beam types for front lights (strong steady beam, flashing beam and weak steady beam) were tested further under dynamic conditions in an urban setting which included some street lighting. A gap acceptance test with 20 participants acting as pedestrians who want to cross a street investigated the factors of beam type (including no lamp at all), lamp mounting position and cyclist speed on the minimum accepted gap for crossing in front of the cyclist. For each combination, the setup was also rated on five subjective scales (overall satisfaction, blinding, identifiability, ease of speed and distance judgement). It turned out that the only factor influencing the accepted gap was the cyclist’s speed, with the accepted time gap decreasing with speed. Still, the participants rated the lamps as having different qualities, generally preferring the bright, steady beam. This shows that the participants’ subjective preferences were not linked to their actual behaviour.

In addition to the three studies, several demonstrations were recorded on film, that illustrate additional dimensions of generic bicycle light features, like how flashing versus static rear lights are perceived from a following cyclist’s perspective, how mounting affects glare, how biomotion can enhance identifiability, and how the mounting position in relation to eye height affects retroreflectivity.

Sammanfattning

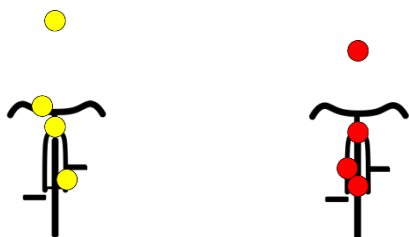
Test av cykellysen. Metodutveckling och utvärdering

av Katja Kircher (VTI) och Anna Niska (VTI)

Bakgrund

Cykellyset är dels till för att en cyklist ska synas, dels för att cyklisten ska kunna se. Det senare är mycket relevant nattetid i områden utan gatubelysning, men även med gatubelysning kan cykellyset hjälpa cyklisten att exempelvis upptäcka hinder och läsa relevanta skyltar. Enligt diskussioner i fokusgrupper, har dock cyklister uttryckt att cykellysen varken ger tillräckligt ljus för att de själva ska kunna se ordentligt eller för att andra ska kunna se dem (Fors & Nyghårds, 2010). I synnerhet då det är vått väglag upplever cyklister att bilister har svårt att se dem i mörker. Cyklister upplever också att cykellysen sällan är tillräckligt stark för att kunna lysa upp vägen så att potthål och andra skador i beläggningen kan upptäckas när det är mörkt (Niska, 2007).

Enligt gällande regelverk måste en cykel ha belysning och reflexer vid färd under mörker (TSFS 2010:144). Framtill ska det vara en strålkastare eller lykta med vitt eller gult ljus och baktill en lykta med rött ljus. Bakljuset får vara blinkande om antalet blinkningar per minut är minst 200. Cykellysen ska tydligt kunna ses på ett avstånd av 300 meter. Vad som kan anses vara "tydligt" och under vilka omgivande förhållanden det ska gälla framgår dock inte av regelverket. Det finns idag inget system för märkning eller godkännande av att de produkter som finns på marknaden uppfyller gällande krav. Spannet av cykellysen som säljs på marknaden är väldigt brett – det finns allt ifrån små lysdioder som fästs med gummisnodd på någon del av cykeln till stora strålkastare som kan fästas på hjälm eller cykel. Speciellt bakåt men även framåt förekommer varianter med blinkande sken, fast sken och "rinnande" ljus (cykellyset har flera lysdioder som tänds sekventiellt så att minst en diod är tänd vid varje tidpunkt), och ljusstyrkan samt ljuskäglan varierar. Cykellysen kan vara placerade på många olika ställen, där Figur 1 enbart visar på några exempel.



Figur 1. Olika typiska positioner för cykellysen både fram (gult) och bak (rött).

En litteratursökning visar att forskningen på området är mycket begränsad. År 2004 gjordes en metaanalys av 29 forskningsartiklar som undersökte effekten av "visibility aids" på olycksinblandning (Kwan & Mapstone, 2004). Även studier som undersökte reflekterande kläder analyserades, och dessa utgjorde den största andelen av materialet. Mätvariabler var detektionsfrekvens, avstånd vid detektion, reaktionstid, avstånd vid igenkännande (t.ex. är det en cyklist eller en gående) och frekvens för igenkännande. Även om datamaterialet som ingick i metaanalysen varierade kunde rapporteras att fluorescerande kläder syns bättre dagtid, att cyklar med lysen och reflektorer syns bättre än cyklar med enbart reflektorer, och att så kallad "biomotion" verkar underlätta upptäckandet och igenkännandet av cyklister och fotgängare. Det fanns dock inget material som undersökte ett möjligt samband med trafikolyckor. Enligt analyser av skadade cyklister inrapporterade i den svenska olycksdatabasen Strada under åren 2007–2012, har Niska och Eriksson (2013) konstaterat att mörker beskrivs som en bidragande orsak i endast en procent av singelolyckorna. Det resultatet baserades på genomgång av olycksbeskrivningar i fritext, eftersom mörker annars inte är en parameter som registreras i Strada. Genom att utgå ifrån tidpunkten när olyckan inträffade och definiera mörker som att solhöjden är 6

grader under horisonten, kunde de dock dra slutsatsen att ungefär 20 procent av singelolyckorna och ca 13 procent av kollisionerna med annan motpart, inträffat när det var mörkt ute. Om eller vilken typ av cykellyse cyklisten hade vid olyckstillfället är dock oklart. Enligt en analys av data från resvane- och trafiksäkerhetsundersökningen 1995–1997 (Thulin & Kronberg, 1998) skedde 17 procent av cykelresorna i mörker och cykellyse användes vid ungefär hälften av dessa.

Synbarhet, upptäckbarhet och igenkännande beror på många faktorer, däribland kontrast, storlek, positionering, rörelse, belysning och hur rörlig bakgrunden är ("clutter"), samt även faktorer som är relaterade till observatörens förväntan, fysiologiska faktorer, etc. För att kunna göra en systematisk utvärdering av olika cykellysen som har praktisk betydelse är det viktigt att identifiera vilka faktorer som behöver varieras, vilka som behöver hållas konstanta och vilka testsituationer som är relevanta. Det finns en mängd olika situationer då ett cykellyse bidrar till att synliggöra cyklisten, exempelvis då en cyklist blir omkörd av ett snabbare fordon (baklyse i förarens centrala synfält); en cyklist som närmar sig från sidan i en korsning (framlyse från det perifera mot det centrala synfältet), eller en mötande cyklist (framlyse i det centrala synfältet). En cyklist kan också närma sig bakifrån, t.ex. en bil som stannat vid rött ljus och måste då kunna upptäckas via backspeglarna. Därtill sker interaktioner med fotgängare och andra cyklister i ett flertal tänkbara situationer.

Det är känt att det centrala och det perifera seendet fungerar på olika sätt (Rosenholtz, 2016), vilket gör att det inte nödvändigtvis behöver vara samma egenskaper på lyset för bra upptäckbarhet och igenkännbarhet i det centrala som i det perifera synfältet. Utöver det behöver inte samma egenskaper vara främjande för upptäckbarhet och till exempel avståndsbedömning.

För att andra trafikanter ska kunna se cyklisten bör ett bra cykellyse ha (minst) följande egenskaper i så många olika situationer som möjligt:

- bra upptäckbarhet, dvs. uppmärksammas även utan aktiv avsökning i det området
- bra synbarhet, dvs. syns bra vid avsökning
- tillförlitlig avståndsbedömning, även i rörelse
- bra igenkänning, dvs. andra trafikanter ser att det handlar om en cykel, men även ytterligare information kan vara viktig, t.ex. om cykeln har släp, är en bredare lastcykel, etc.
- bra intentionsbedömning, dvs. underlättar att förutse cyklistens handlingar.

Utöver det ska lyset inte blända andra, samt vara praktisk att hantera och för framlysen ska detta förenas med att cyklisten även ska kunna använda lyset för att se. Viktiga egenskaper här är att vägbanan behöver vara upplyst tillräckligt mycket och tillräckligt långt fram i förhållande till cyklistens hastighet, samt att potthål, kanter och andra hinder kan upptäckas, att andra trafikanter, särskilt de utan egen belysning, kan upptäckas, kännas igen och förutses samt att vägmärken och annan relevant information kan uppfattas i tid.

Syfte och avgränsning

Det här projektet syftar till att öka kunskapen om variationen i belysningstekniska egenskaper för de cykellysen som förekommer på den svenska marknaden och undersöka hur stor andel som uppfyller kraven i gällande lagstiftning. I projektet ingår också att utveckla metoder för att på ett mer vetenskapligt sätt kunna jämföra olika cykellysens funktionalitet samt att beskriva metodernas styrkor, svagheter och användningsområde. Framförallt studeras hur väl olika cykellysen hjälper cyklisten att se, bidrar till cyklistens synbarhet och till en bra igenkänning och en tillförlitlig avståndsbedömning.

Eftersom det sker en kontinuerlig utveckling och finns en stor uppsjö av olika cykellysen på marknaden, är syftet med studien inte att jämföra cykellysen av olika tillverkare. Syftet är snarare att utvärdera olika generiska egenskaper hos cykellysen såsom ljusstyrka och spridning, blinkande kontra fast sken, monteringsposition på cykeln etc., baserat på ett urval cykellysen på marknaden. Studien har

begränsats till att omfatta statiska ljustester och en situation i rörelse där en cyklist närmar sig en fotgängare från sidan.

Genomförande

Projektet har omfattat både statiska laboratoriestudier inomhus och utomhus samt fältstudier i verklig trafikmiljö med en cyklist i rörelse (dynamiska förhållanden). Några belysningstekniska egenskaper har också illustrerats genom demonstrationer med hjälp av fotografering och filmning. Det är egenskaper som inte kunnat studeras som oberoende faktorer i de studier som varit möjliga att genomföra inom projektramen, men som ändå ansetts vara av betydelse (och kan studeras vidare i framtida studier). I Tabell 1 nedan sammanställs de egenskaper som studerats eller demonstrerats i projektet.

Tabell 1. Översikt av studerade faktorer/egenskaper i vilken typ av test och hur. F=framlyse; B=baklyse. "Gap acceptance" = det minsta avståndet till en ankommande cyklist i vilket en försöksperson kunde tänka sig att korsa vägen.

	Faktor/egenskap	Lab inomhus	Lab utomhus	Fältstudie	Demonstration
1	Höjd/montering	-	-	F: styre eller framgaffel	F: monteringsvinkel och bländning F: monterad bakåt (lyser upp cyklist) F: belysningsfunktion (från cyklistens perspektiv)
2	Ljusstyrka	F, B: lux mätt i nio punkter	F, B: subjektiv bedömning	F: muntliga kommentarer, oberoende faktor för 6 & 7	
3	Blinkfrekvens	-	F, B: subjektiv bedömning	F: muntliga kommentarer, oberoende faktor för 6 & 7	B: olika frekvenser, från efterföljande cyklists perspektiv
4	Ljusspridning	F: foto	F: foto	-	F: olika design
5	Synbarhet	-	F, B: identifiering av ljusstyp	F: gap acceptance	F, B: synbarhet från sidan
6	Igenkänning	-	F, B: subjektiv bedömning	F: muntliga kommentarer	F: monterad bakåt (lyser upp cyklist) B: biomotion
7	Uppskattad färdväg och hastighet	-	-	F: gap acceptance	
8	Design	F, B: foto	-	-	F, B: synbarhet från sidan

För att kunna utveckla metoder som på ett relevant sätt beskriver skillnader mellan olika cykellysen och dessutom tillämpa metoderna för att utvärdera några utvalda lysen, behöver urvalet omfatta en så stor variation som möjligt. Det ökar sannolikheten att kunna identifiera skillnader i olika egenskaper. Vi bestämde att enbart studera nyinköpta och fulladdade cykellysen för att utesluta skillnader till följd av slitage eller effektförlust. I urvalet av lysen till projektet försökte vi istället fånga ett så brett spektrum som möjligt med avseende på pris och design. Vi inkluderade alltifrån mycket billiga

cykellysen som delas ut gratis eller kan köpas i dagligvaruhandel, via mellanklasslysen tillgängliga i cykelaffärer till mer exklusiva lysen som behöver specialbeställas. Flera inställningar/funktioner testades på 9 olika framlysen och 9 olika baklysen, vilket resulterade i att 42 olika ljusuppsättningar ingått i studien (se Table 2, sidan 33).

Statiska förhållanden

För att jämföra ljusstyrka och ljusspridning för de olika cykellysena, tog vi fram och genomförde ett försöksupplägg för inomhusmätningar i laboratoriemiljö. Vi valde att göra mätningar i ett stort mörkt rum utan belysning (förutom ljus från en nödutgång och skärmen till en bärbar dator). Varje lyse monterades på ett stativ och centrum av ljuskäglan riktades in mot en bestämd punkt på en vit vägg 6 meter bort. Med en handhållen luxmätare mättes ljusstyrkan i 9 olika punkter på 2 meters avstånd från ljuskällan, valda så att de skulle ge en representativ bild av ljusspridningen från lyset (se Figure 1 och Figure 2 i avsnitt 4.1 i rapporten). Dessa mätningar gjordes endast för inställningar med fast sken. För att få ytterligare en bild av ljusspridningen från framlysena placerades de 2 meter från den vita väggen och ljuskäglan på väggen fotograferades. Ljusstyrkan från baklysena var inte tillräckligt starkt, och ljuskäglans form inte heller lika relevant, för att motivera ett liknande förfarande för dessa lysen.

För att jämföra hur olika cykellysen upplevs under statiska förhållanden och utvärdera hur väl de uppfyller kraven enligt svensk lagstiftning (är synliga från 300 meters håll), genomförde vi en laborationsstudie utomhus. Alla de 18 utvalda cykellysena monterades på en meters höjd på en specialtillverkad rigg och tändes en och en med fast, blinkande eller rinnande ljus, i slumpmässig ordning (totalt 42 olika ljusuppsättningar). Sex försökspersoner – i åldrarna 15 till 69 år och med de synhjälpmedel de normalt använder i trafiken – fick från 300 meters håll notera om de såg ett framlyse, ett baklyse och huruvida lyset hade fast, blinkande eller rinnande ljus. De skulle också bedöma, på en skala från 0 (mycket dåligt) till 10 (mycket bra), hur bra de ansåg att respektive ljusuppsättning var som cykellyse. Varje uppsättning visades två gånger för att kunna avgöra hur konsekventa försökspersonerna var i sina bedömningar (de kommenterade att de justerade sina bedömningar över tid allteftersom de såg de olika uppsättningarna). Emellanåt tändes inget lyse alls – för att kontrollera att de inte influerats att svara att de såg ett lyse. Försökspersonerna noterade sina bedömningar på en enkät och hade då också möjlighet att kommentera om de exempelvis upplevde att lyset var irriterande, bländande eller svårt att se. För varje uppsättning av framlyse med fast sken fotograferades också ljusflödet på vägen (se Table 4, sidan 46).

Lagkravet specificerar inte under vilka omgivande förhållanden som kravet ska gälla och därför valde vi ett försöksupplägg som skulle vara enkelt att upprepa. Försöket genomfördes i mörker, en dag efter nymåne, på en rak grusväg utan belysning. Omgivande ljus uppmättes till 0,01 lux. Det var torrt och klart väder med en lufttemperatur på 3°C vid tillfället. Lysena bedömdes rakt framifrån, så studien säger alltså ingenting om synbarheten från exempelvis sidan. Det är emellertid något vi studerade i en av demonstrationerna där samtliga cykellysen fotograferades från sidan (se Table 10, sidan 66).

Dynamiska förhållanden

För att undersöka hur cykellysen med olika placering och inställning påverkar andra trafikanters möjlighet att avgöra avstånd och hastighet hos en ankommande cyklist, genomförde vi slutligen en fältstudie i verklig trafikmiljö. Vi utvecklade och genomförde ett testupplägg baserat på tidigare studier av "gap acceptance" (Petzoldt, Schleinitz, Krems, & Gehlert, 2017; Schleinitz & Petzoldt, 2019) i kombination med en subjektiv bedömning. Totalt 20 rekryterade deltagare fick agera "fotgängare" och ange det minsta avståndet till en ankommande cyklist i vilket de kunde tänka sig att korsa vägen, framför cyklisten ("minimum gap acceptance"). Cyklisten utgjordes av en försöksledare klädd i mörka kläder utan reflexer. Fyra olika ljusinställningar och 2 olika placeringar av cykellysen ingick i försöket, liksom tre olika cykelhastigheter: 15, 20 och 25 km/h. Hastigheten varierades för att det inte bara skulle vara avståndet som avgjorde försökspersonernas "gap acceptance".

Endast framlysen ingick i fältstudien och ett mindre urval av de lysen och de inställningar som ingick i de statistiska studierna inkluderades (se Table 7, sidan 54). Målsättningen var att studera så många olika egenskaper som möjligt och samtidigt hålla nere försöket till en rimlig nivå. Vi valde ett cykellyse i mellanprisklassen för att representera ett lyse med stark ljusstyrka (F9); ett vanligt förekommande lågprislyse för att representera ett cykellyse med svag ljusstyrka (F7) och för blinkande ljus valde vi ett vanligt förekommande lyse som vid fast sken var något starkare (F5) än den med svagast ljusstyrka. Två lysen av varje sort monterades på cykeln – en på vänstra sidan av framgaffeln och det andra på styret (se Table 8, sidan 56). I försöket ingick också en uppsättning helt utan något tätt lyse.

Två till fyra deltagare åt gången stod placerade på trottoaren längs en väg på 4, 8, 12 respektive 16 meter från närmaste korsning. Cyklisten startade från omkring 100 meter från den närmaste deltagaren och kom cyklande i riktning mot korsningen. När cyklisten närmade sig indikerade varje deltagare sitt "gap acceptance" genom att lyfta ett ben eller räcka ut en arm. En kamera monterad på cykeln registrerade deltagarnas indikeringar. Deltagarna fyllde också i en enkät med fem frågeställningar för att gradera den aktuella ljusuppsättningen, på en skala från 0 till 10:

- Generell uppfattning/nöjdhet med ljusuppsättningen.
- Är ljusuppsättningen bländande.
- Gör ljusuppsättningen det lätt att identifiera att det är en cyklist som kommer?
- Är det lätt att avgöra cyklistens hastighet med den aktuella ljusuppsättningen?
- Är det lätt att avgöra cyklistens position med den aktuella ljusuppsättningen?

Två försöksomgångar genomfördes innan det riktiga testet för att säkerställa att deltagarna förstått proceduren. Efter 21 genomförda turer (3 hastigheter * 2 monteringspositioner * 3 ljusfunktioner + 3 hastigheter utan lyse) bytte deltagarna plats så att de som stått i position A och B bytte till position C och D. Varje försöksperson deltog alltså i två bedömningsomgångar på två olika positioner.

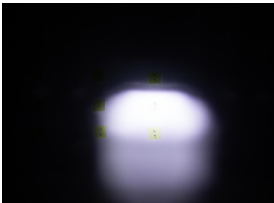
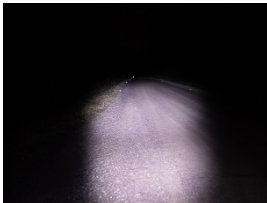
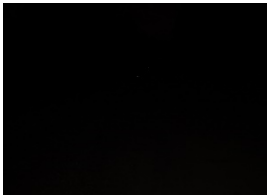
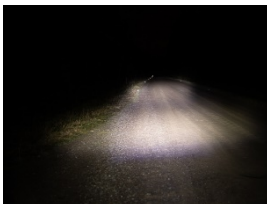
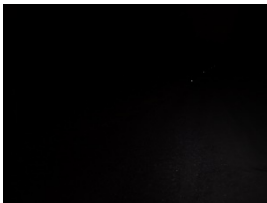
Resultat

Olika cykellysens funktion under statistiska förhållanden

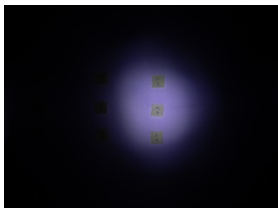
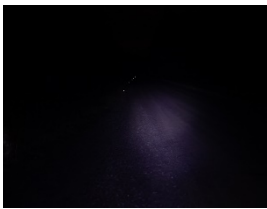
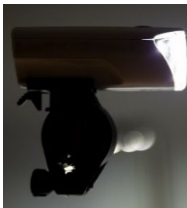
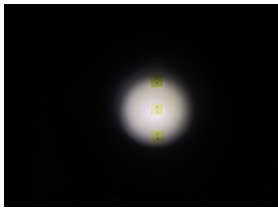
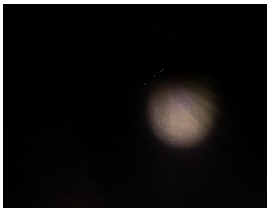
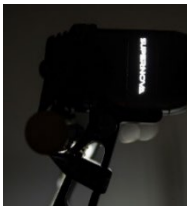
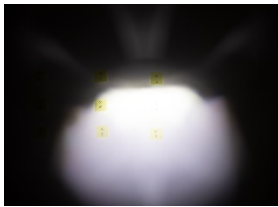
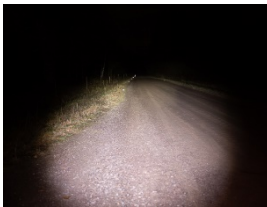
Laboratoriestudien inomhus visade på en stor variation i ljusstyrka (lux) mellan olika cykellys och mellan de olika mätpunkterna för respektive lyse – särskilt för framlysen. Även ljuskäglans form varierade genom att några lysen hade en skarp avgränsning uppåt (F1, F4, F8 och F9) med en vid ljuskägla vid marknivå i vissa fall (F4, F8 och F9), några lysen resulterade i en rund och smal ljuskägla (F6 och F7) medan andra knappt lyste upp väggen alls på 2 meters avstånd (F2, F3 och F5). Även laboratoriestudien utomhus visade på en variation i ljuskäglans form och den effekt det hade på hur väl vägytan belystes (Tabell 2).

Det går inte att direkt översätta dessa resultat till cyklisters synbarhet eller möjlighet att se i verklig trafik, men vissa slutsatser kan ändå dras. Utifrån cyklistens perspektiv är det sannolikt att ett starkare ljus också gör det lättare att se. Om ljusbilden på en vägg är starkare upptill och mörkare längre ner, är det troligt att det resulterar i ett relativt jämnt upplyst område framför cykeln eftersom ljuset högre upp har en längre sträcka att färdas innan det träffar marken, i jämförelse med ljuset längre ner från lyset. Fotografering av ljuskägla i laboratoriestudien utomhus bekräftade att så också är fallet. För medtrafikanterna är det bra om lyset inte avger så mycket ljus ovanför den starkaste punkten (och långt ut till vänster) med tanke på risken för bländning. Cykellys ska synas tydligt utan att vara bländande. De absoluta mätvärdena (lux) ger i sig ingen vägledning kring var gränsen går däremellan.

Tabell 2. Fotograferade ljuskäglor och luxvärden i ljusaste punkten för fast sken med samtliga framlysen som ingick i studien. Som jämförelse kan sägas att en yta är belyst med 0,05–0,3 lux vid fullmåne en klar natt, med 80 lux vid "normal" korridorsbelysning och med 320–500 lux vid vanlig kontorsbelysning. Fullt dagsljus utan direkt solsken ger mellan 10 000 och 25 000 lux och direkt solljus resulterar i 32 000 till 100 000 lux¹. För lysen med flera lägen visas endast värden och bilder för maxläget – för mer detaljerade uppgifter se Table 2, Table 3 och Table 4 i rapporten. Foto: Katja Kircher, VTI.

#	Framlyse märke	Foto från sidan	Läge (antal)	Ljuskägla mot vägg	Ljuskägla på väg	Max ljusstyrka mot vägg (lux)
F1	Litecco Highlux.30		Power (2)			682.6
F2	Knog Cobber		Max (2)			3.1
F3	Silva Tyto					0.9
F4	Red Pro 25 Lux					861.6
F5	Kayoba (Jula)					6.0

¹ <https://en.wikipedia.org/wiki/Lux>

#	Framlyse märke	Foto från sidan	Läge (antal)	Ljuskägla mot vägg	Ljuskägla på väg	Max ljusstyrka mot vägg (lux)
F6	Kayoba power beam (Jula)					62.0
F7	Biltema					155.2
F8	Supernova E3 Pro 2					831.6
F9	Sigma Aura 60 USB		Max (3)			1541.6

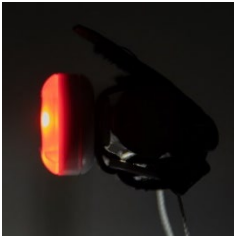
Laboratoriestudien utomhus visade att alla de utvalda cykellysena, oavsett inställning, uppfyllde gällande lagkrav genom att vara synliga från 300 meters håll. Alla försökspersoner kunde korrekt identifiera om det var ett fram- eller baklyse som var tänt alternativt att inget lyse tänts. Av totalt 256 klassificeringar av **framlysen**, gjordes missbedömningar i 16 fall (6,3 %) om huruvida ljuset var fast eller blinkande. I 13 fall klassificerades ett blinkande ljus felaktigt som rinnande och i två fall missbedömdes ett fast ljus som rinnande. Av totalt 252 klassificeringar av **baklysen**, bedömdes 29 (11,5 %) felaktigt med avseende på lysets inställning. I 12 fall var det ett fast ljus som klassificerades som rinnande och i 10 fall ett rinnande ljus som missbedömdes vara blinkande.

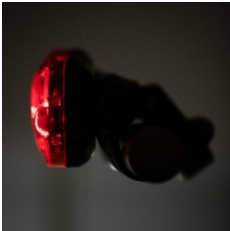
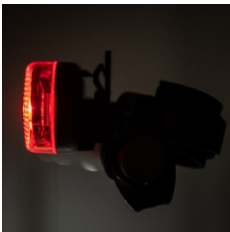
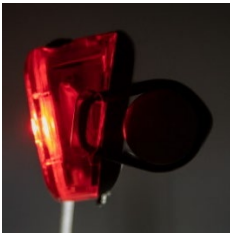
Försökspersonernas bedömningar av **framlysena** stämde ganska väl överens med fotografiernas illustration av hur bra ett lyse var utifrån en cyklists perspektiv. De uppsättningar som lyste upp vägen väl rankades högt av försökspersonerna men fick också kommentarer om att upplevas vara bländande. Framlyse F7 rankades högt med alla dess inställningar, men fotot av ljuskäglan indikerar att det sannolikt är svårt att navigera med hjälp av det lyset. De svagare lysena tenderade annars att rankas lägre och kan heller inte anses godtagbara för att kunna hjälpa cyklisten att se tillräckligt i en icke upplyst miljö. Det var ingen signifikant skillnad i rankingen av framlysen med fast ljus ($6,5 \pm 2,0$) i jämförelse med blinkande ljus ($6,3 \pm 2,1$). Eftersom enbart de svagare framlysena hade en blinkfunktion gjordes ytterligare en analys där ljusuppsättningarna delades in i starkt fast sken, svagt fast sken respektive blinkande sken. För denna uppdelning visade analysen på signifikanta skillnader

där starkt fast sken rankades högst ($6,5 \pm 2,0$), följt av blinkande sken ($6,5 \pm 2,0$) och därefter svagt fast sken ($6,5 \pm 2,0$).

Baklyset med den högst uppmätta ljusstyrkan (R7) var också det lyse som fick högst betyg av försökspersonerna i den statistiska fältstudien. Annars var det inte nödvändigtvis de baklysen med högst uppmätt ljusstyrka som rankades högst av försökspersonerna. Det kan förklaras av att det fanns skillnader mellan baklysen i ljusstyrka vid sidan av den ljusaste punkten i mitten (se Table 3 på sidan 40) och att försökspersonerna rankade blinkande bakljus något högre än fast eller rinnande ljus (fast: $5,4 \pm 1,7$; blinkande: $5,8 \pm 1,8$; rinnande: $4,9 \pm 1,9$). Relevansen av en bedömning av ett stillastående cykellyse på 300 meters avstånd kan dock ifrågasättas, i annat syfte än att undersöka om gällande lagkrav uppfylls. För en bakomliggande cyklist kan ett för starkt baklyse vara bländande och i det avseendet är en bedömning på ett betydligt kortare avstånd mer relevant. I verklig trafikmiljö ska bakljuset bidra till att en cyklist kan urskiljas bland andra tänkbara ljus i omgivningen – en egenskap vi inte utvärderat i våra studier. Våra resultat för baklysena ska alltså tolkas med försiktighet.

Tabell 3. Foton från sidan och luxvärden i ljusaste punkten för samtliga baklysen som ingick i studien. För mer detaljerade uppgifter se Table 2, Table 3 och Table 4 i rapporten. Foto: Katja Kircher, VTI.

#	Baklyse, märke	Foto från sidan	Läge (antal)	Max ljusstyrka mot vägg (lux)
R1	Litecco G-Ray			2.4
R2	Knog Cobber		Max (2)	1.9
R3	Silva Tyto			0.2
R4	Red Cycling Products			3.6

#	Baklyse, märke	Foto från sidan	Läge (antal)	Max ljusstyrka mot vägg (lux)
R5	Kayoba (Jula)			2.8
R6	Kayoba power beam (Jula)			0.3
R7	Biltema			53.2
R8	Supernova E3 taillight			0.7
R9	Sigma Nugget II		high power (2)	3.2

Demonstrationen där de studerade cykellysena fotograferades från sidan visade att det var en stor variation i synbarhet från sidan beroende på lysets design. Exempelvis syntes framlyse F1 knappt alls från sidan, trots att det gav ett mycket skarpt ljussken sett framifrån, medan framlyse F2 var designat så att ljuset var mer eller mindre lika starkt från sidan som framifrån. Andra framlysen hade en design som gjorde att de hade ett specifikt utseende sett från sidan (F8 och F9). Samtliga baklysen hade åtminstone någon synbarhet från sidan. För att utröna huruvida det är fördelaktigt med en särskild design för att signalera att det kommer en cyklist från sidan, behövs vidare studier. Här kan vi bara konstatera att det finns en stor variation mellan de testade lysena och att det sannolikt är fördelaktigt med en design som ger en viss synbarhet från sidan.

Olika cykellysens funktion under dynamiska förhållanden

Resultaten från fältstudien i trafikmiljö visade att varken ljusstyrka, ljusinställning eller monteringsposition påverkade försökspersonernas "gap acceptance". Däremot hade cykelhastigheten en signifikant effekt, där en högre hastighet innebar ett kortare "gap acceptance" mätt i tid. Den genomsnittliga "gap acceptance"-tiden minskade med 0,6 sekunder per 5 km/h, från 4,6 sekunder vid 15 km/h till 3,3 sekunder vid 25 km/h. På grund av hastighetens inverkan var det fysiska avståndet trots allt större för högre hastigheter. Det innebär att fotgängare antagligen upplever det fysiskt större avståndet som lika säkert, även om tidsluckan faktiskt blir mindre. Det fanns även ett samband mellan hastighet och monteringsposition vars praktiska betydelse bedöms som försumbar.

Enligt försökspersonernas subjektiva bedömning var "blinkande ljus" den ljusuppsättning som, förutom "inget lyse", fick den lägsta rankingen på samtliga frågeställningar. Generellt upplevdes en montering av cykellyset på framgaffeln inte lika bra som en montering på styret. Montering på framgaffeln upplevdes framförallt leda till mer bländning i jämförelse med monteringen på styret, särskilt vid blinkande ljus. En montering av cykellyset på styret underlättade också möjligheten att identifiera att det var en cyklist som kom. Hastighets- och avståndsbedömning påverkades däremot inte av monteringspositionen. De olika cykelhastigheterna påverkade inte den subjektiva bedömningen nämnvärt. Däremot hade deltagarnas position betydelse eftersom den omgivande belysningen skilde sig märkbart med starkare belysning i position C och D i jämförelse med position A och B. På de mörkare positionerna var det svårare för deltagarna att känna igen den ankommande cyklisten och där upplevde de också att de blev bländade i större utsträckning.

Den faktor som påverkade den subjektiva bedömningen mest var typen av cykellyse och därmed ljusinställningen. Det starka och fasta ljuset rankades högst följt av svagt fast ljus. Ett cykellyse med starkt och fast ljus monterat på styret upplevdes göra det lättare för deltagarna att bedöma den ankommande cyklistens hastighet. Detsamma gällde för avståndet till cyklisten. Det starka och fasta ljuset upplevdes inte leda till mer bländning än det svaga fasta ljuset. Några av deltagarna kommenterade att bländningen i regel (gäller inte den aktuella studien) påverkas mer av hur cykellyset är monterat snarare än av typen av lyse. Det var också något vi kunde visa i en av de genomförda demonstrationerna. Två framlysen filmades då de vinklades från korrekt läge, riktade nedåt mot marken, uppåt till att vara riktade parallellt med marken. I filmen kan man tydligt se att bländning sker när lysena är riktade uppåt medan ett korrekt vinklat lyse inte leder till bländning även om ljusstyrkan på lyset är starkt. Demonstrationerna kan hittas i en film, under rubriker som inleds med "Test av cykellysen"².

Deltagarna i fältstudien kommenterade vidare att cykellyset med det starka fasta ljuset lyste upp vägytan framför cyklisten vilket underlättade bedömningarna. Det blinkande ljuset däremot kritiserades av deltagarna för att det gjorde det svårare att bedöma hastighet och avstånd till cyklisten, samt att det var bländande och allmänt irriterande.

Diskussion

Reflektioner kring erhållna resultat

Starkt fast sken på framlyset var det som rankades högst av försökspersonerna och är även bäst ur cyklistens perspektiv då det bättre lyser upp vägytan. I våra studier upplevdes inte det starkare lyset som mer bländande än det svagare med fast sken, men det är möjligt att det finns en övre gräns för ljusstyrkan med avseende på vad medtrafikanter tycker är acceptabelt. Var den gränsen går är oklart men tycks inte ha överskridits med de lampor som vi inkluderade i vår studie. Värt att notera är att bländningen påverkas av vinkeln på lyset, så genom att vinkla ner lyset vid möte kan risken för

² <https://www.youtube.com/playlist?list=PLW8KqekouZadA82qeGzhqTUc-M9KhaVUH>

bländning minskas avsevärt även med ett starkt lyse. En montering av cykellyset på styret tycks vara att föredra framför en montering på framgaffeln eftersom försökspersonerna då lättare upptäckte och ”kände igen” cyklisten. Det finns också en del praktiska fördelar med en montering på styret som exempelvis att lyset inte skymms av hjulet eller att hjulet därmed inte kastar någon skugga i cyklistens synfält.

Utifrån demonstrationerna genomförda i projektet är vår spontana reflektion att det är bra med ett lyse som också har ett specifikt utseende sett från sidan, men det är inget vi kunnat verifierat i mer vetenskapliga studier.

Trots att blinkande sken på framlyset uppfattades bättre än ett svagt fast sken kritiserades det av deltagarna i den dynamiska fältstudien för att det gjorde det svårare att bedöma hastighet och avstånd till cyklisten, samt att det var bländande och allmänt irriterande. Försökspersonerna i den statiska fältstudien var mer positiva till det blinkande ljuset. Det kan naturligtvis bero på skillnader i individuella preferenser mellan de olika försöksgrupperna men skulle också kunna förklaras av att det blinkande ljuset, i verklig trafikmiljö med fler intryck, innebär en oönskad ”överbelastning”. Även för baklyset kan blinkandet vara irriterande för cyklister som följer efter, samt att det antagligen försvårar positions- och hastighetsbedömningen. Det är emellertid inget vi studerat vetenskapligt men utifrån demonstrationsstudierna tycks så vara fallet.

Det är anmärkningsvärt att de olika ljusuppsättningar som testades i fältstudien inte påverkade försökspersonernas ”gap acceptance”, inte ens de scenarier då cyklisten cyklade utan lyse. Detta trots att den subjektiva bedömningen visade på en klar negativ uppfattning av cykling utan lyse. För cykelhastighet är förhållandet det omvända – hastigheten påverkade inte den subjektiva bedömningen men var den faktor som hade störst betydelse för ”gap acceptance”. Det här innebär att enbart fråga personer om deras uppfattning av olika ljusuppsättningar inte ger tillräcklig information om de funktionella egenskaperna hos ett cykellyse.

De motsägelsefulla resultaten mellan subjektiv bedömning och det faktiska beteende väcker frågan om de mäter olika saker, om personer i allmänhet har svårt att göra subjektiva bedömningar relaterade till trafiksäkerhet (som beskriver deras möjlighet att interagera i trafiken) eller om det finns andra faktorer som förklarar denna inkonsekvens. Det kan vara så att komfortfaktorer eller sociala normer har större betydelse för den subjektiva bedömningen – ett blinkande ljus kanske upplevs mer obehagligt och att cykla utan lysa ogillas eftersom det är olagligt.

Det minsta acceptabla tidsutrymmet i studien var omkring 2 sekunder, utan någon egentlig koppling till typen av lyse. Vid 25 km/h innebär det ett avstånd på ungefär 14 meter till den ankommande cyklisten. Det är lite oroväckande att deltagare tror att de kan bedöma cyklistens hastighet och avstånd korrekt samtidigt som det inte avspeglar sig i det tidsutrymme som de anser är tillräckligt för att hinna passera. Eftersom stoppsträckan ökar med kvadraten på hastigheten, behövs ett större tidsutrymme vid högre hastigheter för att erhålla samma säkerhetsmarginal - något som försökspersonerna i vår studie inte verkade ta hänsyn till. Eftersom ljusuppsättningen inte tycktes påverka deltagarnas minsta acceptabla tidsutrymme behövs andra sätt att underlätta bedömningen av cyklisters hastighet. Det blir alltmer viktigt i och med att andelen elcyklar ökar vilket också kan innebära en ökad sannolikhet för höjda medelhastigheter.

Olika metoders tillämpning för att jämföra olika cykellysens funktion

Sammantaget visar resultaten att de metoder som använts i projektet har kompletterat varandra på ett bra sätt och kunnat visa på skillnader mellan de testade cykellysena.

Den typ av laboratoriestudie inomhus som vi gjorde är relativ enkel och billig att genomföra. Det som krävs är en luxmätare, ett mörkt rum och en kamera för att fotografera ljusspridningen. Det resultat som erhålls är den absoluta ljusstyrkan för olika positioner i ljuskäglan, liksom en bild av ljuskäglans form. För blinkande ljus kan den genomsnittliga ljusstyrkan beräknas genom att multiplicera den

uppmätta ljusstyrkan vid fast sken med andelen tid (i procent) som ljuset är på vid en blinkande inställning.

Den stora variationen i ljuskäglornas form (ljusspridningen) som i vissa fall visar på en kraftig gradient med minskande ljusstyrka, visar att luxmätningar bör kompletteras med en illustration av ljusflödet som indikerar var mätningen är gjord. Ett fotografi av ljuskäglornas form mot en vägg ger en god indikation om hur väl ett framlyse belyser vägytan för en cyklist. En statisk laboratoriestudie som denna ger emellertid ingen information om eventuella för- eller nackdelar med blinkande eller pulserande ljus eller om effekterna av rörelse. För det krävs någon typ av fältstudie, där en dynamisk studie i verklig trafikmiljö är att föredra eftersom den tar hänsyn till fler faktorer än en statisk fältstudie.

Det faktum att deltagarna i fältstudien i verklig trafikmiljö gjorde olika bedömningar till följd av monteringsposition och typen av lyse visar att man har tydligt olika uppfattningar av olika cykellysens/ ljussuppsättningar. Metoden var således relevant för att påvisa skillnader mellan olika typer av cykellys och båda delarna i studien, såväl den subjektiva bedömningen som ”gap acceptance”, tillförde värdefull information.

Upplägget för utvärdering av baklysen som ingått i vår studie är egentligen alltför enkelt för att kunna dra några tillförlitliga slutsatser kring lysenas funktionella egenskaper och det finns en risk att resultaten är vilseledande. Vid en statisk synbarhetsbedömning rakt framifrån, på 300 meters håll, är det inte förvånande att det lyse som syns mest får högst betyg. På närmare avstånd kan emellertid ett sådant lyse vara bländande och från en annan vinkel kan det vara andra egenskaper som är av värde. Liksom nämnts tidigare hade det alltså varit värdefullt att utvärdera även baklysena i en studie i faktisk trafikmiljö med en cyklist i rörelse. Att designa ett sådant försöksupplägg var dock alltför komplext i förhållande till projektramarna i den här studien, men det vore värdefullt om ett sådant upplägg kunde utvecklas och testas i en uppföljande studie.

Slutsatser

Alla cykellysena oavsett inställning uppfyllde våra gällande lagkrav att vara synliga på 300 meters avstånd. Alla hade också ett läge med fast sken, vilket motsvarar lagkravet. De var främst de svagare, billigare lamporna som hade en blinkande funktion, vissa med många olika blinklägen (kanske främst som en kul effekt). Flera av dem blinkade långsammare än 200 gånger per minut, vilket innebär att de inte uppfyller gällande lagkrav.

De bästa cykellysena

Starka framlysen med fast sken – helst med en ljuskägla med skarp avgränsning uppåt och vidare spridning vid marknivå – är sammantaget den typ av lyse som ger bäst förutsättningar för en cyklist att synas och att kunna se. Framlysena ska monteras på styret för bästa möjliga igenkänning och riktas någon nedåt för att undvika bländning.

Även för baklysena är ett starkt fast sken ett vinnande koncept. Skillnaderna mellan baklysena var emellertid inte lika märkbara och eftersom de inte heller utvärderades i den dynamiska fältstudien är det en mer osäker slutsats.

Utvärderingsmetoder

De metoder som använts i projektet har kunnat visa på skillnader mellan de testade cykellysena. En laboratoriestudie inomhus är enkel och billig att genomföra, men ger bara viss information. Den bör därför kompletteras med fältstudier med en cyklist i rörelse i verklig trafikmiljö som innefattar både subjektiva bedömningar och beteendestudier som exempelvis ”gap acceptance”.

Rekommendationer

Tips till cyklisten

Även enkla och billiga cykellysen uppfyller gällande lagkrav. Däremot är det bra för dig som cyklist att ha ett starkt framlyse med fast sken med en ljuskägla som ger en vid spridning i marknivå eftersom det gör det lättare för dig att se omgivningen och upptäcka hinder och skador i vägytan. Vi rekommenderar en ljusstyrka på minst 500 lux (mätt på 2 meters avstånd från lampan). För att inte blända dina medtrafikanter bör lyset ge en ljuskägla med skarp avgränsning uppåt och riktas något nedåt. En montering av framlyset på styret är att föredra. Undvik blinkande ljus – det gäller såväl framlyse som baklyse. Se ett filmklipp som bland annat demonstrerar bländning och betydelsen av cykellysets placering (under rubriker som inleds med "Test av cykellysen")³.

Tips till handeln och genomförare av konsumenttest

Eftersom ljuskäglans form har stor betydelse för funktionaliteten hos ett framlyse vore det värdefullt om cyklist kunde få information om detta inför ett potentiellt inköp av cykellyse. Exempelvis skulle de cykellysen som saluförs i en butik kunna sättas upp för demonstration innan köpet. Med en schablon som hålls upp på ett visst avstånd framför ett cykellyse skulle betydelsen av ljuskäglans form kunna illustreras. Ljuskäglans form från ett framlyse bör alltid ingå i konsumenttest av cykellysen

Reflektioner till lagstiftare och kravställare

Det kan ifrågasättas om lagkravet att ett cykellyse ska ses från 300 meters avstånd verkligen är relevant. Ett cykellyses egenskaper på närmare avstånd har större betydelse. Det är också svårt att utvärdera och följa upp ett krav som gäller för ett så långt avstånd, utan det vore bättre att ställa krav på en viss ljusstyrka som kan följas upp med en enkel mätning i labbmiljö. Det vore också önskvärt med tydligare specifikationer i lagkraven, baserade på vetenskapliga studier, så att kraven omfattar egenskaper som har faktiskt betydelse för trafiksäkerheten.

Fortsatt forskning

I det här projektet har vi genomfört ett begränsat antal utvärderingar och det finns mycket mer som hade varit intressant att studera och många fler aspekter som är av betydelse. Vi har i våra studier exempelvis inte inkluderat det praktiska handhavandet/användarvänligheten vilket kan ha betydelse för om en cyklist har lyse eller inte. Med tanke på risken för stöld bör ett cykellyse antingen vara fast installerat på cykeln eller mycket enkelt att montera loss och ta med. En god tillförlitlighet är också viktigt liksom miljöaspekter som material och energiförbrukning.

Vidare studier behövs för att utveckla och testa metoder för utvärdering av baklysen i faktisk trafikmiljö med en cyklist i rörelse. En sådan studie skulle exempelvis kunna innefatta bilförare i bil som närmar sig en cyklist från olika vinklar och avstånd. Det behövs också fortsatt forskning för att på djupet studera upptäckbarhet i förhållande till synbarhet i en situation där en cyklist förväntas komma, samt kring trafikanters förutsägelse av medtrafikanters intentioner.

För en djupare förståelse, bland annat som underlag till eventuella förändringar av lagkraven, finns en mängd studier som också vore värdefulla att genomföra. Följande är några exempel:

- Ytterligare tester i trafikmiljö, för att bland annat studera vad som krävs för att en cyklist ska synas där det finns bakgrundsljus och andra lyktor.
- Studera cykellysets betydelse för upptäckbarhet, synbarhet och igenkänning utifrån olika trafikantperspektiv: bilförare, lastbilsförare, cyklist eller fotgängare.

³ <https://www.youtube.com/playlist?list=PLW8KqekouZadA82qeGzhqTUc-M9KhaVUH>

- I vilka situationer finns risk för bländning från cykellysen för olika trafikantgrupper?
- Cykellysens placering och egenskaper beroende av typen av cykelfordon. Exempelvis placering av lysen på lådcyklar för att i mörker lättare kunna avgöra deras bredd.
- Betydelsen av ljusstyrka, vinkel och ljuskäglans form för att bäst upptäcka potthål eller andra skador i vägytan; för avläsning av vägmärken; för risken för bländning.
- Cykliststudier i trafikmiljö för att studera hur långt framför sig en cyklist behöver se i olika situationer, exempelvis för att kunna undvika olyckor till följd av ojämnheter, is, grus etc.; för att kunna se vägmarkeringar, vägmärken och i tid upptäcka andra trafikanter eller fasta hinder.

1. Background

Lighting on a vehicle in darkness serves two purposes – to see and to be seen. In areas without external illumination, a headlight is necessary to see where one is going. This is self-evident and applies to any road transport mode. However, a vehicle should also be visible and recognisable to other road users, which is an important precondition for smooth and safe interactions. For this purpose, lights and reflectors can be used. Here, we focus solely on lights, investigating both vision and visibility.

These two purposes do not necessarily require the same type of light setup. To see, the area in the direction of travel needs to be illuminated with a light source that is bright enough for the travel speed and covers the relevant area in front. It is advantageous if potholes, edges, and other obstacles can be identified, and if other road users – especially those without own lighting – are noticed and identified in time. Also, relevant signage and other information should be discernible and readable in time. To be seen, the vehicle should be discernible from all angles from which it can be approached. It also helps if the future trajectory of the vehicle can be predicted. It is an international standard to use white or, in some countries, yellow lights for the front (this light usually serves both the purpose to see and to be seen), and red lights for the rear. The latter are solely intended for the purpose to be seen, and it is conventional and required at least for motor vehicles to indicate a speed reduction through braking by increasing the brightness of the rear light. The arrangement of lights can also aid in recognising the type of vehicle. Cars usually have two lights in the front and two in the back, demarcating the outer edges of the vehicle, with a centre high mount brake light. Trains have three front lights in the shape of a triangle. Bicycles are required to have at least one front light and one rear light in darkness.

1.1. Earlier studies regarding bicycle lighting

While it is notoriously difficult to obtain reliable figures on bicyclist prevalence both for location and time of day, there are indications that crashes resulting in a bicyclist fatality are more frequent in darkness than in daylight (ADFC Allgemeiner Deutscher Fahrrad-Club, European Cyclists' Federation, & Fietserbond NL, 2012; Cairney, 1998; Mazharul Hoque, 1990; Twisk & Reurings, 2013). While factors like expecting a cyclist to be present and a driving speed adequate for the conditions are likely to play a role (Rogé et al., 2017), enhanced visibility and recognisability of the cyclist might be assumed to be beneficial, even though no clear evidence for a connection between bicycle lighting and traffic safety could be established, possibly due to a lack of pertinent data (ADFC Allgemeiner Deutscher Fahrrad-Club et al., 2012). A large New Zealand study found factors like cycling in urban areas and also where cycling is less common to increase crash risk, with visibility enhancement having no effect (Tin Tin, Woodward, & Ameratunga, 2013, 2014). A Danish study, on the other hand, found that bicycle lighting during daytime could reduce the overall accident frequency with 19 per cent and the number of collisions with 47 per cent (Madsen, Andersen, & Lahrman, 2013).

Analyses of Swedish accident data show that darkness was a contributing factor in one per cent of single bicycle crashes recorded in Strada⁴, according to subjective accident descriptions (Niska & Eriksson, 2013). However, by considering the time of the accidents and defining “darkness” as the sun being 6 degrees below the horizon, it was found that 20 per cent of single bicycle crashes and 13 per cent of cyclists colliding with another counterpart occurred during darkness. No information regarding the use of bicycle lighting could be found in the database. Due to the lack of data no accident risks could be calculated, but a travel survey performed in 1995-1997 (Thulin & Kronberg, 1998) indicates a 17 per cent share in darkness of the cycling frequency in Sweden. Other Swedish studies conclude that cyclists often perceive bicycle lighting to be insufficient, both for seeing and to be seen properly (Fors & Nyghårds, 2010). Especially during wet road conditions cyclists believe that it is difficult for

⁴ <https://www.transportstyrelsen.se/sv/vagtrafik/statistik/Olycksstatistik/om-strada/>

car drivers to see them. Cyclists also state that bicycle lights do not provide enough lighting to discover potholes and other road deficiencies (Niska, 2007).

Some studies which evaluated bicycle light visibility do not usually make a direct connection to crash occurrence. In a setting with static cyclists in a naturalistic environment, Cairney (1998) found a flashing taillight to perform well in a cluttered environment and in a dark environment, meaning that it could be seen from a large distance. Also for headlights, a flash mode was identified as having a higher visibility than its steady counterparts, but generally headlights were seen later than taillights, in spite of their generally higher luminosity. Like Cairney, Edewaard (2017) used cyclists pedalling on a stationary trainer. She, too, found flashing lights to be visible from a greater distance than steady lights, but the highest conspicuity was achieved with steady lights on the cyclist's heels, with the cyclist pedalling. The average brightness of the flashing light in the study was the same as for the steady light, meaning that it was several times brighter while on, as the off-period was longer than the on-period. Neither of the studies investigated the ability to judge distance. Importantly, in both studies the cyclist was stationary, such that the bicycle did not move relative to the background. Toet, Beintema, de Vries, van der Leden, and Alferdinck (2008) investigated the visual angle and the distance at which a bicycle light was recognised as such in different situations and different environments. They concluded that the effect of flashing lights depended on the situation – flashing front lights improved conspicuity in urban environments, whereas a flashing rear light in a rural environment rather led to diminished conspicuity when approached from behind. The authors discuss the difficulty of reliable measurements in dynamic settings and chose to opt for static bicycle lights and a moving test vehicle. Further results from this study include that brighter lights tend to increase the angle at which a light was recognised (however, this was 2008 – today's lights can be much brighter, and it has yet to be determined whether this relationship has an upper boundary), and that it did not matter for conspicuity whether the light was attached to the bike or the cyclist's clothing, as long as it was not covered or hidden due to posture variations. Lastly, it was found that conspicuity was influenced by how the lamp was mounted – slanted or angled positioning diminished the functionality of the light.

All above mentioned studies used stationary cyclists or stationary bicycle lights and moving observers (usually in cars) for their assessments. The recognition distances or angles can provide an indication for which lamp or lamp setup might be better than another, if it can be assumed that farther is better. However, it might also be the case that there either is a threshold above which increased recognition distances/angles do not improve the situation, and this threshold may very well be related to the relative speed between the two road users.

When it comes to the predictability of a bicyclist's path, Walker and Brosnan (2007) found that drivers tend to seek out the cyclist's face to make eye contact. Again, the study was conducted with photographs as stimulus material, but it can still be speculated that intention prediction in the dark must be more difficult than in daylight. Westerhuis and de Waard (2017) used video material of a cyclist filmed from behind for an online survey on intention prediction, finding that predictions were no better than chance. The participants indicated which cue(s) they used for prediction. Depending on whether the cyclist was turning or going straight, the cues proved to be of varying value. Head movements were predictive for left turns, speed was predictive for going straight, and for turning right a change in speed was the best cue, but not many people indicated using it. Another video-based study with a viewpoint from slightly above an intersection corroborated this – head movements were associated with correct predictions of turns and speed with correct predictions of going straight on (Hemeren et al., 2014).

1.2. Regulations for bicycle lighting

There are standards for vehicle lights, and in many countries the lights get tested on a regular basis as part of the mandatory vehicle inspection. Requirements for bicycle lights vary widely between

countries, and the lights sold in a country do not necessarily meet the local requirements. A list of regulations for a number of European countries from 2012 is provided by ADFC Allgemeiner Deutscher Fahrrad-Club et al. (2012). For Sweden, according to the Swedish Transport Agency⁵ the current (2020) legal visibility requirements in darkness for cyclists are:

- a rear light emitting red light backwards, which can be seen clearly from a distance of 300 m
- the rear light is allowed to flash, provided that the frequency is at least 200 flashes per minute
- a front light emitting white light with such power that the bicycle can be ridden safely in darkness, or a front light which emits white or yellow light forward, which can be seen clearly from a distance of 300 m
- If the front light is of the type that it can blind other road users, it must be possible to dim the light quickly
- red reflector rearward
- white reflector forward
- white or amber reflector sideways

It is not specified, however, whether the lights should be “clearly” visible in darkness or daylight, in an otherwise dark area or in a lit urban environment, and what “clearly” means. The distance of 300 metres is not motivated either, and it is not explained what “riding safely” means. It is not specified how the lights should be powered.

Lights flashing at lower frequencies are not permitted, even though they are used frequently, mostly as rear light but also as front light, and on cyclist forums arguments can be found both for and against continuous and flashing lights. Typical arguments are that flashing lights attract more attention but make distance judgements more difficult and can be distracting and disturbing, especially if they are very bright.

The country with one of, if not the most specific prescriptions for bicycle lighting is Germany: Lights have to be mounted in darkness and under dim lighting conditions. The white front light must be mounted at a height of between 40 cm and 120 cm. A second front light is allowed, and both can be powered by either dynamo or batteries. The front light is not allowed to flash or to dazzle other road users, but interestingly, no minimum (or maximum) requirement for brightness is given. A daylight running light and a high beam are specifically allowed, but the high beam must be dimmable quickly. The red rear light may be powered by a dynamo or batteries and must be mounted at a height of 25 cm to 120 cm. If both the front and the rear light are powered by a dynamo, they must have one common switch. A brake light function is specifically allowed, and the light is not allowed to flash. Direction indicators for bicycles are specifically prohibited.

1.3. Bicycle light tests

An abundance of different bicycle lights exists on the market, and the price range is huge, from virtually free to several hundred Euros. Shape, power, beam shape, mounts, material and other features vary. Typically, dynamo powered lights are mounted steadily to the bike, while most battery powered lights can be removed.

When assessing the quality of a bicycle light, there are a host of aspects to consider. First and foremost, it should be guaranteed that it fulfils its main purpose, which is to make the cyclist visible to

⁵ https://www.transportstyrelsen.se/TSFS/TSFS%202009_31k.pdf

others and, in many cases, to help the cyclist see. In addition to this, robustness, ease of mounting, battery life, stability and price are just a few of the factors that could be included in an evaluation.

Consumer magazines and other interest groups are typical candidates for publishing bicycle light tests. As there are no standard procedures, they usually choose their own performance indicators and benchmarks, and they select themselves which lamp types and brands to investigate. On Youtube⁶, numerous bicycle light tests and recommendations can be found. However, they are often based on subjective opinions rather than on scientific results and can be sponsored with a risk of being biased.

An Austrian test⁷ was conducted by riding over cobblestone with the light mounted to the bike. Measures like mounting, user interface, brightness, duration to fully charged, dazzle and water resistance were tested, but the test method is not described, and results are hidden behind a pay wall. No information is provided on how the tested lamps were selected. For the German speaking market, the consumer organisation “Stiftung Warentest” conducted a test in 2013⁸. While the results are not relevant for today’s market, given the now widespread use of LED lamps, it is noteworthy that the test procedure is described in some detail. Also, in this test several aspects relating to handling, brightness and durability were investigated.

The Swedish site Inspekto collected and presented results from different tests⁹, and the company Testfakta conducted their own test of bicycle lights in 2013¹⁰. The test procedure was not described in any detail. Testing included handling, durability after having been dropped, and the shape of the light beam. Further consumer tests were made, but generally without a useful description of the test method used¹¹.

⁶ <https://www.youtube.com/watch?v=w4d5O4O8TxU>

⁷ <https://www.konsument.at/test-fahrradbeleuchtung-112018>

⁸ <https://www.test.de/Fahrradbeleuchtung-Dynamo-oder-Batterie-4597096-0/>

⁹ <https://inspekto.se/cykelbelysning/>

¹⁰ <https://www.testfakta.se/sv/sport-fritid/article/basta-lampan-till-cykelfarden>

¹¹ <https://www.adac.de/rund-ums-fahrzeug/tests/fahrrad/fahrradlicht-test/>; <https://www.t3.com/features/best-bike-light-front>

2. Aim and delimitations

The aim of this project was to illustrate the breadth and variation of bicycle lights that are available on the Swedish market and to investigate to which extent they fulfil the legal requirements for bicycle lighting. Furthermore, the project aimed to develop methods such that different generic features of bicycle lights can be evaluated and compared in a scientific way. The strengths, weaknesses and application areas of the different methods are discussed, too. Further, we assessed how well different types of bicycle lights can help the cyclist to see, be seen and recognised as a cyclist, and whether the lights contribute to a reliable distance estimation.

Given the fact that bicycle lights undergo continuous developments and quickly become outdated, we did not focus on particular manufacturers and their lamps, but rather on generic features like brightness, beam shape, flashing versus steady beam and mounting position, based on a selection of bicycle lights on the market. The situations selected here were static light tests and a dynamic situation with a cyclist approaching a pedestrian from the side. The focus in this project was on lamps, therefore retroreflective materials were not investigated.

2.1. Method considerations

The used test procedure can influence the resulting ranking of the tested lights. There is no standard procedure for testing bicycle lights, and there are no scientifically proven standards as to what should be required of a good bicycle light setup. Given that different countries have different requirements, which are not always phrased in a way that they lend themselves to easy operationalisation, using them is not straightforward either. The ultimate goal should be to develop a method with which it can be tested reliably that a given lighting setup is above a certain threshold in providing information about a cyclist's presence and the relative position to the observer and heading, even though the observer did not know beforehand that he or she might encounter a cyclist.

Bottom-up conspicuity and the recognisability of objects is heavily influenced by motion. This is beautifully illustrated in a film by the BioMotion Lab¹². Both motion relative to a lit background (e.g. a bicycle that moves along an inner-city street) and the motion pattern of the light itself (e. g. a light attached to a seat post as compared to lights attached to the cyclists' feet, which can either be pedalling or resting, see also Edewaard, 2017) influence conspicuity and provide cues about the vehicle in question. Thus, testing light setups only under static conditions may miss important factors. Not considering a placement on the rider's body, as this placement does not conform to the rules stipulated in many countries, may lead to an exclusion of the most efficient setups to begin with. Consequently, regulations are unlikely to be changed, which likely prevents a development of improved lighting setups.

Typically, the test persons are aware that they should be on the lookout for cyclists. This influences their search pattern and makes them more prone to notice cyclists and their lighting than if they had not received such a cue. An ideal test procedure would include a situation where the test person is not primed for a top-down search for cyclists.

¹² <https://www.youtube.com/watch?v=1F5ICP9SYLU>

3. Test Overview

Table 1 illustrates which generic light factors were either investigated or demonstrated within the project. The demonstration was included for factors of interest, which could not be included as proper independent factors within the scope of the present project, but which, nonetheless, are deemed to be of importance and hold potential for future studies.

Table 1. Overview of which factors were investigated in which of the tests and how. f: front light; r: rear light.

		lab indoors	lab outdoors	field	demo
1	height/ mounting	-	-	f: handlebar vs. fork	f: mounting angle and blinding f: mount backwards (illuminating cyclist) f: capacity to illuminate (from cyclist's perspective)
2	brightness	f, r: lux measured in nine points	f, r: subjective assessment	f: verbal comment, independent factor for 6, 7	
3	flash/steady	-	f, r: subjective assessment	f: verbal comment, independent factor for 6, 7	r: from following cyclist's perspective (different patterns)
4	light field	f: photograph	f: photograph	-	f: different designs
5	visibility	-	f, r: identification of light type	f: gap acceptance	f, r: side visibility
6	recognisability	-	f, r: subjective assessment	f: verbal comment	f: mount backwards (illuminating cyclist) r: biomotion
7	trajectory estimation	-	-	f: gap acceptance	
8	lamp design	f, r: photograph	-	-	f, r: side visibility

3.1. Which lights to test?

We intended to develop a method for a meaningful test of bicycle lights, while at the same time applying the method to a number of lights as a first orientation about how they perform, and to investigate whether the suggested test procedures can differentiate between different lights. For these purposes, a wide range of different lights is desirable, as this increases the likelihood of detecting differences in performance indicators.

It was decided to test newly acquired lamps with fully charged power sources, ruling out differences that might have occurred by wear and tear as well as half-drained batteries. The lamps were selected to represent the whole range from very cheap products available in any convenience store, over mid-range lights typically available in bicycle stores and at on-line bicycle retailers, to high-end products, which can usually be acquired from dedicated stores. In addition to a wide range in retail prices, we opted for a variation in design. *Table 2* shows the selection of lamps that were used for the method development, and which were tested in the different method development steps.

Table 2. Overview of the lamps and their modes used for the method development. The information in the table shows what the manufacturer printed on the packaging. Note that there is no “standard labelling” which makes it difficult to compare the lights based on that information. Price segment (for front and rear light together): low: up to around 20 €; med: around 20 € to 60 €; high: above ca. 60 €. Lumen: Quantity of visible light emitted by a source per unit of time. Lux: Lumen per square metre.

		Lamp brand	name	bulb type	charge method	battery type	run time	lux	lumen	visible angle	visibility distance	sight distance	weight	mode	price segment
front lights															
1	F1	Litecco	Highlux.30	LED	USB	Lithium Polymer	2.5 h	30		220	1000 m	60 m	55 g	power	med
2	F1	Litecco	Highlux.30	LED	USB	Lithium Polymer	2.5 h			220			55 g	eco	
3	F2	Knog	Cobber	LED	USB		1.5 h		110	330	800 m			max	med
4	F2	Knog	Cobber	LED	USB		4 h			330				mid	
5	F2	Knog	Cobber	LED	USB		10 h			330				flash	
6	F2	Knog	Cobber	LED	USB		60 h			330				eco flash	
7	F3	Silva	Tyto	LED	battery	2x CR2032	24 h						12 g	on	low
8	F3	Silva	Tyto	LED	battery	2x CR2032							12 g	flash	
9	F4	Red	Pro 25 Lux urban led set	LED	USB			25						on	med
10	F5	Kayoba (Jula)		LED	battery	2x CR2025								on	low
11	F5	Kayoba (Jula)		LED	battery	2x CR2025								flash	

		Lamp brand	name	bulb type	charge method	battery type	run time	lux	lumen	visible angle	visibility distance	sight distance	weight	mode	price segment
12	F6	Kayoba (Jula)	power beam	LED	battery	3 x AAA								on	low
13	F6	Kayoba (Jula)	power beam	LED	battery	3 x AAA								fast flash	
14	F6	Kayoba (Jula)	power beam	LED	battery	3 x AAA								slow flash	
15	F7	Biltema		LED	battery	3 x AAA	5 h							on	low
16	F7	Biltema		LED	battery	3 x AAA								fast flash	
17	F7	Biltema		LED	battery	3 x AAA								pulse flash	
18	F8	Supernova	E3 Pro 2	LED	dynamo				205				110 g (without clamp)	on (and DRL)	high
19	F9	Sigma	Aura 60 USB	LED	USB		10 h	60				70 m		max	med
20	F9	Sigma	Aura 60 USB	LED	USB									med	
21	F9	Sigma	Aura 60 USB	LED	USB									low	
rear lights															
22	R1	Litecco	G-Ray	LED	USB	Lithium Polymer	up to 12 h			220 deg	up to 2000 m		44 g	on	med
23	R2	Knog	Cobber	LED	USB		1.4 h		30		800 m			max	med
24	R2	Knog	Cobber	LED	USB		3.5 h		10					mid	

		Lamp brand	name	bulb type	charge method	battery type	run time	lux	lumen	visible angle	visibility distance	sight distance	weight	mode	price segment
25	R2	Knog	Cobber	LED	USB		3.0 h		45					steady pulse	
26	R2	Knog	Cobber	LED	USB		7.0 h		50					flash	
27	R2	Knog	Cobber	LED	USB		40 h		10					eco flash	
28	R3	Silva	Tyto	LED	battery	2x CR2032	24 h						12 g	on	low
29	R3	Silva	Tyto	LED	battery	2x CR2032							12 g	flash	
30	R4	Red	Pro 25 Lux urban led set	LED	USB			25						on	med
31	R5	Kayoba (Jula)		LED	battery	2x CR2025								on	low
32	R5	Kayoba (Jula)		LED	battery	2x CR2025								flash	
33	R6	Kayoba (Jula)	power beam	LED	battery	3 x AAA								on	low
34	R6	Kayoba (Jula)	power beam	LED	battery	3 x AAA								flash 1	
35	R6	Kayoba (Jula)	power beam	LED	battery	3 x AAA								flash 2	
36	R7	Biltema		LED	battery	2 x AAA	5 h							on	low
37	R7	Biltema		LED	battery	2 x AAA	5 h							fast flash	
38	R7	Biltema		LED	battery	2 x AAA	5 h							slow flash	

		Lamp brand	name	bulb type	charge method	battery type	run time	lux	lumen	visible angle	visibility distance	sight distance	weight	mode	price segment
39	R8	Supernova	E3 Tail Light 2	LED	dynamo								18 g	on	high
40	R9	Sigma	Nugget II	LED	USB		7 h				400 m			standard	med
41	R9	Sigma	Nugget II	LED	USB		3 h				400 m			high power	
42	R9	Sigma	Nugget II	LED	USB		8 h				400 m			high power flash	

4. Laboratory test indoors

Nine front and nine rear lights were tested. All lights were bought for the purpose of the study, such that all would be new when tested. The goal was to achieve diversity in price and design.

All lamps were powered by either fresh batteries or, in case of dynamo-driven lights, with an external power source connected to the cable, to simulate sufficient and stable input from a dynamo. We aimed for ideal conditions both for easy replicability and to ensure that the lamps are tested for their best performance. It can be expected that performance will degrade both with increasing age of the lamp and the batteries, but this process would have to be investigated for each individual lamp.

A front light should ideally not spread much light upwards, as this will produce glare and disturb oncoming traffic. This is more important the stronger the lamp is. Sideways and downwards, a homogeneous distribution of the light is desirable, such that a wider area in front can be seen reliably by the cyclist. For comparison, a surface is illuminated with 0.05-0.3 lux¹³ in full moon on a clear night, with 80 lux in an office building hallway, and with 320-500 lux in typical office lighting. Full daylight without direct sun ranges from 10 000 – 25 000 lux and direct sun yields 32 000 to 100 000 lux¹⁴. Theoretically, the brightness in lux decreases with the square of the distance, but fog or other particles in the air additionally reduce brightness.

There are no particular requirements on the light field of a rear light, as its main purpose is to be seen from behind and, in some traffic situations, from the sides.

4.1. Method

Laboratory-style measurements were taken in a large hall without any illumination except for an emergency-exit sign and the screen of a laptop computer.

Each lamp was mounted on a tripod such that the brightest central area of the light field, according to the visual judgement of two experimenters, was directed at a pre-defined point (X respectively point 6 in *Figure 1*) on a wall about 6 metres away from the lamp, with the lamp being placed at the same height as the X on the wall (111 cm in our case). The distance of 6 metres was chosen such that the brightest point could still be identified for all tested lamps while keeping a large enough distance to the measuring point to avoid any noticeable influence of the measured values due to possible light reflection.

For each lamp, measurements were taken with a hand-held lux meter in nine pre-defined points (*Figure 1*) at a distance of 2 metres from the lamp. At that distance the measurements could be performed reliably in the same measurement points, while still keeping a large enough distance from the wall as described above. The light fields of all tested lamps were symmetrical with respect to the vertical axis, which is why measurements were taken on the central axis and on the left-hand side. Measurements were only taken for modes with a steady beam, as the average incident light in flash mode depends on the percentage of time during which the light source is active. Ambient light measurements for the nine spots were taken and then subtracted from each measurement.

Subsequently, the lamps were placed 2 metres from a white wall. The pattern of the measurement points was marked up on the wall, and a photograph of the light field of each front lamp was taken for all steady beam states with the following settings: Canon 5D MkIV; lens: 24-70 mm f/2.8 set to 42 mm; aperture: f/2.8; shutter speed: 1/50; ISO 400 (*Figure 2*). Rear lamp light fields were not

¹³ Measures how brightly a surface is illuminated by a light source. If the same amount of light (measured in lumen) is spread over a larger surface, the measured lux per surface is smaller.

¹⁴ <https://en.wikipedia.org/wiki/Lux>

photographed, as their light field is less important, and most of the lamps operated at too low power for the light field to be visible with the same camera settings.

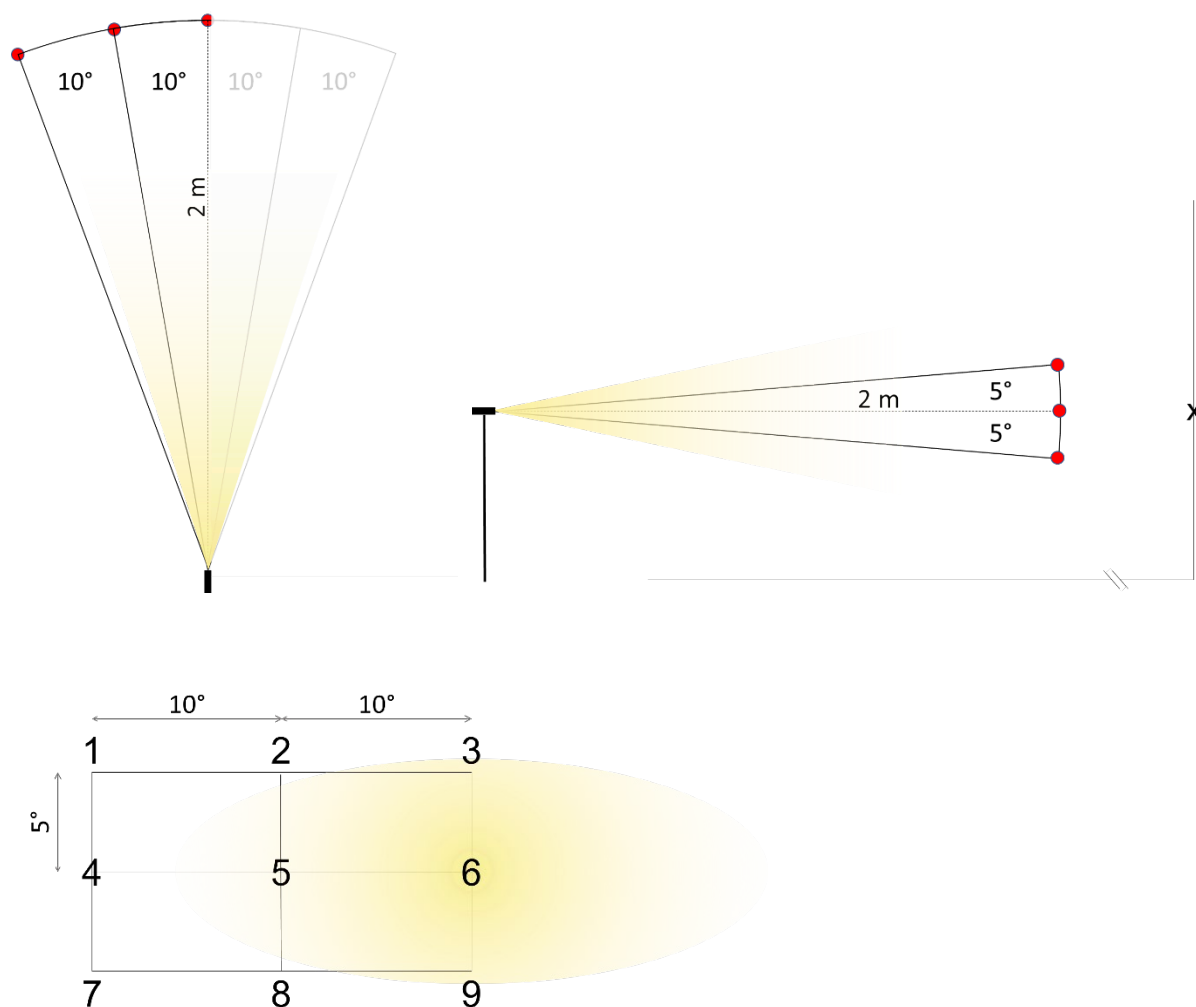


Figure 1. Top view (upper left) and side view (upper right) of the setup for the lux measurements in the points indicated with red dots, resulting in the measurement pattern presented in the lower row.

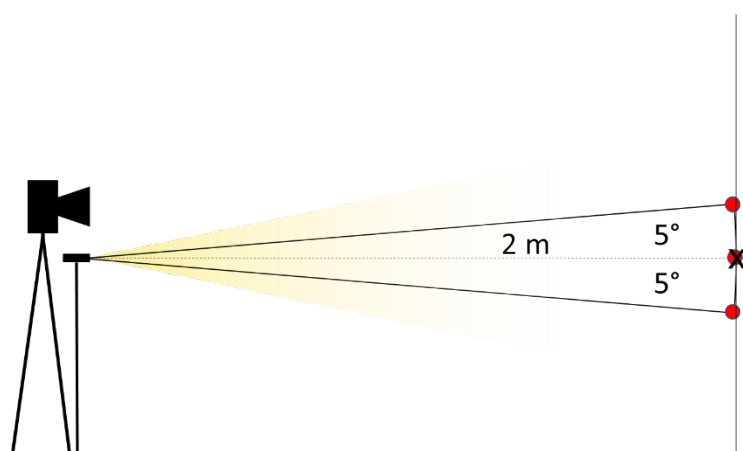


Figure 2. Side view of camera setup for photographing the light field.

4.2. Results

Front lights: As illustrated in Table 3, the lux measurements vary substantially both between lamps and for the same lamp in different measuring spots. The pictures show that the light fields could have complex shapes, with some lamps cutting the beam sharply in the upper field (F 1, F4, F8, F9), some lamps having a wide light field at street level (F4, F8, F9), some producing a round, narrow cone (F6, F7) and some barely illuminating the wall at all, at 2 metres distance (F2, F3, F5). The different shapes of the light fields, some of which have steep gradients, show that lux measurements should be accompanied with a light field picture indicating where the measurements were taken.

4.3. Discussion

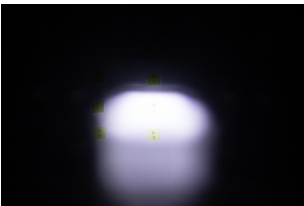
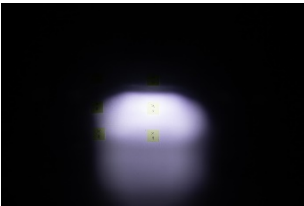
A laboratory setup of the type tested here is rather inexpensive. Required instruments are a lux meter, a dark room and a camera to photograph the light field. Obtainable results are absolute values of brightness across the light field of the lamp, as well as a representation of the light field. For flashing lights, the average brightness can be computed by multiplying the measured brightness with the percentage of time during which the lamp is on.

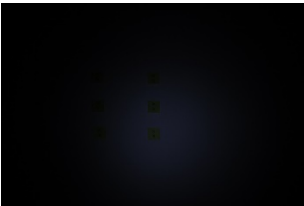
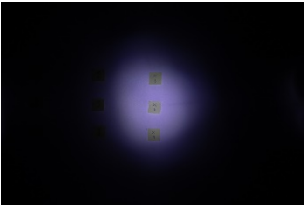
How these values translate to vision and visibility in real traffic cannot be assessed directly, although some conclusions can likely be drawn. From the cyclist's perspective it can be assumed that brighter lights provide better vision. If the light field on a wall is brighter on top and darker further down, this is likely to result in a rather homogeneously lit field in front of a bicycle, as the light higher up has to travel further before it reaches the road surface than the light further down. From the perspective of surrounding traffic, it should be beneficial if the lamp does not emit a lot of light above the brightest spot and in the far-left field, as the risk of blinding is reduced. Rear lights should be clearly visible but not blinding. The absolute values alone do not allow an assessment as to where the border is.

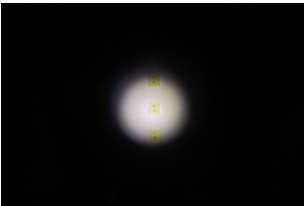
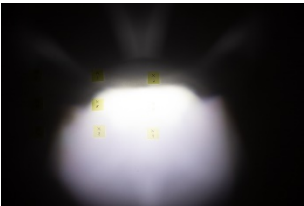
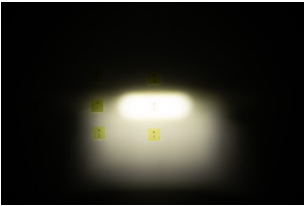
A static setup like the one used here does not provide any information about the advantages or disadvantages of flashing or pulsing lights or about the effects of motion.

Based only on the results available from this setup, F8, F9 and F4 would be considered to perform well, as they are bright lights with a light field shaped such that it is likely to provide good vision, at the same time as it probably does not disturb other traffic. For rear lights, it would need to be established whether R7 is too bright or not, given that its highest reading (point 6) lies almost 20 times above the next brightest light. R2 and R9 are otherwise the brightest lamps with the additional advantage that they produce similar readings also further off to the sides, which makes it likely that they can also be seen from an angle.

Table 3. Lux values for each steady beam mode for each of the tested lamps, measured in nine points as indicated in Figure 1. For each front light, a photograph of the light field is included. For the front lights, the shading for measurement points 1-9 gives a rough indication of whether it is desirable with a brighter (light shading) or not too bright (dark shading) illumination. Points 1-3 are on the top row above the brightest spot, 4-6 are on the middle row (the brightest spot aimed at 6) and 7-9 are the row below the brightest spot. Photo: Katja Kircher, VTI.

#	lamp – front		mode	image	1	2	3	4	5	6	7	8	9
1	F1	Litecco Highlux.30	power		1.1	2.2	9.8	0.9	3.8	682.6	1.1	3.5	169.1
2	F1	Litecco Highlux.30	eco		0.5	1.1	3.9	0.5	2.0	327.6	0.6	1.6	99.8
3	F2	Knog Cobber	max		3.3	3.2	2.9	3.4	3.3	3.1	3.4	3.3	3.1
4	F2	Knog Cobber	mid		1.4	1.3	1.2	1.4	1.4	1.2	1.4	1.4	1.2

#	lamp – front	mode	image	1	2	3	4	5	6	7	8	9
7	F3	Silva Tyto		0.8	0.9	0.9	0.8	0.9	0.9	0.7	0.8	0.8
9	F4	Red Pro 25 Lux		1.3	2.8	10.0	1.3	7.7	861.6	2.1	57.0	307.6
10	F5	Kayoba (Jula)		1.0	3.2	4.3	1.2	4.3	6.0	1.0	4.6	6.5
12	F6	Kayoba power beam (Jula)		0.7	3.7	27.8	1.3	5.1	62.0	0.8	3.0	30.9

#	lamp – front		mode	image	1	2	3	4	5	6	7	8	9
15	F7	Biltema			0.6	0.8	52.7	0.8	1.0	155.2	0.8	0.6	42.6
18	F8	Supernova E3 Pro 2			2.8	6.5	13.4	2.3	16.6	831.6	2.4	158.0	413.6
19	F9	Sigma Aura 60 USB	max		2.0	6.6	13.9	2.6	69.7	1541.6	2.1	110.1	294.6
20	F9	Sigma Aura 60 USB	med		1.0	2.9	6.0	1.3	32.6	809.6	1.1	47.4	147.6

#	lamp – front		mode	image	1	2	3	4	5	6	7	8	9
21	F9	Sigma Aura 60 USB	low		0.7	2.3	4.3	0.9	19.6	561.6	0.7	37.8	102.6

lamp – rear				1	2	3	4	5	6	7	8	9
22	R1	Litecco G-Ray		0.2	0.9	1.5	0.3	1.0	2.4	0.1	0.6	1.6
23	R2	Knog Cobber	max	1.7	1.8	1.8	1.8	1.9	1.9	1.8	1.8	1.9
24	R2	Knog Cobber	mid	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
28	R3	Silva Tyto		0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
30	R4	Red Cycling Products		0.4	0.6	1.4	0.3	0.7	3.6	0.2	0.5	1.3
31	R5	Kayoba (Jula)		0.1	0.7	1.7	0.1	0.9	2.8	0.1	0.8	1.2
33	R6	Kayoba power beam (Jula)		0.1	0.1	0.3	0.1	0.2	0.3	0.1	0.2	0.4
36	R7	Biltema		0.3	1.4	8.6	0.4	2.5	53.2	0.3	1.5	9.0
39	R8	Supernova E3 taillight		0.3	0.5	0.6	0.3	0.5	0.7	0.3	0.4	0.6
40	R9	Sigma Nugget II	standard	0.4	0.4	1.3	0.4	0.4	1.4	0.4	0.4	1.3
41	R9	Sigma Nugget II	high power	1.0	1.0	2.9	1.0	0.9	3.2	0.9	0.9	2.8

5. Laboratory-type test outdoors

This study examined whether the lamps fulfil the Swedish legal requirement of being visible from at least 300 metres. As the requirements do not specify ambient lighting nor whether adaptation to darkness is assumed, or whether the test should be made while sitting in a car or not, we used conditions that are easily replicable.

5.1. Method

5.1.1. Participants

Six participants (3 females) with an age range of 15 to 69 years took part. Participants used the same correction of vision as they would have in traffic.

5.1.2. Material

The bicycle lights were mounted on a rig (see *Figure 3*) such that they all had comparable height from the ground. For front lights, the angle of the light was determined such that the road ahead was illuminated in the best possible way, as seen from a cyclist's point of view. If the light field was very homogeneous, the light was angled slightly downwards. Rear lights were positioned such that the centre of the light cone would be parallel with the ground.

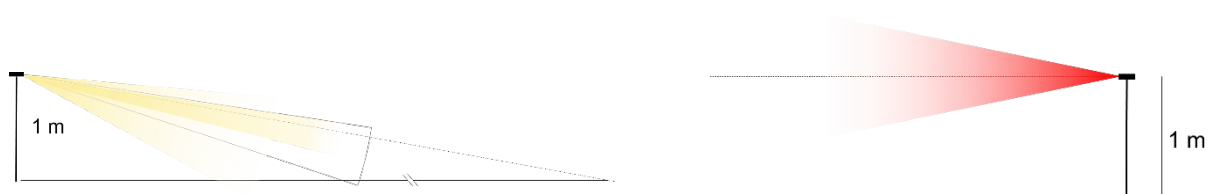


Figure 3. Setup of the lamps for the outdoors laboratory-style test. The lamps were positioned at a height of 1 m, with the front lights angled downwards towards the road surface for optimum illumination, the rear lights were mounted parallel to the ground.

The questionnaire contained a short demographic section (gender, age, possible vision corrections). For each light the participant should note whether it was a front, rear or no light, and in case of the former two, whether it was steady (constant light), flashing (on/off in various intervals) or “rolling” (continuous light, but over time changing brightness or which LED is presently on). Each setting should be judged on a scale from 0 (very bad) to 10 (extremely good) how well the setting was suited as a bicycle light, and there was room for a short comment, e.g. on glare.

5.1.3. Test location

The test was conducted in Tinnerö Eklandskap (at the parking spot Rödberget) in Linköping on a straight gravel road in darkness. The ambient light level was 0.01 lux. The test was conducted one day after new moon. No additional light sources, like street lighting etc., were in the vicinity. The weather was dry with clear skies, the temperature was 3 degrees C, and air humidity was 73 %, according to SMHI (the Swedish Meteorological and Hydrological Institute).

5.1.4. Design

The order with which the lights were illuminated was randomised, with different settings of the same lamp being treated as different lamps. Altogether 21 front and 21 rear light settings were shown. In three additional cases, no light was illuminated to ascertain that participants were not biased into saying that they saw a light. Each light setting was shown twice, such that within-subject consistency could be assessed.

5.1.5. Procedure

The participants were positioned 300 metres from the rig. They stood close together, each with free view of the rig. Each participant had a writing pad with a reading lamp attached, which illuminated the pad. Each participant received a paper-and-pencil questionnaire with which to evaluate the different lights. Experimenter 1 operated the rig and Experimenter 2 took care of the participants. The experimenters communicated by walkie-talkie.

The participants filled in the questionnaire each time a new setting was announced. When all participants were done with the setting, Experimenter 2 asked Experimenter 1 to activate the next setting. Experimenter 1 held a black screen between the light and the participants, activated the correct setting on the light (e.g. steady, flashing or rolling mode), and then removed the screen. The participants filled in the questionnaire. When they were ready, the procedure was repeated with the next light. The rating procedure took around one hour.

An SLR camera (Canon 5D Mk IV, lens Canon 24-70 mm f/2.8 set to 41 mm) was mounted on a tripod behind the rig with the lamps. For each setting, a photograph of the light cone was taken with the camera settings of 400 ISO, f/2.8, 2 seconds shutter speed. Reflectors were placed on the ground with a spacing of 20 m.

5.2. Results

All participants could identify all lights correctly as being a front respectively a rear light, and they all identified the occasions where no light was shown as such. Two participants missed one rating each, and one setting was repeated at the end, as a wrong setting had been shown.

For front lights, out of altogether 256 ratings, 16 (6.3 %) misclassifications were made with respect to whether the beam was steady or flashing. In 13 cases a flashing beam was mistaken for a rolling beam and in two cases a steady beam was mistaken for a rolling beam.

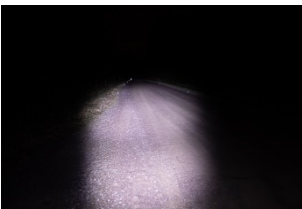
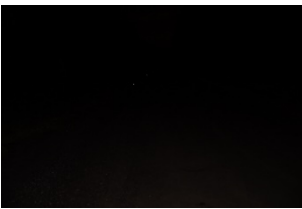
For rear lights, out of altogether 252 classifications, 29 (11.5 %) were misclassifications with respect to whether the beam was steady, flashing or rolling, with 12 cases in which a steady light was considered rolling and 10 cases where a rolling light was considered flashing.

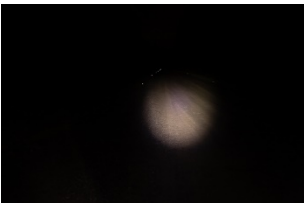
For front lights, the mean ratings ranged from 4.2 to 8.0 and for rear lights, the ratings ranged from 3.4 to 7.2 on a scale from 0-10 (*Table 4*). A comparison of the front light ratings with the photographs indicates that lamps that illuminate the road surface more and therefore should be of higher usefulness for the cyclist to see, also tended to receive higher subjective observer ratings. Those settings that illuminate the roadway well from a cyclist perspective (e.g. 9, 18, 19-21 and possibly 1-2, even though here the beam is rather narrow) receive ratings in the higher spectrum but are also commented upon as being blinding. Lamp F7 (15-17) receives good ratings for all settings, but the photograph shows that it is likely difficult to use for navigation. The weaker lamps also tend to receive lower ratings. They are not suitable for navigation in unlit areas.

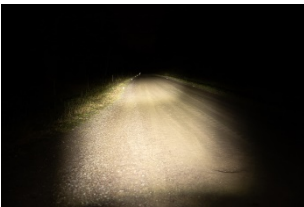
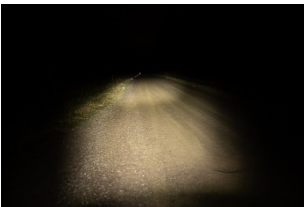
For front lights, no significant difference in ratings could be found for settings with a steady beam (6.5 ± 2.0) or flash (6.3 ± 2.1) as per a oneway ANOVA ($F(1, 254) = 0.48$). Due to the fact that only the weaker lamps had a flashing mode, another oneway ANOVA was conducted, splitting up the settings into “strong steady beam”, “weak steady beam” and “flashing”. For this segmentation, the strong steady beam received significantly higher ratings (7.2 ± 1.9) than the flash settings (6.3 ± 2.1), which in turn received higher ratings than the weak steady beam (5.8 ± 1.9).

The rear lights with the brightest measured values in the lab (23, 30, 36, 41) were not necessarily those that received the highest subjective ratings. This can be linked to the fact that for rear lights, the flash settings tended to receive higher mean ratings than steady beams or the two “roll” settings (steady: 5.4 ± 1.7 ; flash: 5.8 ± 1.8 ; roll: 4.9 ± 1.9) as per a oneway ANOVA ($F(2, 249) = 3.3$; $p < .05$).

Table 4. The average ratings and standard deviation for each tested setting of the nine front and nine rear lamps as well as the comments given. For ratings, within front respectively rear lamps, the darker the green shading is, the better the rating for the lamp, and the darker red the shading is, the worse was the rating. Within standard deviations, higher values are indicated with darker red (low unity among ratings) and lower values with darker green (high unity among observations). For the steady beams of the front lamps, the photographs are also shown. Photo: Katja Kircher, VTI.

#	lamp – front		mode	image	rating	std	comments
1	F1	Litecco Highlux.30	power		7.4	2.3	a bit too strong strong, highly visible could be a car very blinding
2	F1	Litecco Highlux.30	eco		7.1	1.6	violet colour of light
3	F2	Knog Cobber	max		5.4	1.2	weak, yellow
4	F2	Knog Cobber	mid		5.0	1.3	a bit too weak yellow light
5			flash		5.1	2.0	
6			eco flash		4.3	2.3	weak too long intervals
7	F3	Silva Tyto	on		4.2	1.7	weak not good, not very visible weak yellow, weak
8			flash		5.0	1.8	flash – not obviously bicycle weak irritating

#	lamp – front		mode	image	rating	std	comments
							weak
9	F4	Red Pro 25 Lux	on		7.7	1.5	a bit too strong good strong, could be car somewhat blinding
10	F5	Kayoba (Jula)	on		5.6	1.6	
11			flash		6.6	1.6	
12	F6	Kayoba power beam (Jula)	on		6.7	1.5	
13			fast flash		7.2	0.9	strong
14			slow flash		7.6	1.2	
15	F7	Biltema	on		7.4	1.7	blinding
16			fast flash		8.0	1.5	irregular flash strong strong
17			pulse flash		7.7	1.2	flash – not obviously a bicycle clearly visible long intervals

#	lamp – front		mode	image	rating	std	comments
18	F8	Supernova E3 Pro 2	on (and DRL)		6.7	1.9	shifting, yellow, too strong strong blinding
19	F9	Sigma Aura 60 USB	max		7.2	2.7	very strong, like a car almost blinding too strong as bike light? maybe somewhat strong blinding
20	F9	Sigma Aura 60 USB	med		7.4	2.2	like car headlight strong, could be car blinding
21	F9	Sigma Aura 60 USB	low		7.0	1.4	

#	lamp – rear		mode	rating	std	comments
22	R1	Litecco G-Ray	on	5.9	1.5	
23	R2	Knog Cobber	max	6.2	1.2	
24			mid	5.8	1.3	
25			steady pulse (roll)	5.8	1.4	
26			flash	6.5	1.3	irregular flashing
27			eco flash	4.7	1.7	long intervals weak long intervals too few flashes

#	lamp – rear		mode	rating	std	comments
28	R3	Silva Tyto	on	3.5	1.6	weak weak weak
29			flash	3.4	1.1	weak weak
30	R4	Red Cycling Products	on	5.3	1.7	
31	R5	Kayoba (Jula)	on	5.8	1.4	
32			flash	6.2	1.6	
33	R6	Kayoba power beam (Jula)	on	5.0	1.3	
34			flash 1	5.6	2.0	
35			flash 2 (roll)	4.0	2.1	weak, short intervals flickering
36	R7	Biltema	on	5.9	2.0	
37			fast flash	6.8	1.3	
38			slow flash	7.2	0.8	
39	R8	Supernova E3 taillight	on	5.1	2.2	weak
40	R9	Sigma Nugget II	standard	4.7	1.5	
41	R9		high power	6.3	1.7	
42	R9		high power flash	6.3	1.3	

The participants commented that over time their ratings changed, as they recalibrated the rating scale over time while seeing the different settings.

5.3. Discussion

All lamps passed the requirement of being visible from a distance of 300 metres, which was ascertained by the fact that they also could be identified as either front or rear lamp. However, the lamps were evaluated in total darkness, without any disturbing light sources in the vicinity. Results are

likely to be different in an urban setting with both ambient illumination and other vehicles around. Also, the lamps were judged in a static setting with participants who did not have any other task than to watch for a light for which they knew they would receive a signal when it was illuminated. How this can be translated to how easily a light can be detected spontaneously while dealing with a traffic situation is unknown.

The lamps were only tested for their visibility directly from the front/rear, but not for their visibility from the side. Depending on the design of the lamp, visibility from the side can vary substantially. Especially at closer distances, visibility from the side can be relevant, for example when a bicycle is about to or is in the process of crossing an intersection in front of another road user.

Also, the viewing distance of 300 metres should be put into perspective: A road user travelling at 30 km/h needs 36 seconds to cover 300 metres, and a road user travelling at 90 km/h still needs 12 seconds for the same distance. *Table 5* illustrates the times to contact for scenarios if one part is standing still, approaching the other part or travelling away from the other part at either 15 km/h or 25 km/h. Thus, when driving at 90 km/h and catching up with a cyclist travelling at 25 km/h, the required sight distance of 300 metres means that it will take 16.6 seconds until the vehicle and the cyclist have reached the same spot. In a scenario where the vehicle is standing still, checking for cross traffic at an intersection, it would take a cyclist travelling at 25 km/h 43.2 seconds to reach the intersection from a distance of 300 metres.

Table 5. The time in seconds which is needed until A and B arrive at the same spot from the point in time when A and B are 300 m apart, depending on the speed of A and B and the direction of travel.

	B standing still	A and B travelling in same direction		A and B travelling in opposite directions	
speed A km/h		B travels at 15 km/h	B travels at 25 km/h	B travels at 15 km/h	B travels at 25 km/h
10.0	108.0			43.0	31.0
15.0	72.0			35.9	27.1
20.0	54.0	221.3		30.8	24.1
25.0	43.2	109.3		26.9	21.7
30.0	36.0	72.6	209.3	23.9	19.7
50.0	21.6	31.0	42.9	16.6	14.4
70.0	15.4	19.7	23.9	12.7	11.4
90.0	12.0	14.4	16.6	10.3	9.4

These theoretical experiments illustrate that it may not be relevant whether and how well a bicycle light can be seen from a distance of 300 metres. In traffic, it is much more likely that tactical decisions, for example how to perform an overtaking manoeuvre, whether to wait and let oncoming traffic pass before turning left, and whether to wait for cross traffic, are made for shorter time frames and therefore for scenarios covering much shorter distances. Thus, it would be desirable to repeat the measurements for closer distances, possibly 100 metres and below, as well as in an urban environment with ambient light sources. For rear lights, it may also be relevant to test short distances of 1-5 metres, as these are frequent for bicyclists travelling behind each other.

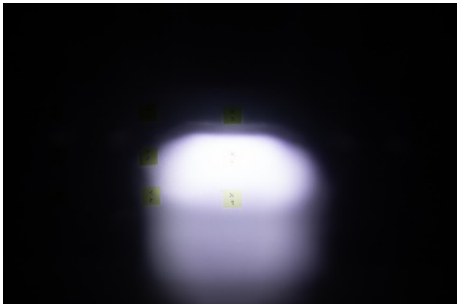
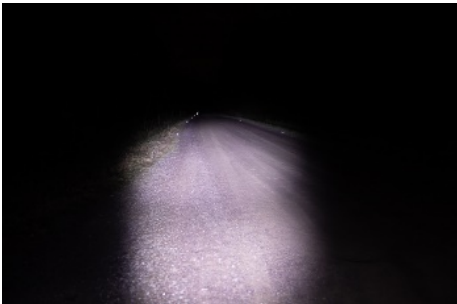
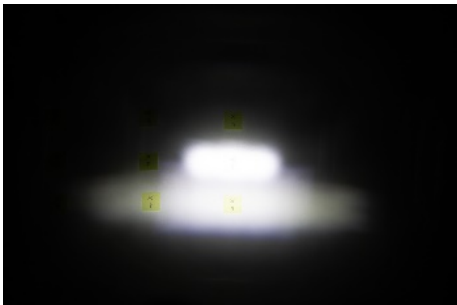
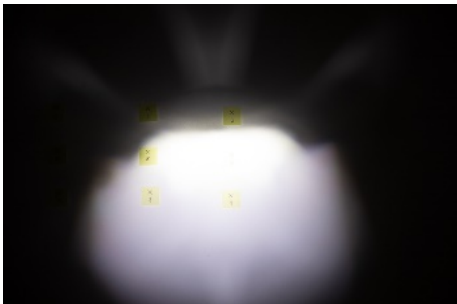
It should also be considered if there are differences depending on whether the other road user is a driver of a motorised vehicle or another cyclist or pedestrian, who might share the same path as the cyclist in question.

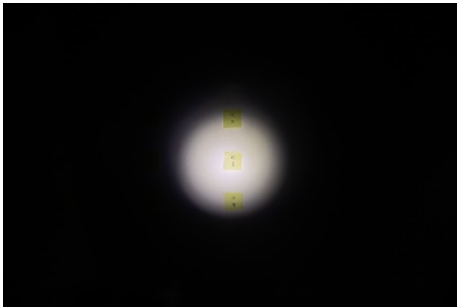
Based on this test setup, F1, F4 and F9 would be considered as most recommendable as front lights, combining the road visibility in the pictures and the ratings from the participants. As rear light, R7 received high ratings regardless of the setting, whereas other lamps only received high ratings when on high power or in flash mode (R2, R9, R5).

6. Comparison of laboratory-type tests

An environment in which conditions can be held constant enables reliable comparisons also over time. Absolute brightness values in pre-defined points allow for comparisons between lamps, giving an indication of how far ahead the lamp will be able to illuminate the road. The side-by-side comparison of the same light beam against a wall and in naturalistic conditions, illuminating a road (*Table 6*) shows that it is possible to translate the light field apparent in the laboratory to the field setting. Beams that in the laboratory appear brighter in the upper area will illuminate the road more evenly (see numbers 18 and 1). The sharp transition from bright to less bright becomes apparent as a darker area for number 9 and to some extent for number 1. Setting number 15 shows clearly that a beam that is homogeneously bright in the lab is darker at a distance in the naturalistic setting. Also, the edge shape of the beam in the lab can tell about how much and how brightly the side areas will be illuminated in the field. Out of the current selection of lamps, number 18 provides the most homogeneous illumination from close to the bicycle to far into the distance, also covering the side areas. Also setting number 9 illuminates the side areas well but is darker closer to the bicycle.

Table 6. Comparison of the light beam appearance for four lamps in the laboratory, directed at a vertical wall with a distance of 6 m, and in the field on a gravel road in darkness, mounted on a rig for optimal visibility from a cyclist's perspective. Photo: Katja Kircher, VTI.

#	lamp	Laboratory	Field Lab
1	Litecco Highlux.30		
9	Red Pro 25 Lux		
18	Supernova E3 Pro 2		

#	lamp	Laboratory	Field Lab
15	Biltema		

The field test showed that under the selected conditions (almost total darkness) all lamps easily fulfil the legal requirement of visibility from 300 metres distance. This test is not easy to implement in the laboratory due to the demands on space but appears to be superfluous to conduct for the majority of lamps on the market. In the present study, subjective user ratings were only conducted in the field setting. However, as mentioned above, it may be more meaningful to conduct such ratings not from the maximum required visibility distance, but rather from distances with more relevance for traffic. At least for ratings based on a static setting, this might also be possible to conduct in a laboratory.

6.1. Recommendations for laboratory-style testing

To summarise, we recommend a laboratory style measurement where conditions can be kept constant. This is also more convenient and cost effective and more robust in the sense that replications are made easier. We recommend a combination of lux measurements at a pre-defined distance at pre-defined points with photographs of the light beam distribution.

In the current setting, we used nine measurement points for **lux measurements** arranged in a rectangle, where the light beam was positioned such that the brightest spot was directed at the same point (here, point 6). It is recommended to increase the number of measurement points to also include the area corresponding to the field closer to the bicycle, underneath the lowest row in the current setting. For asymmetrical lamps, measurements should be taken both on the left and the right side of the brightest spot. A field test may be required to identify a suitable spot to measure for the assessment of the risk to blind other road users.

The **photographs of the light beam distribution** should be taken with the same camera settings to allow comparison between lamps. It may be meaningful to complement those photographs with additional ones adapted to the brightness of the light beam. Thus, also the light shape of weaker lamps can be made visible. As the human eye adapts to the surrounding light levels, a somewhat weaker beam may be sufficient and even superior under conditions with available ambient light. To simulate this in a laboratory setting, additional photographs with settings adapted to the lamp and an additional ambient light source of known brightness can be taken. With some practice, it should be possible to translate the shape of the light beam on a white wall to the light beam shape that can be expected in a naturalistic setting.

7. Field study

The goal of this study was to investigate how easy it is to identify the distance and speed of an oncoming cyclist in a naturalistic environment, depending on beam mode and mounting position of the lamp. The study was conducted in real traffic for high external validity. The method was based on a gap acceptance study by Petzoldt et al. (2017) and Schleinitz and Petzoldt (2019), who compared how people judged the approach speed of e-bikes, regular bikes and scooters. The gap acceptance was combined with a subjective judgement of each light setup. The method was chosen as it is an established method for comparing different features of vehicles in interaction with other road users. Gap acceptance is relevant for road safety, and the method is rather easy to implement in a realistic road environment.

To keep the setup manageable in this study, we did not consider systematically how easily a cyclist is recognisable as such or how easy it is to identify the intended direction of travel. These factors were only included if the participants decided to mention them in their commentary. Also, the participants knew when and from where to expect the cyclist, and they themselves remained stationary.

7.1. Method

7.1.1. Design

The design was within subjects for all factors except “position”, with an orthogonal variation of the factors described in *Table 7*. The investigated beam types were chosen based on the results from the outdoor laboratory style test.

Table 7. Description of the factors investigated in the study. Factors in parentheses were included to control for potentially confounding variables.

factor	levels	more detailed description	further comments
<i>lux in lab test, brightest point</i>			
light beam	bright steady	1542	Sigma Aura full power (F9)
	weak steady	6	Jula Kayoba (F7)
	flashing	155 (in steady mode)	Biltema (F5)
	no light	-	-
mounting position	high	ca. 100-105 cm from ground (handlebar)	
	low	ca. 50-55 cm from ground (left leg of fork)	
cyclist speed	ca. 15 km/h ca. 20 km/h ca. 25 km/h		as indicated by bicycle computer and measured by bicycle computer Wahoo Elemnt Bolt/Garmin Virb
(participant position)	A, B, C, D	along roadside	not tested as independent factor, but noted for control purposes
(block)	1 st , 2 nd	first or second round of ratings	not tested as independent factor, but noted for control purposes

Theoretically, it would have been preferable to use the same front light for all three beam settings, to keep variation of non-investigated factors to a minimum. However, none of the available lamps had a large enough range of brightness levels, and a flash mode was available predominantly on the weak lamps. For the bright beam, we opted for a lamp from the mid-range price segment, for the weak beam, we chose a cheap, commonly available lamp, and for the flash mode, we chose a commonly available lamp that, in steady mode, was somewhat brighter than the weak lamp. In the no lights condition, all lamps were switched off.

The cyclist's speed was varied on three levels, such that the estimation of the minimum acceptable gap would not only depend on distance. The target speeds were 15 km/h, 20 km/h and 25 km/h. The experimenter on the bike accelerated from around 100-120 metres away from the first participant and attempted to keep the target speed until having passed the last participant. The actual achieved speed was logged by both the bike computer (Wahoo Elemnt Bolt) that also served as speed indicator for the cyclist, and by the GPS-capable action camera (Garmin VIRB 30) mounted on the handlebars of the bicycle. Spray markings on the asphalt, which were recorded by the camera, indicated the distance of the bicycle from the participants.

Each participant took part in two "rounds" of judgements on two different positions, to control for position effects (*Figure 4*).

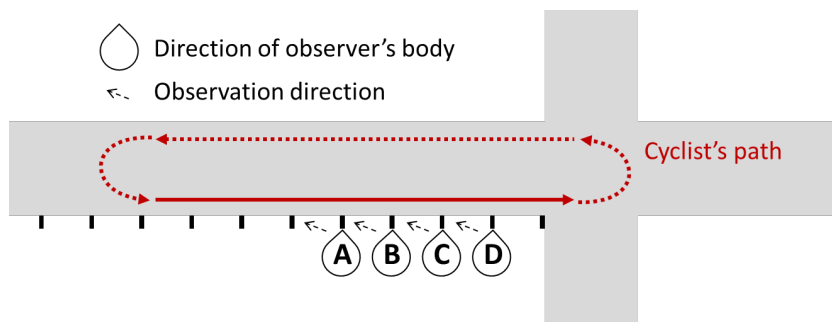


Figure 4. Illustration of the cyclist's path (red arrow) and the participants' observer positions (A, B, C, D), including the direction in which the participants' bodies are being turned, and the observation angle.

7.1.2. Equipment

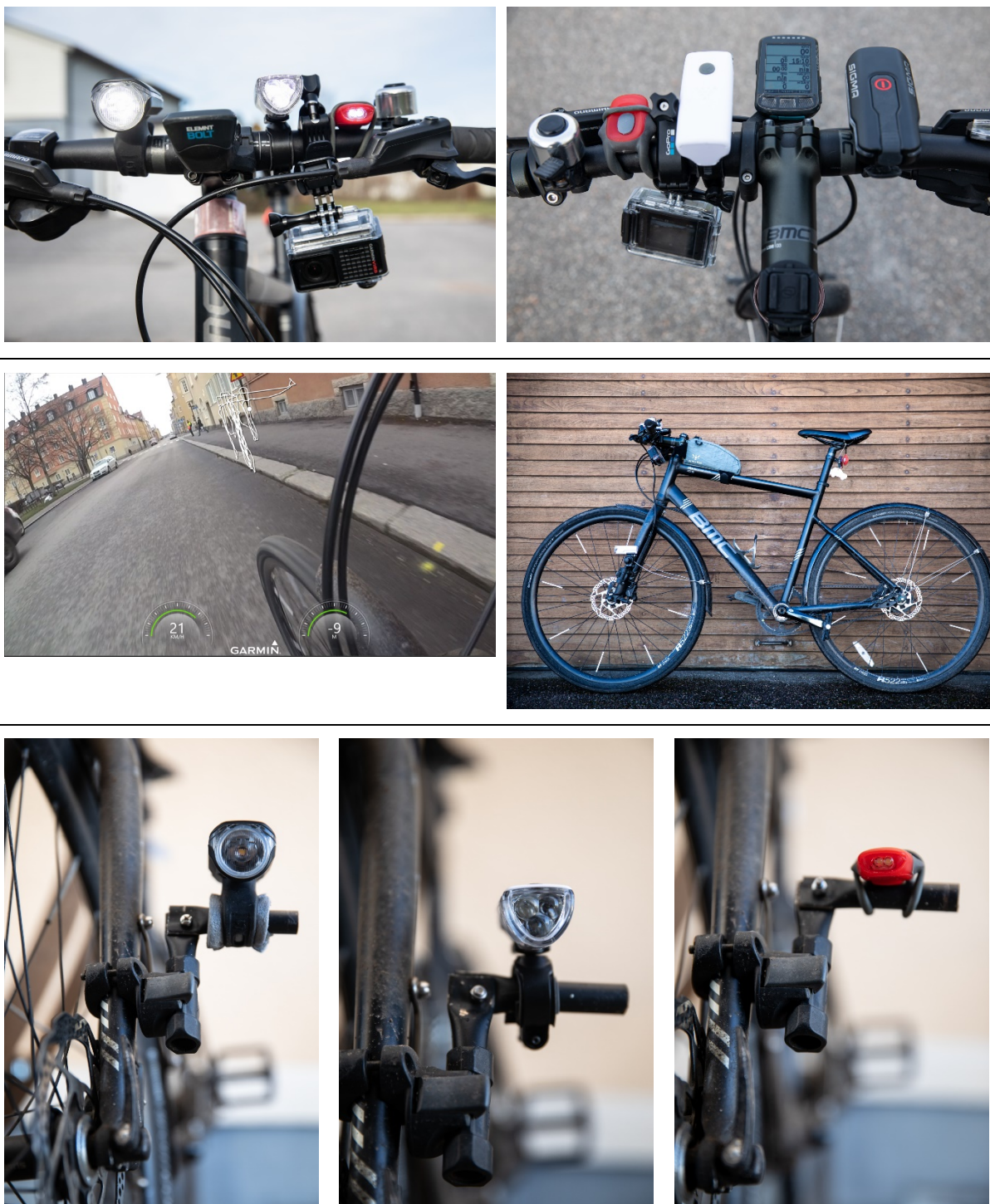
Three lamps, representing the three beam configurations, were mounted on the bicycle (*Table 8*) – either on the left leg of the fork, or close to the middle of the handlebar, depending on the tested mounting position. The lamps were mounted such that the beam of each lamp was perceived as being ideal for seeing the road in front. Thus, the angle was not the same for all three lamps but depended on the beam type. A dedicated construction was used for the fork mounting to allow the lamps to be mounted in the same orientation as on the handlebars, to avoid a confounding in judgement associated with lamp orientation. The construction allowed for a quick replacement of the lamps between trials.

The GPS-capable action camera (Garmin Virb 30) was mounted underneath the handlebar, filming in wide angle to capture the front scene as well as the roadside with the distance markers (see *Table 8*, middle row left for a daylight picture). This setup allowed a distance judgement of the nearest acceptable gap for each participant, as the participants' indicating the accepted gap was recorded.

The experimenter on the bicycle had a list showing which light to use for each ride, and at which speed to ride. She wore dark clothing without reflexes and a dark bicycle helmet and had a small backpack in which a walkie-talkie was placed. As mentioned above, the cyclist experimenter used a Wahoo Elemnt Bolt as speed indicator and logging device for the actual riding speed. The speed was also recorded by the action camera. The walkie-talkie was used by the experimenter who remained

with the participants to inform the cyclist experimenter when the participants were ready to start the next trial.

Table 8. The three tested lamps (from left: F9, F7, F5) mounted on the handlebars/fork of the test bicycle. The bicycle computer was used to gauge the target speed and the action camera below the handlebars filmed the forward scene in wide angle, showing the test person and the distance markings at the same time. The lamps mounted on the fork could be exchanged quickly between trials. Photo: Katja Kircher, VTI.



The rating scale consisted of five items, which should be rated on a scale from 0 (not at all) to 10 (maximum possible). The items were:

- Overall satisfaction with the light setup
- Is the light setup blinding?
- Does the light setup make it easy to identify the vehicle as a bicycle?
- With the given light setup, is it easy to judge the bicycle's speed?
- With the given light setup, is it easy to judge the position of the bicycle?

7.1.3. Participants

The participants were recruited from a database with interested participants as well as by word of mouth. Each participant was sent an e-mail with some information on the study and a link to a questionnaire for basic background information like age and gender.

The participants were contacted by e-mail with information about the location of the research intersection, the planned dates and times for testing and the experimenter's contact details. The e-mail also included a link to a Doodle-form, where the participant could book one of four spots offered per scheduled test time. The booking form only showed the spots still available, but not other participants' contact details. In total, three days with two test times per day were offered.

The final group of participants consisted of 20 people (9 female) with a mean age of 32.8 years $\pm$ 10.2 years.

7.1.4. Procedure

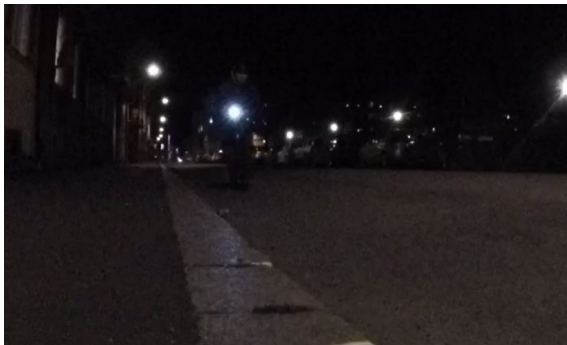
In preparation for the test, the experimenters marked every metre along the road on which the cyclist would travel with spray, starting at the position of the participant farthest away and continuing to 50 metres in front of the first participant. Every 5th and 10th metres were marked specifically.

Upon the participants' arrival at the test site, one of the two experimenters informed the participants about the purpose and procedure of the study. The participants were then given the opportunity to ask questions, whereupon they were asked to sign an informed consent form, confirming that they were aware that they could abandon their participation at any time, and indicating whether they allowed that video material from the trial in which they were visible would be shown in public. Next, each participant received a writing pad and pen with the observer rating sheet. The participants were instructed to imagine that there was dense traffic on the road, and that they should indicate the minimum gap they would accept to cross the road in front of the cyclist by lifting a leg as if taking a step, or by extending an arm. A change was implemented after the first day (see below). Two practice trials were conducted before the actual data collection began, to make sure that the participants had fully understood the procedures. The practice trials were conducted with the lamp that in the study would be used for flashing, but with steady beam or a different flashing mode, either in the high or low mount position, at random speeds.

Before the sharp trials began, the action camera mounted to the cyclist experimenter's bicycle was started. Each trial started with the cyclist, turned away from the participants, choosing the correct lamp setting. With all the participants ready, the experimenter told the cyclist via walkie-talkie to start riding and mentioned the number of the trial to avoid possible confusions. Upon that, the cyclist turned towards the intersection and accelerated to the desired speed. The observers watched the cyclist and indicated their minimum accepted gap as described above. Upon this, the participant filled in the observer sheet, answering five structured questions about the light setup with a rating between 0 and 10. Meanwhile, the cyclist returned to the starting position and changed to the next light setup (see *Table 9* for the different lamps and mounting positions as seen from the participants' position).

Table 9. View of the cyclist from the position of the participants, but with the camera at a height of around 30 cm. Photo: Katja Kircher, VTI.

weak beam, handlebars



weak beam, fork



strong beam, handlebars



strong beam, fork



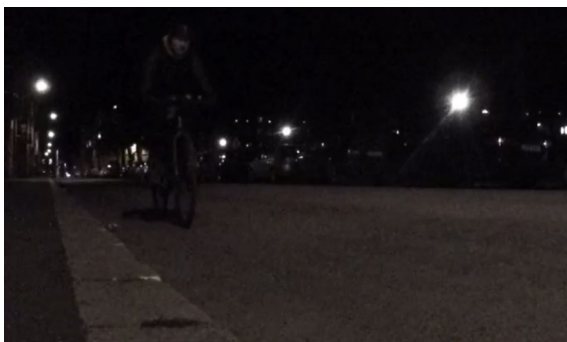
flashing beam (illuminated phase), handlebars



flashing beam (illuminated phase), fork



no light



When one block of 21 trials (3 speeds x 2 two mounting positions x 3 beam modes + 3 speeds without light) were completed, the participants changed places so that the participants in positions A and B swapped with those in positions C and D. The position change was requested to compensate for potential biases in positioning, such as ambient lighting conditions and the possibility being influenced by other participants down the line. The participants were granted a break if they wanted, and then the same procedure was repeated.

After the first day of trials it was noted that the video recording was too dark to assess the movement to indicate gap acceptance and to see the distance markings on the pavement. Therefore, the ISO settings on the camera and the EV value were increased to max to improve visibility. Also, small lights were attached to those limbs that the participants moved for gap acceptance.

7.1.5. Location

In the pilot session, two intersections in Linköping were investigated as study sites. They differed in the amount of traffic and the number of light sources. It turned out that in the busier and brighter intersection, traffic volumes were too high, causing unpredictable stops and interactions which would likely influence the investigated factors. Therefore, it was decided to use only the calmer location, and it was also decided not to use the intersection itself, but one of the streets leading up to the intersection (*Figure 5*). The reason for this was to avoid disturbances by other traffic, to make the setup more homogeneous across participants, and because there was a no-parking zone along the area of interest, enabling a smooth approach of the cyclist.



Figure 5. Photograph of the study site close to the intersection Platensgatan/Gustav-Adolfsgatan. The cyclist rode in the direction towards the camera position on the side without car parking. The participants were positioned along the pavement, with Participant D standing at 5 m distance from the intersection, Participant C at 10 m from the intersection etc. Photo: Katja Kircher, VTI.

7.2. Analysis

Gap acceptance: The film from the camera mounted on the handlebars was analysed with respect to the cyclist's position when the different participants indicated their minimum gap acceptance by a foot or hand movement. The cyclist's actual speed was logged when she was 30 metres away from the participant in position D, based on the measurement provided by the Garmin Virb camera. As

mentioned, the film recorded on the first day was too dark for a reliable analysis, therefore only the data from the twelve participants from the last two days were included in the analysis.

Additionally, the experimenter who remained with the participants also performed a gap acceptance indication. As it was the same person in all four sessions, thus, resulting in eight judgements per light setup, this allows for a within-subject consistency analysis, albeit for one person only.

Gap acceptance reactions at distances of more than 40 metres could not be judged reliably, therefore those were subsumed under “above 40 metres” and collectively set to 45 metres. With the actual speed of the cyclist, the gap acceptance time in seconds was calculated per judgement.

Subjective ratings: Preliminary tests showed that there was no effect of “block”, that is, between the first and second round of ratings, therefore, for the following analyses the ratings were aggregated over this variable. Several participants mentioned that their perception of the bicycle lights was influenced by their position. In positions C and D, the street was illuminated by a street lantern (in *Figure 5*, closer to the intersection in the foreground), while in positions A and B the environment was darker. Participants reported more glare in the darker spots, and that it was more difficult to recognise the silhouette of the cyclist when positioned in the darker spots. The subjective ratings were not influenced too much by position, with the highest difference of one point for glare (3.0 for the bright position, 4.1 for the dark position on a scale from 0: *not at all* to 10: *maximum*). In the main analyses we aggregated over position.

7.3. Results

7.3.1. Gap acceptance

Preliminary analyses showed that neither block ($t(502) = 0.18$, $p = .85$) nor position ($t(502) = -1.46$, $p = 0.14$) influenced the gap acceptance time, therefore we aggregated over these factors.

As shown in *Figure 6*, gap acceptance times range from around 2 seconds to around 9 seconds, with most of them lying in the range of 3-5 seconds. A univariate analysis of variance with the three independent factors lamp, mounting position and target speed showed that there was a significant difference for target speed ($F(2, 487) = 36.6$, $p < .001$), and that there was an interaction between target speed and mounting position ($F(4, 487) = 4.4$, $p = .013$). The average gap acceptance time decreases with ca. 0.6 seconds per 5 km/h, starting with 4.6 seconds at 15 km/h and arriving at 3.3 seconds for 25 km/h. Thus, while the absolute distance to the cyclist increases with speed, it does not compensate fully for the speed gain. As suggested by *Figure 6*, the main reason for the longer mean gap acceptance times in the low speed condition are a number of relatively high gap acceptance times and generally a larger spread at the lower speeds. The interaction with mounting position results mainly from the fork mount leading to 0.3 seconds longer gap acceptances at the two lower speeds, but to a 0.1 seconds shorter gap acceptance at 25 km/h. This is neglectable in comparison to the effect of target speed. Lamp type did not influence gap acceptance, and neither did mounting position.

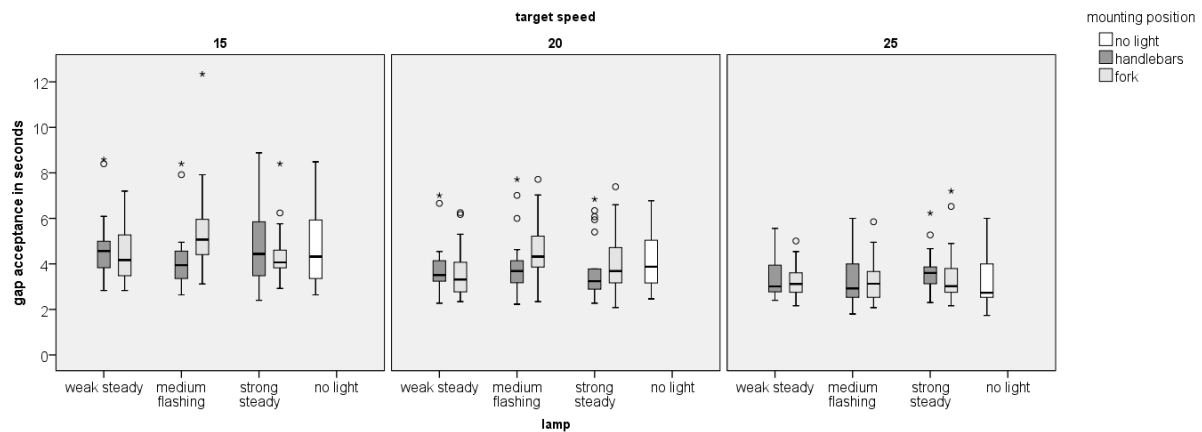


Figure 6. Boxplots for gap acceptance in seconds for 12 participants, split by the three independent variables target speed, lamp and mounting position.

As a side note, a separate analysis of all eight judgements made by the experimenter of each lighting setup showed that the gap acceptance times varied also within this person (Figure 7), but that the same pattern emerged as for the participants. Speed had a high impact on gap acceptance time ($F(2, 151) = 11.9, p < .001$), and instead of an interaction, there was a weak and practically irrelevant main effect of mounting position ($F(1, 151) = 4.5, p = .035$), where the handlebar position led to around 0.3-0.5 seconds shorter gap acceptance times than the fork mount or no light at all.

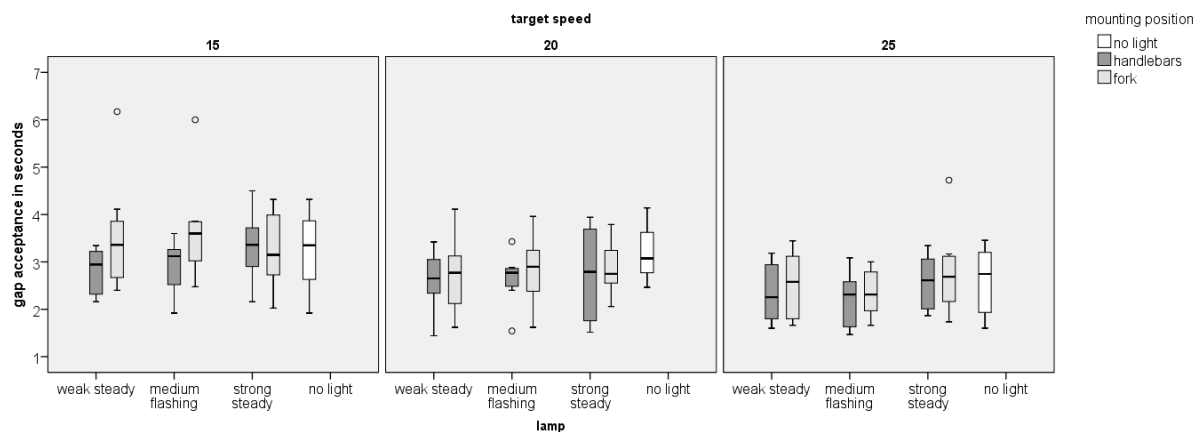


Figure 7. Boxplots for gap acceptance in seconds for the eight ratings per lamp performed by one single person (the experimenter), split by the three independent variables target speed, lamp and mounting position.

7.3.2. Subjective ratings

Except for not producing any glare, not having any light at all received low ratings on all scales (Figure 8 to Figure 12). It was more difficult to recognise the cyclist as such, and speed and distance estimations were harder to make. Compared to the no-light condition, the setups with lamps were rated as rather acceptable, with all average ratings being higher than 5.

Apart from the no-light setup, the flashing light received the lowest ratings on all scales. Generally, the fork mounting was not perceived as good as the handlebar mounting. The different cycling speeds did not affect the ratings very much.

A multivariate analysis of variance was conducted with the five rating scales as dependent variables and the independent factors lamp, mounting position and speed, to ascertain whether there were any statistical differences between the setups. The no-light condition was not included in the analyses, as mounting position did not apply. There was one significant interaction effect between lamp and

mounting position (Wilk's lambda $F(10, 1396) = 5.0$; $p < .001$). The between-subjects effect test showed that the main difference was for glare ($F(2, 702) = 18.3$; $p < .001$), where the fork position led to more perceived glare especially for the flashing lamp (4.0/10 on handlebars, 6.2/10 on fork).

The handlebars were rated as a slightly better mounting position in the general judgement, which was mainly reflected in the lower glare rating for this position. The handlebar mount was also perceived to be slightly more representative of a bicycle than the fork position. Speed and distance estimations were not rated as being very dependent on the mounting position. The speed of the cyclist did not influence the ratings substantially. The factor influencing the ratings the most was the lamp and thereby the beam type (Wilk's lambda $F(10, 1396) = 24.2$; $p < .001$). The strong, steady beam was experienced as best overall, followed by the weak steady beam, with the flashing beam receiving the lowest ratings.

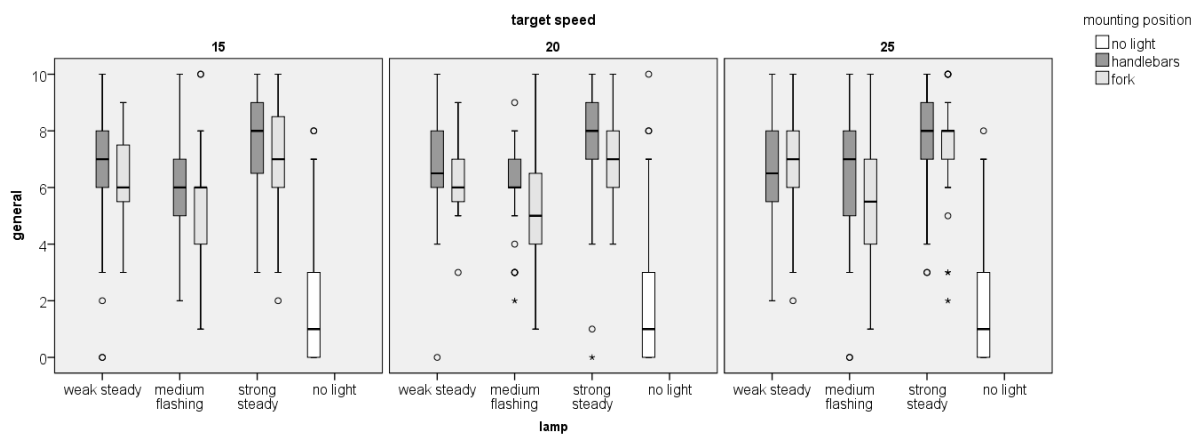


Figure 8. Boxplots for ratings of the general impression of the lighting setup, split by the three independent variables target speed, lamp and mounting position.

The strong, steady beam mounted on the handlebars received the highest average ratings and also the lowest amount of low ratings. Not having any light was generally perceived as substantially worse than any of the setups including a light, but some of the participants rated not having a light as over 5/10, while some of the setups with light were rated by some participants as below 5/10.

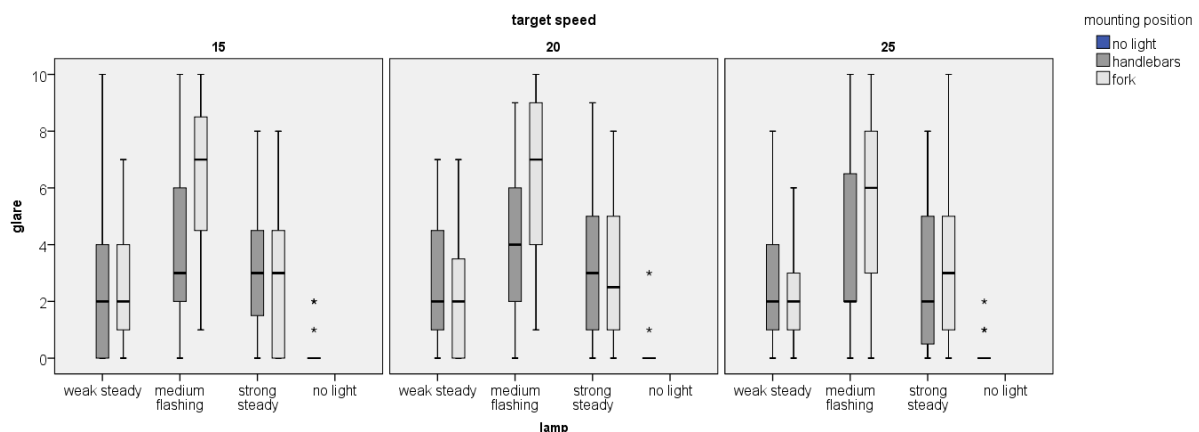


Figure 9. Boxplots for ratings of glare, split by the three independent variables target speed, lamp and mounting position.

Not having any light did not lead to any perceived glare, except for one participant who gave ratings between 1 and 3, and two additional participants who gave one rating of 1 each. The flashing light on the fork was perceived as producing much glare, with more than half of all ratings higher than 6/10. The stronger steady beam was not perceived to produce more glare than the weaker steady beam.

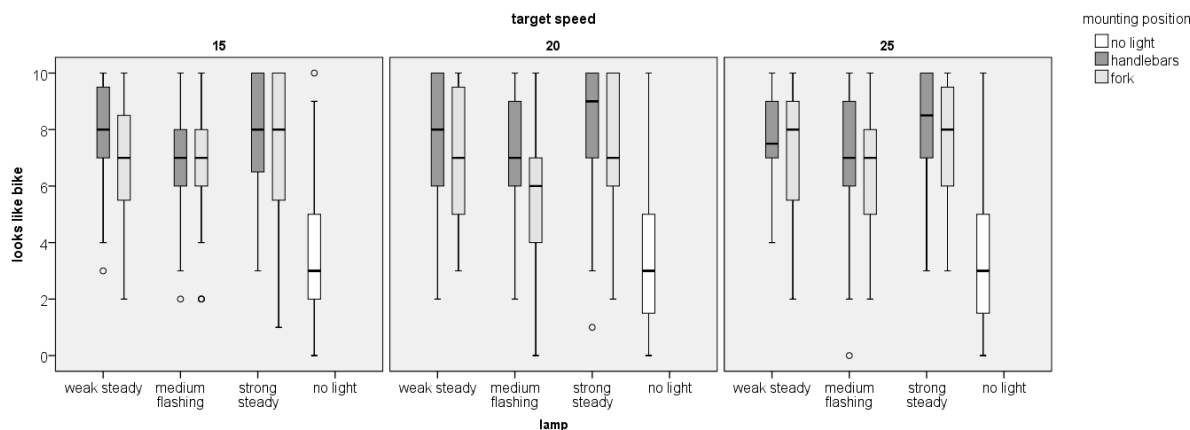


Figure 10. Boxplots for ratings of how much the lighting setup helped to recognise the approaching road user as a bicyclist, split by the three independent variables target speed, lamp and mounting position.

The boxplots show that the slightly higher average ratings for the handlebar mount mainly stem from a lower number of low ratings, that is, the range of ratings is slightly smaller for the handlebar mount. Not having any light led to low ratings, but almost all participants gave ratings above zero, with half of the ratings being above 3/10.

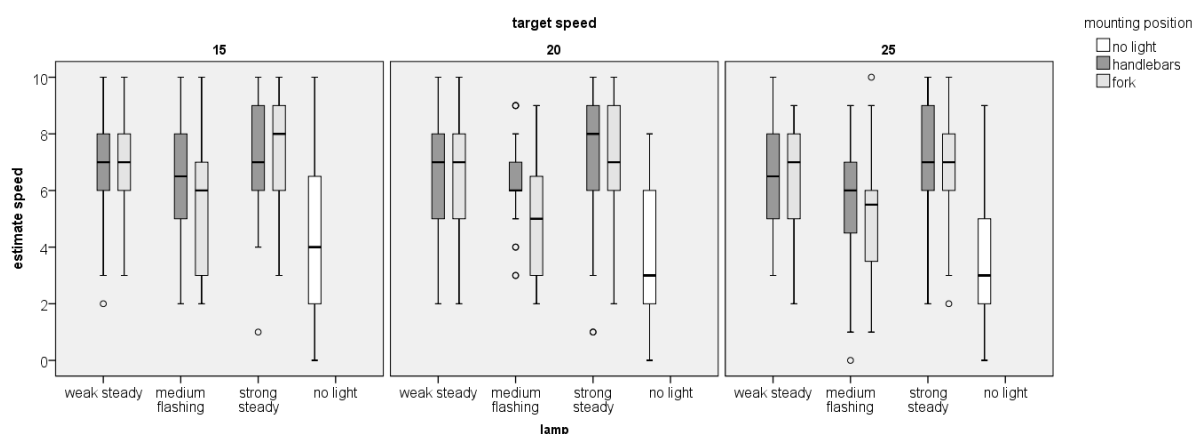


Figure 11. Boxplots for ratings of how easy it was to estimate speed, split by the three independent variables target speed, lamp and mounting position.

Participants perceived to be able to rate the cyclist's speed best with the strong, steady beam mounted on the handlebars. The largest amount of lowest ratings was given to the flashing light mounted on the fork. Not having any light led to 50 % of the ratings being above 3/10, with higher speeds leading to slightly lower ratings.

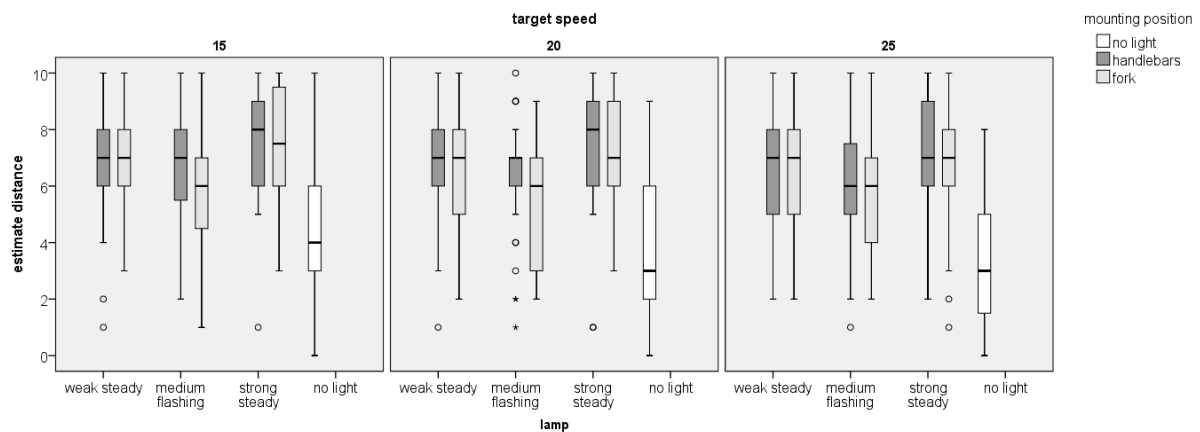


Figure 12. Boxplots for ratings of how easy it was to estimate distance, split by the three independent variables target speed, lamp and mounting position.

Distance estimation received ratings very similar to speed estimation, which is not surprising, as the two are closely related.

7.3.3. Verbal comments

After each data collection the participants were asked to comment upon their general impression and asked whether they had any additional remarks about the lamps or anything else in the setup. Recurring comments were that the position at which they themselves stood made a difference, with the position not illuminated as much by a street lantern leading to more glare and more difficulties in recognising the cyclist as such. Also, it was mentioned frequently that the strong, steady beam illuminated the road surface in front of the cyclist, which was perceived to be very helpful. The flashing beam received much criticism, both for not allowing a good estimation of speed and distance, for producing glare and for being perceived as irritating in general. Some participants also mentioned that glare in general (outside of the current study) was more dependent on how the light is mounted than what type of light it is, and that glare prevents an observer from seeing the silhouette of the cyclist, which impedes judgements of speed, distance and road user type.

7.4. Discussion

Interestingly, even though the participants were clearly negative towards the cyclist having no light at all, followed by the flashing light, this did not have any impact on their gap acceptance behaviour. In contrast, target speed did not affect the subjective ratings, but had the by far biggest impact on gap acceptance. These results clearly show that simply asking people about their opinion how good a lighting setup is does not provide the whole picture. The experienced difficulties in judging speed and distance varying with light setting did not entail any performance differences in gap acceptance. Not even the absence of a light changed gap acceptance behaviour substantially.

The inconsistency between subjective ratings and actual behaviour leaves the question open whether the two measure different things, whether people are badly calibrated about their judgements, or whether there can be additional factors explaining the inconsistencies. It could be that opinions are influenced by how the light setup is experienced in terms of comfort or by societal norms – a flashing light may be experienced as less comfortable and no light at all may be frowned upon, as it is known to be against the regulations. That the participants are still able to make similar gap acceptance judgements may not fall within their assessment criteria. It may even be the case that they think that their judgements become worse, even though they do not.

The lowest accepted gaps were at around two seconds, without any obvious relation to lamp type. At 25 km/h, this means that the distance to the approaching cyclist is around 14 metres. It is somewhat

concerning that the participants believed that they could judge distance and approach speed rather well, but that their gap acceptance time did not reflect this. Given that the stopping distance increases with the square of the speed, for similar safety margins a longer gap acceptance time for higher speeds would have been required, instead of the found shorter gap acceptance time. As the lighting setups, as tested here, did not influence the gap acceptance time, other ways need to be considered to make other road users aware of cyclist speed. This is especially relevant with the increased share of e-bikes, which makes approaches at higher speeds more likely (Schleinitz, Petzoldt, Franke-Bartholdt, Krems, & Gehlert, 2017).

In this simple setup, only minimum gap acceptance was tested, which is just one of several situations in which an appropriate lighting setup can be crucial. Also, we only tested front lights, as a realistic and relevant setting with a rear light would involve approaching the rear light. This could have been realised with the participant as passenger in a car, but this would have incurred costs beyond the scope of this project. In a further study, a test could show whether such an approach would yield different results from the cyclist approaching the test person, as done in the present study.

The method used here is analogue to what has been used in previous studies on gap acceptance (Schleinitz & Petzoldt, 2019; Schleinitz, Petzoldt, & Gehlert, 2020). The strong dependence of gap acceptance time on speed indicates that the participants did make non-random gap acceptance judgements, and the differentiation between lamp types and mounting position in the subjective assessment shows that participants do have systematically different opinions about the lamps. This indicates that the method in itself is able to catch differences between the lighting setups. It also shows that both parts of the method – the physical indication of minimum gap acceptance and the subjective rating - add new information.

8. Demonstration

Several additional factors affect the visibility and recognisability of cyclists and their intentions. Some of the factors that could not be investigated here, due to the scope of the project and the efforts that would have been necessary for rigorous testing, were demonstrated instead. This was done by either photographing or filming the relevant situation. Each situation is described below. Photographs are included and links to films are provided.

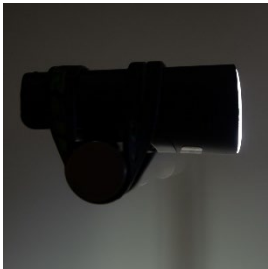
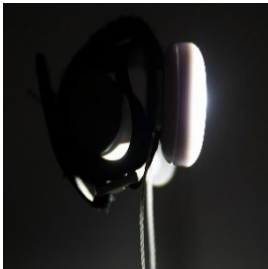
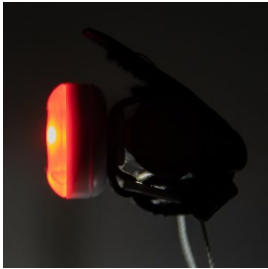
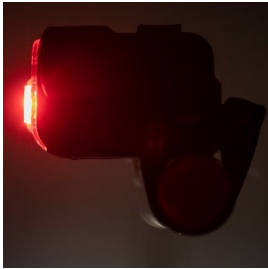
8.1. Observer perspective

Different aspects of cyclist visibility, recognisability and predictability are demonstrated in a non-scientific fashion, to illustrate further questions that could be interesting to investigate in future studies.

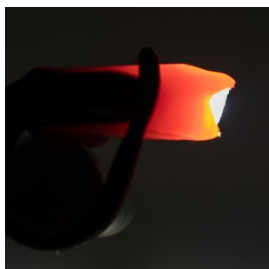
8.1.1. Light from the side

Depending on the design of the lamp, their visibility from the side varies substantially (*Table 10*). Lamp F1, which was found to be very bright from the front, is hardly visible at all from the side, whereas F2 is designed such that the light is more or less equally bright to the sides as to the front. F8, another lamp which is very bright from the front, only uses its illuminated brand name for side visibility. F9, the third of the rather bright front lights, is specifically designed for side visibility. F5 with its red plastic casing resembles a rear light when seen from the side. All rear lights in the study have at least some side visibility. It could be speculated whether a distinct design could be especially good at communicating that a cyclist is coming from the side, but this would need to be tested in a controlled manner. For this demonstration, we conclude that side visibility varies, and that it is likely beneficial to design in visibility from the side to a certain extent.

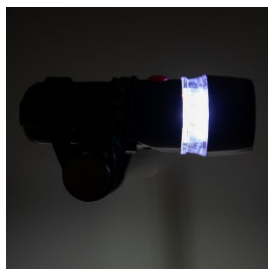
Table 10. The lamps used in the project photographed from the side. The camera settings were adapted to the brightness of the lamps to demonstrate the shape and visibility from the side, which means that the relative brightness cannot be compared here. Photo: Katja Kircher, VTI.

F1: Litecco Highlux.30	F2: Knog Cobber	F3: Silva Tyto	F4: Red Pro 25 Lux
			
R1: Litecco G-Ray	R2: Knog Cobber	R3: Silva Tyto	R4: Red Cycling Products
			

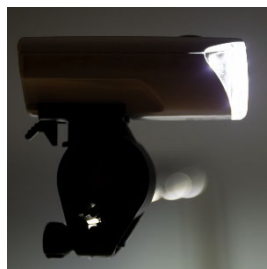
F5: Kayoba (Jula)



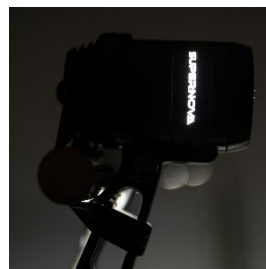
F6: Kayoba power beam (Jula)



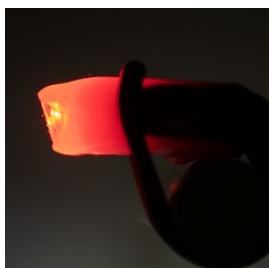
F7: Biltema



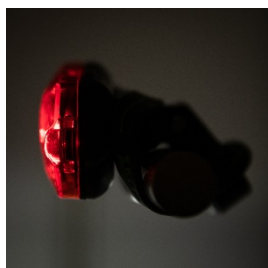
F8: Supernova E3 Pro2



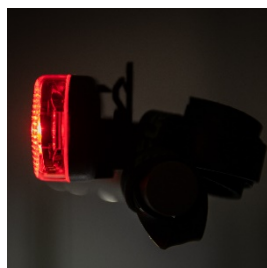
R5: Kayoba (Jula)



R6: Kayoba power beam (Jula)



R7: Biltema



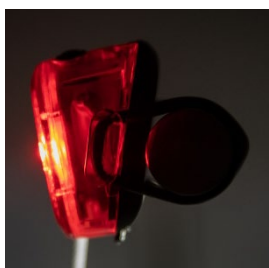
R8: Supernova E3 taillight



F9: Sigma Aura 60 USB



R9: Sigma Nugget II



8.1.2. Biomotion

To demonstrate the effects of biomotion when travelling in the same direction as the cyclist or oncoming, small lights were attached to the cyclist's heels and foot insteps. The cyclist moved away from and approached a stationary camera, once pedalling and once coasting, demonstrating the effect of accentuating the movement of the feet with the help of light. The cyclist also passed the camera from the side, both pedalling and coasting, with small lights attached to the ankles, the knee, the hip

and the hand. This demonstration is found in a film, under the heading "Test av cykellysen: Biomotion"¹⁵.

8.1.3. Rear light from perspective of following cyclist

One cyclist used three different rear lights with different beam types consecutively, while filmed with a camera mounted on the handlebars of a following cyclist. This demonstrated the effect of steady rear lights versus different types of flashing or rolling lights for a close follower. You can find this demonstration in a film, under the heading "Test av cykellysen: Baklysen – efterföljande cyklist"¹⁶.

8.1.4. Glare effect depending on mounting

Glare is less dependent on the lamp itself but on how it is mounted. This was demonstrated with two different front lights mounted on the handlebar of a stationary bicycle. They were first turned slightly downward, like they would have been for normal riding, and then slowly turned up until they reached an angle that was approximately parallel to the ground, before being turned downward again. See the film, under the heading "Test av cykellysen: Bländning"¹⁷. The film demonstrates that mounting a lamp with the beam directed too high upwards leads to glare, but the same lamp, even though it can be strong, does not produce glare if mounted correctly. While not captured on the video, the eye height of the observer has to be considered – observers with low eye height (e.g. children, people on a recumbent bike, or possibly drivers of sports cars) may experience glare already at a lower angle. Also, asymmetrical lamps, which in countries with right-hand traffic are built such that the beam is cut off on the upper left side, but not on the upper right side, can produce glare for drivers of oncoming vehicles when the cycle path is located on the left side of the road.

8.2. Cyclist perspective

8.2.1. On/off-axis light

The limitations of retroreflectivity of reflexes depending on the angle between the incident light source and the eyes is demonstrated with a pedestrian walking away from and towards a stationary camera. The pedestrian wears reflexes on the ankles, knees and wrists. A bicycle front light is mounted first at fork height, then at handlebar height and finally as if on a bicycle helmet. It is demonstrated that the retroreflectivity works much better with on-axis light (i. e. the helmet-mount position), where the reflexes are visible also after the pedestrian has left the range of the beam of light. See the demonstration in a film, under the heading "Test av cykellysen: Lysets position - cyklistperspektivet"¹⁸.

¹⁵ <https://www.youtube.com/playlist?list=PLW8KqekouZadA82qeGzhqTUc-M9KhaVUH> .

¹⁶ <https://www.youtube.com/playlist?list=PLW8KqekouZadA82qeGzhqTUc-M9KhaVUH>

¹⁷ <https://www.youtube.com/playlist?list=PLW8KqekouZadA82qeGzhqTUc-M9KhaVUH>

¹⁸ <https://www.youtube.com/playlist?list=PLW8KqekouZadA82qeGzhqTUc-M9KhaVUH>

9. Discussion, conclusions and recommendations

The main purpose of this project was to investigate and compare different methods for bicycle light testing while at the same time testing a few generic factors. Not surprisingly, different methods yield different types of information. Maybe more surprisingly, lighting setups can be ranked rather differently, depending on the testing method chosen. Therefore, it is necessary to consider which aspects to test for and to keep in mind that different setups may rank differently depending on the question asked and method chosen.

9.1. Result discussion

The project results show that all lights tested fulfilled the Swedish legal requirement of being visible from at least 300 metres distance (in the dark), and all of them could be set to a steady beam, which is also required by law. The brightness and light field varied immensely between the lights, which could also be demonstrated by photographs taken in the lab and in the field.

Based on the results obtained in the study, for a cyclist to see well enough in unlit conditions we recommend a front lamp with at least 500 lux (measured 2 metres from the lamp) in the brightest spot, preferably with a wide beam shape in the lower area, such that the road sides and the road ahead are more or less homogeneously illuminated.

While brightness, beam type and mounting position did not influence gap acceptance, the subjective judgement of the participants showed that flashing light and a fork mounting were less appreciated than a somewhat stronger light and handlebar mounting. The latter proved to be marginally better for glare avoidance especially for the flashing light, such that this mounting position may be more recommendable than fork mounting. The fact that not having any light produced similar gaps as any light setup tested is congruent with the findings that the presence of conspicuity aids may not necessarily be related to crash risk (Tin Tin et al., 2013, 2014).

Gap acceptance seems to be more steered by the absolute distance in metres than by time gap. Similar results were found by Schleinitz and Petzoldt (2019), except that the accepted gaps were about twice as long as in the present study. This may be connected to the circumstance that their participants were seated in a car instead of acting as pedestrians but could also be linked to the fact that their study was conducted in daylight. Cyclists travelling at higher speeds will experience a larger number of short time gaps, than cyclists at lower speeds. This is aggravated by the fact that the stopping distance increases with the square of the speed. Unfortunately, none of the light setups tested here influenced the speed perception of the participants, even though the participants themselves judged their speed estimation capabilities with the steady beams as rather good. Future studies may show whether there are possibilities to indicate the speed of a cyclist better, which could be especially relevant with an increasing share of e-bikes on the roads.

9.1.1. Positioning of the light

A light source that is close to the line of sight (on-axis) reflects the light from all surfaces that are also visible to the eye. This implies that no visible shadows are created, which can make it more difficult to see if the road surface is uneven. On the other hand, retroreflective material is constructed such that the incident light is reflected back in the same direction. Therefore, if the light source is far away from the line of sight, the retroreflective power will be diminished. For a cyclist to see retroreflective material, have a light source that can make road unevenness visible by creating shadows, and allow legal mounting for example in Germany (below 120 cm), a different construction of reflectors could be a good solution. They would need to be constructed such that the incident light is reflected back at a greater angle.

From the bicyclist's perspective, it is also relevant where the lamp is mounted with respect to how the beam will behave in curves. A mount on the handlebar or fork will point the beam of light into the direction where the handlebars are turned. A mount on the head tube will lead to the beam pointing in the direction of the bike frame, making it more difficult to look into the curves especially for narrow beams and tight curves. Mounting the lamp on the cyclist's head means that the beam will point where the head is directed, both to the sides and up and down.

The height at which a lamp is mounted can also influence visibility and perception. Lower mounted lights, e.g. on the fork or just above the wheel, can cause the wheel to cast a shadow, and at the same time of course hide the lamp from view from those directions. Also, at least for the flashing light, the fork mount proved to produce more glare than the handlebar mount.

Even though regulations today typically demand that the lights be mounted on the bicycle instead of on the rider, research on biomotion indicates that a visible indication (by lamp or reflector) of the joints of moving bodies facilitate recognition (Edewaard, 2017; Hemeren, Johannesson, Lebram, & Eriksson, 2017; Kwan & Mapstone, 2004). Therefore, small rear lights mounted to the heels of a cyclist should aid in identifying the pedalling motion.

In the following, we discuss a few bicycle light features more broadly, based on regulations, the results found here and the demonstrated features, but also in relation to aspects that were not investigated in the present study.

9.1.2. Brightness

Most regulations only provide some sort of minimum value, which, in darkness, is achieved by practically any lamp. However, typically no upper limit is given. Seen from the cyclist's perspective, a front light should be bright enough for the cyclist to see what is ahead, considering both the cyclist's speed and the ambient light conditions. It can be counterproductive to have a light that is brighter than necessary, as the eyes adapt to the brightness of the light. An overly bright light will therefore render the non-illuminated surroundings darker, thereby compromising ambient vision. Being able to adapt the brightness of the light to the circumstances can, thus, save battery life and also reduce the risk to blind other road users.

Considering the perspective of other road users, an ideal light is visible early enough, does not produce glare and can easily be identified as a bicycle light. Very bright lights could be mistaken as belonging to another type of vehicle. As a measure to reduce glare, German laws require the beam to be cut off on the upper left side, such that it does not blind oncoming road users. This regulation presupposes that bicycles move on the right side in traffic, and it mainly considers car drivers as oncoming road users. Pedestrians to the right of the cyclist will not benefit from this regulation, and in countries like Sweden, where bidirectional cycle paths are commonplace, it occurs frequently that cyclists travel on the left side of the motorised traffic.

In addition, the brightness of the light perceived by the other road user influences whether and how well the silhouette of the bicyclist and bike can be discerned. Overly bright lights may prevent this, such that important hints for size estimation, which can provide information about distance, may be concealed.

9.1.3. Beam mode

The three main types of beams are steady (constant light), flashing (on/off in various intervals) or "rolling" (continuous light, but over time changing brightness or which LED is presently on). Existing research with respect to beam mode has been discussed above. It is possible that the shape of the on/off intervals both with respect to the relationship of the on-time to the off-time and the pattern of the flashes (e.g. regular vs. flash bursts) can affect how the light is perceived. For rear lights, the

comfort of following cyclists has to be considered too, especially as bright flashing lights can be perceived as disturbing.

9.1.4. Lamp design

Apart from durability and ease of handling, which are not treated here, lamp design also influences how visible the light is from the side. Some lamps are designed such that the light can be seen from a wide angle, while others do not allow the light to be visible from the side.

9.1.5. Recognisability

To aid in the prediction of a road user's speed, likely trajectory and likely positioning, it is helpful if the road users can be recognised as what they are. Therefore, it is positive if bicycle illumination can help others in recognising the cyclist as such. Typical appearance of the light, including brightness, positioning, beam mode etc. can all contribute to recognisability. However, light can also be used to accentuate the cyclist's shape. One unconventional option would be to turn the front light towards the cyclist, thereby illuminating his or her body. This could, of course, be combined with a forward-facing lamp. With such a setup, the cyclist should not be blinded by the backwards-facing lamp. Another option is to capitalise on biomotion. For cyclists, most body parts except the legs do not move very much in relation to each other, and when seen from the side, one leg is partially hidden by the other leg and the bicycle frame. Therefore, biomotion should be most effective when applied to the feet and knees. For recognisability from behind, the heels are an obvious placement of biomotion lights or reflector. For visibility from the side, ankles and knees, possibly in combination with the hip as anchor point, should be good starting points for biomotion-inspired light placement.

9.2. Method discussion

The methods investigated here require different amounts of resources to be conducted. The lab test can be done cheaply and quickly and can provide useful information about whether a front light is useful for the cyclist to see. Given that the other methods did not indicate a clear disadvantage of the lights that were best suited for seeing, it seems like the lab method can be a good starting point for cheap light assessment. That said, there are still many open questions, and the methods compared against each other here comprise only a fraction of possible testing scenarios. Gap acceptance was tested from a pedestrian's point of view, and the comparison with the results from Schleinitz and Petzoldt (2019) indicates that the accepted gap can vary depending on the type of interacting road user. How well this type of gap acceptance test corresponds to actual behaviour in traffic is not clear, and validation tests are difficult to make. Also, gap acceptance has only been tested for the interacting road user standing still, however, scenarios with a dynamic interaction where both parties move, like a left or right turn across the path of a cyclist, require quick and accurate assessments, which have not been tested so far. In real traffic, this requires a complicated experimental setup, but it is uncertain how valid simulator results would be. Other types of interaction, like whether car drivers' choice how to overtake cyclists depends on the lighting setup, have not been investigated either.

Furthermore, the field test here, as well as the tests reviewed, investigated situations where the participants knew that there would be a cyclist and from where he or she should be expected. It is important, however, that cyclists, just like any other road user, are seen even though they were not expected beforehand. Whether this can be supported by bottom-up stimuli like certain types of light setups, or whether this is a question of top-down processing, namely the expectation that a cyclist may be there, should also be investigated systematically.

In addition to the selection of factors and their effect on a subset of relevant aspects, many other effects can be considered or investigated. A few of those have been discussed here, showing that compromises between different goals likely have to be made.

9.3. Conclusions

Which method to choose for testing bicycle lights depends on the question asked. It has to be kept in mind that behaviour and opinion do not always go hand in hand, such that a test based on opinions alone may not be a good indicator for traffic safety predictions. For the same behavioural results, however, it may be advantageous to recommend lights that are least disturbing to other road users.

While static lab-like testing methods appear sufficient to test lamps for their quality as lights to see with, it seems that dynamic tests are needed for questions regarding traffic safety as a product of an interaction with another road user. If dynamic tests are conducted, it is advantageous to collect both behavioural data and subjective opinions, as the two may lead to different conclusions.

Finally, some questions are of physical nature and can be demonstrated or answered based on computations. An example of the former is the shape of the light beam and its benefits for seeing, and an example of the latter is the necessary distance that needs to be lit depending on the cyclist's speed.

9.4. Recommendations

9.4.1. Recommendations to cyclists

Even small and cheap bicycle lights fulfil the legal requirements. However, for you as a bicyclist it is advantageous to have a strong enough front light with a steady beam that spreads wide and in a regular manner on the ground in front of you, because this will help you to see the relevant surroundings and recognise obstacles and a damaged road surfaces in time, especially when you are riding in unlit areas. To avoid blinding other road users, the reflector of the light should be constructed such that the light spread is cut off sharply on the upper edge. Thus, if you position the light pointing slightly downward, you will be able to see far ahead without disturbing any oncoming traffic. If you mount the light on the handlebars instead of on the fork, the risk for blinding others is reduced, and your front wheel will not cast any shadows.

Mounting a light on the helmet can help in detecting reflectors and reading retro-reflective signs, but makes it harder for you to see edges and holes in the road. Also, there is a risk that you cause glare for other road users when you look straight at them, so if you have a helmet mounted lamp, consider making it your secondary lamp with a weaker beam that you can switch off easily in areas with oncoming traffic.

View films that demonstrate glare ("Test av cykellysen: Bländning")¹⁹ and the effect of placing the bicycle light in different heights on the bicycle or your head ("Test av cykellysen: Lysets position - cyklistperspektivet")²⁰.

Rear lights should help other road users see you and predict your movements and, like front lights, should not be irritating to others. So far, there is no conclusive evidence that flashing lights can fulfil those requirements better than static lights, however, especially strong flashing lights can be perceived as irritating for a road user that is following you, for example another cyclist (for a demonstration view the film "Test av cykellysen: Baklysen – efterföljande cyklist")²¹. While it is still necessary to investigate this question further in a scientific manner, we recommend using a static light in the rear.

¹⁹ <https://www.youtube.com/playlist?list=PLW8KqekouZadA82qeGzhqTUc-M9KhaVUH>

²⁰ <https://www.youtube.com/playlist?list=PLW8KqekouZadA82qeGzhqTUc-M9KhaVUH>

²¹ <https://www.youtube.com/playlist?list=PLW8KqekouZadA82qeGzhqTUc-M9KhaVUH>

9.4.2. Recommendations to manufacturers, retailers and test producers

Given the relevance of the shape of a front light beam, it would be valuable if a potential buyer could easily obtain information about this before making a purchase. The packaging of the lamp could include an illustration of the beam shape, and for lights sold in stores, a demonstration of the beam shape should be possible. This could then be compared to a template which illustrates how the features of a light beam against a wall can be translated to how the beam is perceived on the road. The light beam shape should always be subject of consumer tests.

The information provided on the package should be relevant to the user. Stating a lux measurement without any references to the distance from the lamp or the size of the area that is illuminated with this light intensity is meaningless. Stating lumen provides more information, as it can help in a direct comparison between lamps, but without any information about the spread of the light beam, the lumen cannot either be used as a direct indication for how far the light beam can reach. To help consumers, a list with recommended voluntary information to provide on light packages could be established.

9.4.3. Reflections addressing legal authorities

It is questionable whether the legal requirement that a bicycle light should be visible from a distance of 300 metres is of any practical relevance. The properties that are noticeable at a closer distance may be of greater significance. Also, from a practical standpoint it is difficult to investigate whether a light fulfils the requirements that involve such long distances. It is easier to measure a certain light intensity in a controlled laboratory environment, for example like the one described in chapter 4 in this report. It is desirable to base the legal requirements on scientifically validated results, such that the requirements actually target properties that are of relevance for enhancing traffic safety and road user comfort.

9.5. Further research

Within the frame of this project, the amount of evaluations that could be conducted was limited. We have neither investigated intention prediction nor distance estimation for rear lights in a dynamic situation, such as an overtaking manoeuvre. Further, no practical aspects like durability, power sources, battery life and environmental issues, nor mounting and handling in general were considered. Deeper understanding of which factors are relevant for safety is required as basis for possible changes in the legal requirements. Below, we list a number of topics that are valuable to achieve increased knowledge about:

- How do different bicycle light setups (including retroreflective material) influence conspicuity, visibility, recognisability, and intention prediction from the perspective of different road user groups (passenger car drivers, truck drivers, pedestrians and cyclists, who have different perspectives and own lighting). Not only static, but also dynamic situations, like overtaking manoeuvres or crossing each others' path should be investigated. Also, consider cargo bicycles, recumbent bikes, bike trailers and other bicycle types where the shape differs from the standard bicycle.
- How does the traffic environment influence the above-mentioned factors? This includes the overall brightness caused by ambient illumination like streetlights or other ambient light, the presence of bright light sources like advertisements or similar in inner-city environments, and the lighting of other vehicles.
- How do light intensity, angle and shape of the beam influence the ease and possibility to recognise edges, potholes and other damages to the road surface, and how do these factors influence the readability of traffic signs and other relevant information? While some of these questions are of physical nature, a test setup with human participants can provide information about the relative importance of different factors for different aspects of "seeing". This also

includes how far a cyclist needs to see ahead, depending on the own speed, to be able to ride comfortably.

With a good scientific base, legal requirements and standards have the potential to make traffic safer, and being able to refer to scientific evidence may convince more people to use the appropriate equipment, especially if it is designed such that it is reliable and can be used with ease.

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ABOUT VTI

The Swedish National Road and Transport Research Institute (VTI), is an independent and internationally prominent research institute in the transport sector. Our principal task is to conduct research and development related to infrastructure, traffic and transport. We are dedicated to the continuous development of knowledge pertaining to the transport sector, and in this way contribute actively to the attainment of the goals of Swedish transport policy.

Our operations cover all modes of transport, and the subjects of pavement technology, infrastructure maintenance, vehicle technology, traffic safety, traffic analysis, users of the transport system, the environment, the planning and decision making processes, transport economics and transport systems. Knowledge that the institute develops provides a basis for decisions made by stakeholders in the transport sector. In many cases our findings lead to direct applications in both national and international transport policies.

VTI conducts commissioned research in an interdisciplinary organisation. Employees also conduct investigations, provide counseling and perform various services in measurement and testing. The institute has a wide range of advanced research equipment and world-class driving simulators. There are also laboratories for road material testing and crash safety testing.

In Sweden VTI cooperates with universities engaged in related research and education. We also participate continuously in international research projects, networks and alliances.

The Institute is an assignment-based authority under the Ministry of Infrastructure. The Institute holds the quality management systems certificate ISO 9001 and the environmental management systems certificate ISO 14001. Certain test methods used in our labs for crash safety testing and road materials testing are also certified by Swedac.

