



Universität Hamburg

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Master's Thesis

Performance-optimized A/B-Testing for E-Commerce-Websites

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A distributed system is one where the failure of some
computer I've never heard of can keep me from getting my work done.
– *Leslie Lamport*

Contents

1	Introduction	1
1.1	Research Question	1
1.2	Goal of this Thesis	1
1.3	Chapter Outline	2
2	Introduction to E-Commerce and Web Analytics	3
2.1	E-Commerce	3
2.1.1	The Internet: Overview	3
2.1.2	E-Commerce	4
2.1.3	User Satisfaction and Performance in E-Commerce	6
2.2	Web Analytics	8
2.2.1	Introduction	9
2.2.2	Brief History of Web Analytics	10
2.2.3	Web Analytics Process	11
2.2.4	Data Collection: Log File Analysis and Page Tagging	12
2.2.5	Web Analytics Metrics	15
3	Web Performance	19
3.1	Introduction	19
3.2	The Website Loading Process	20
3.2.1	The Website Loading Process in the Network	21
3.2.2	The Website Loading Process in the Frontend: Critical Rendering Path	24
3.2.3	Technical Background Conclusion	28
3.3	Measurement Methods	28
3.3.1	Synthetic Monitoring	28
3.3.2	WebPageTest	30
3.3.3	Real-User Monitoring	30
3.3.4	Google Analytics	32
3.3.5	Log Files and Surveys	32
3.3.6	Measurement Methods Conclusion	32
3.4	Web Performance Metrics	33
3.4.1	Page Weight	34
3.4.2	Navigation Timing Metrics	34

Contents

3.4.3	User-Centric Performance Metrics	44
3.4.4	Custom Metrics	49
3.4.5	WebPageTest and Google Analytics Metrics	49
3.4.6	Web Performance Metrics Conclusion	53
4	Related Work	55
4.1	Research	55
4.1.1	some title for first category	55
4.1.2	Research about Tools	56
4.1.3	Research about Metrics	56
5	Approach	57
5.1	Empirical Research Methods	57
5.1.1	Controlled Experiment	57
5.1.2	Test Setup	57
5.1.3	Independent Variables within template	58
5.2	Test Object: HTML Template / Test website ideas	60
5.2.1	WordPress	60
5.2.2	Plain / Skeletal Website	60
5.2.3	HTTP Archive inspired website	60
5.2.4	Mirroring a complete e-commerce website	60
5.3	Test Runs	64
5.3.1	WPT Configurations	64
5.3.2	Test Object (Website) Variations	66
5.3.3	Test Plan. Generate the data	67
5.3.4	Test Protocol	67
5.3.5	Tool support for diagrams and data analysis	68
6	Evaluation	69
6.1	Test Results	69
6.1.1	Metrics for Evaluation	69
6.1.2	Original vs Mock Plain	70
6.1.3	Mock Plain vs Position 1 (which is default position of GA: Check this again!)	70
6.1.4	Position 1 vs 2 vs 3	70
6.1.5	Attribute 1 vs 2 vs 3	70
6.1.6	Other script True vs False	70
6.2	General	70
6.3	Plain / Skeletal Website	70
6.4	Mirroring	70
6.5	HTTP Archive inspired website	70

6.6	WebPageTest Bulk Tests	71
6.6.1	Bulk Test Overview: Description of test result page	71
6.6.2	Summary File for one Test	71
6.6.3	Aggregate Statistics File	71
6.6.4	Compare Section	72
6.7	Internal, external validity	74
7	Future Work	75
7.1	Limitations of this thesis	75
7.2	Other measurement tools and metrics	75
7.2.1	Google Analytics 4	75
7.3	Speed Kit	75
7.4	PWAs, AMPs, Service Workers, Caching, HTTP2 etc.	75
8	Conclusion	77
9	Appendix	79
9.1	WebPageTest Bulk Tests	79
9.1.1	Single Test Raw page data	79
9.1.2	Single Test Raw object data	83
9.1.3	Single Test Http archive (.har)	83
9.1.4	Combined Test Raw page data	83
9.1.5	Combined Test Raw object data	83
9.1.6	Combined Test Aggregate data	83
	Bibliography	85
	Eidesstattliche Versicherung	89

1 Introduction

[tbd]

- Explain structure and main goal of this thesis
- Describe shortly all sections from this chapter and what the reader can expect
- Give short outlook to following chapter

1.1 Research Question

The e-commerce industry is booming and there are no signs that this trend is reversing; on the other hand. Performance plays an important role in terms of customer satisfaction and how this directly affects business revenue. To better understand e-commerce website visitors, page tagging is widely used and implemented.

Several questions and issues can arise in this area and context, such as: Does page tagging affect the website's performance? Intuitively, it can be said that loading additional JavaScript will reduce the performance of the website, depending on parameters such as the script size and network condition. But are there more unpredictable side effects? Do the various techniques of embedding a tracking script affect the data collected and measured? Will the various tracking scripts supplied interfere with each other?

A hypothesis of this work is that tracking tools slow down the monitored websites, reduce the speed and performance of the website and thus have an unfavourable effect on the user experience.

These questions are to be investigated within the scope of this thesis.

1.2 Goal of this Thesis

This thesis has several goals:

The Internet and websites in general are complicated, complex, and tangled. Although basic HTML structures are standardized, each website follows its own form and is unique and sui generis. In order to conduct a controlled experiment and test hypotheses, one goal is to approximate real websites with an artificial, laboratory-generated website that is completely controlled and manipulated by the researcher.

The aim is to create a reliable, but also convincing test environment in order to model and reproduce real behaviour.

1 Introduction

Once the test environment is up and running, performance measurement issues need to be addressed. The aim is to measure, collect, visualize and analyse performance data.

As we will see in chapter X, there are many metrics for measuring performance. Another goal of this work is to establish something like a taxonomy of performance metrics.

1.3 Chapter Outline

[tbd]

Chapter 1 was about... In Chapter 2 we see, Chapter 3...

2 Introduction to E-Commerce and Web Analytics

[tbd]

2.1 E-Commerce

This chapter gives an introduction to e-commerce. Before going into the details, the emergence of e-commerce is described, starting with the Internet in section 2.1.1. In the following, I will briefly discuss the history of e-commerce and its types in section 2.1.2. The relationship between user satisfaction and the website performance is covered in section 2.1.3, which then leads to the chapter 2.2 which is about web analytics.

2.1.1 The Internet: Overview

In the last 50 years, a new technology emerged, spread over the entire world and influenced many aspects of most peoples life. Within the turmoil of the cold war, the United State's *Advanced Research Projects Agency* (ARPA) established in 1957 a communication network to bring together universities and their researches all around the country in order to be able compete against the USSR [CA11]. What started as a tool for scientific collaboration evolved half a century later into the *Internet*, a global network and phenomenon, to which every user with a dedicated device has access and can contribute to. The internet is an integral part, if not the backbone of today's everyday life. Users of the internet use it for almost everything, from sending emails, watching television, chatting with friends, order lunch, checking the weather for the next day or renting motorized scooters.

In 2021, the internet has 4.66 billion users, which is around 60% of the world population.¹ Compared to 2020, the number of internet users increased by 7.3%. In Europe, more than 90% of the population are internet users. For a developed country like Germany, the numbers are even more impressive: 94% of the German population are using the internet with an average daily time of over five hours.

Those numbers demonstrate impressive that the internet is an integral part of our daily life. Along the rise of the internet, transactions and processes falling under the term of

¹Following statistics are taken from <https://datareportal.com/reports/digital-2021-germany> [14.05.2021]

e-commerce are climbing as well. Before discussing the term "e-commerce" and take a grasp at its history and types, some statistics are presented to demonstrate the importance of e-commerce.

2.1.2 E-Commerce

Introduction

From the global data report², one can read out that over 90% of the world population visited an online retail site and over 76% of the world population purchased a product online. As usual, for or a western country like Germany, the figures are higher: 92.5% of the German population visited an online retail site and over 80% purchased a product online. And the usage is expanding: the growth of the amount spent within the category food and personal care is 28.6%, and 17.6% for the category fashion and beauty.

E-commerce sales have grown steadily over the past 20 years, topping to 57.8 billion in 2019.³

The COVID-19 pandemic with its implications had and still has an not negligible impact on the growth of e-commerce. Several measures were taken to stop the spread of the virus and the number of deaths, one of which was to minimize physical interaction between people. This leads consequently to a shift of human interactions to the internet. Along this, e-commerce benefits. Bhatti et al. [BAB⁺20] conclude that "e-commerce enhanced by COVID-19".

Brief History of E-Commerce

E-Commerce, or electronic commerce, is according to the *Encyclopædia Britannica* about "maintaining relationships and conducting business transactions that include selling information, services, and goods by means of computer telecommunications networks."⁴ In short, e-commerce is about buying and selling products and services via the internet.

The success of e-commerce is closely linked to the tremendous advances in Internet technology in recent years: The development of the *Electronic Data Interchange* (EDI) starting in the 1960s standardised the communication between two machines. Personal computers were introduced in the 1980s, and one of the first examples of an online shop is the *Electronic Mall* opened by CompuServe in 1984. Another crucial milestone is the launch of the *World Wide Web* (WWW) in 1990, which made the internet accessible to everyone. With social media visible on the horizon from the 2000s, new possibilities for businesses and consumers alike to participate in e-commerce arise, for example, by enabling new marketing strategies or providing new sales channels. New devices such

²<https://datareportal.com/reports/digital-2021-germany> [14.05.2021]

³<https://einzelhandel.de/presse/zahlenfaktengrafiken/861-online-handel/1889-e-commerce-umsaetze> [14.05.2021]

⁴<https://www.britannica.com/technology/e-commerce> [19.05.2021]

as smart phones and tablets lowered the barrier to participate in e-commerce. While e-commerce was available at any time, the new devices brought flexibility and mobility, making e-commerce available everywhere [Her19].

With the continued advancement in technology, e-commerce can expect a bright future with trends such as AI recommendation systems, outstanding UX thanks to virtual reality, or even more simpler payment methods through cryptocurrencies.⁵

Types

There are several types in e-commerce and they emerge from the possible combinations between the actors *business*, *consumer* and *government* [SSMG17].

	Business	Consumer	Government
Business	B2B	B2C	B2G
Consumer		C2C	C2G
Government			G2G

Table 2.1: Types of e-commerce.

B2C Business to Consumer in e-commerce describes basically online shopping, by means of a business offering its services and products to the consumer over the WWW. The consumer can browse through the products and services presented within an online shop and order them directly via the website. A variety of payment and delivery options conclude the B2C type [Hei20].

For an aspiring business, there are several ready-made software solutions for setting up an online store, as for example. *Shopify*, *ePages*, *Magento* or *WooCommerce* [SBR⁺19].

A famous example of a B2C company is *Amazon*. On the 16th of July in 1995, Amazon launched as a website and entered the stock market on the 15th of May 1997 [SB19]. Amazon has been successful, with the stock starting at \$1.5, which is at around \$3200 as of this writing.⁶ Today, Amazon employs over 1 million people⁷ and serves the desires of 200 million paying prime members.⁸

By taking a quick look at the pros and cons of an online store, it becomes clear that some of the advantages are that: there is no need of a real, physical store to showcase and sell the products; the virtual shop is available to the consumer at any time and has no closing hours; there is a high potential for the online shop as it is part of growing market; online business is scalable; due to tracking algorithms, precise targeting as well as data analysis

⁵<https://www.spiralytics.com/blog/past-present-future-ecommerce/> [19.05.2021]

⁶<https://finance.yahoo.com/quote/AMZN?p=AMZN> [19.05.2021]

⁷<https://www.statista.com/statistics/234488/number-of-amazon-employees/> [19.05.2021]

⁸<https://www.statista.com/statistics/829113/number-of-paying-amazon-prime-members/> [20.05.2021]

is possible; to start an online business, there is not so much floating required and there are generally lower costs; it is possible to provide a personalized customer experience.

Some disadvantages are that the speed of market is rapid, competitors arise everywhere and technology evolves quickly while consumers expectations go high [Her19], [LO20].

Another disadvantage is that there is no direct or physical connection with the consumer. As described above, online shopping takes place on the virtual WWW, i.e. personal interaction between buyer and seller is not possible and the shopping experience takes place on a website, from which it follows that the overall virtual user experience must be excellent in order to compete.

In the next section, I will describe the findings between the correlation between user satisfaction and the performance of the retailers web presence.

2.1.3 User Satisfaction and Performance in E-Commerce

The aim of this thesis is not to deep dive into terms and concepts or the non-trivial problem of defining user satisfaction, usability or the like. Therefore the term user satisfaction is in this context loosely defined as how happy the user is with the website he or she interacts with.⁹

Performance can be understood as the speed of an online shop, e.g. how long it takes the page to load, how quickly the user can interact with the page, and how the user perceives the performance of the website. In chapter X I will discuss that measuring performance is not so trivial and there are a lot of ideas and metrics to measure it.

SpeedHub

A plethora of information and studies about the phenomenon of user satisfaction and web site performance is collected at *SpeedHub.org*, a portal by *Baqend* in cooperation with *Google* which provides "the largest systematic study of Mobile Site Speed and the Impact on E-Commerce."¹⁰ Not only are studies and reports available on the hub, but also collections of videos and blog posts.

In his talk at code.talks 2019, Felix Gessert summarizes the results and provides insights into the most important aspects and questions of the study so far [Ges21]:

The first observation when asking for a correlation between the performance of a system and user satisfaction is that users need to be differentiated, which leads to the concept of a *User Profile*: In terms of gender, young women are the most demanding consumers and are less likely to buy from slow sites. In general, people between the ages of 18 and 24 have higher expectations of a site's speed than their older counterparts.

⁹For a discussion cf. "User satisfaction measurement" in [IKOK10]

¹⁰<https://www.speedhub.org/> [21.05.2021]

There are also differences between nations and regions, for example people from Japan have the highest expectations, which is almost certainly related to technological advancements in that country. Not only the expectations themselves differ geographically, but also how speed influences the users, for example "speed influences New Yorkers more than Californians." [Unb], [GA]

What all users have in common is their human psychology. In terms of performance, researchers generally suggest keeping wait times below one second to keep users' attention. (cf. "Performance perception" in 3.1).

After considering the user himself, the next step is to examine the influence of the device used: Studies show that mobile users are more likely to buy products and services than their colleagues using a desktop computer, where iOS users have generally more expectations regarding site speed [Dev].

Last but not least, the context and state of the user is important, with naturally relaxed and calm users perceiving pages faster than stressed or hurried users. Also users experience websites more slowly while on the go [Akab].

There are many real world examples and studies that prove and demonstrate the importance of website speed in terms of user satisfaction and ultimately sales: *Amazon* found out that a decrease of 100 ms in page loading leads to -1% conversion rates. If the site loads 100 ms faster, *Walmart* observed that the revenue increases by 1%. For *Zalando*, increasing site speed by 100 ms has led to an uplift of 0.7% revenue per session [Lin], [SKG⁺], [CKR].

Search engine optimization is heavily impacted by load speed: For *Google*, 500 ms slower sites led to a decrease of 20% in traffic. *GQs* traffic increased by 80% after the page load went down from 7 s to 2 s. And for *Pinterest*, 40% faster loads led to 15% more SEO traffic [Mos], [May], [MAC].

User engagement and satisfaction also depend heavily on loading times: *Forrester* noted an increase of 60% for the session length while brining down the load time by 80%. *Akamai* monitored that the bounce rate climbed up incredible 103% when the load time increased by 2 seconds. And for the *AberdeedGroup*, the customer satisfaction dropped by 16% at one more second delay in response times [For], [Akaa], [Abe].

In summary, it can be said that many studies and practical examples prove and demonstrate that faster websites and online stores lead to a better user experience and usually to happier customers. In commercial terms, one can conclude that page speed equals money.

In order to properly test the effects of performance on users, a scientific method is required. A/B testing as a controlled experiment is one of them and will be explained in the next section. After discussing A/B testing, I will move on to examining *Web Analytics*, a term that encompasses methods, tools, and instruments for companies to better

understand their business and customers.

A/B Testing

Controlled experiments like A/B testing are not a new tool for scientists and researchers and were used as early as the 1920s [KL17]. With the advent of the Internet in the 1990s, the concept was adopted into the online domain and is now used by large companies such as Amazon, Facebook or Google to test ideas and hypotheses directly on a live system. Controlled experiments such as A/B testing are used to aid decision making and provide a "causal relationship with high probability" [KL17]. They enable a data-driven and quantitative validation of the hypothesis [Mor18].

Controlled experiments help to test hypothesis and questions of form: "If I change feature X, will it help to improve the key performance indicator Y?"

To answer this question, two systems are needed: *Version A*, the control variant or default version, and a slightly different *Version B*, called the treatment. If more than two versions or one treatment should be evaluated at the same time, an A/B/n split test has to be implemented. With a univariable setup, only one variable differs between the systems; with a multivariable structure, several variables are changed at the same time.

Usually, the users of the system are randomly split into two groups and testing is directly performed with real users on a production system. It is advantageous, also compared to other experimental set-ups, that the users and participants are not aware that they are part of an experiment, which leads to fewer biases and side effects. In order to measure the differences and the user behaviour, web analytics has to be integrated within the system [KL17].

A brief and general discussion of controlled experiments in computer science can be found in chapter X.

To continue with the question of performance and user satisfaction, A/B testing allows two different versions of the same site to be served to two groups at the same time, one site being slow and the other being fast, without users knowing.

An implemented web analytics system makes it possible to measure how the various systems and user groups behave. What web analytics exactly is, what tools are available and what a web analytics process looks like, is discussed in the next section.

2.2 Web Analytics

This chapter is about web analytics. I will first discuss definitions and give a short introduction to web analytics in section 2.2.1. Then, a brief history of web analytics will be given in section 2.2.2 to help contextualize. After characterizing two web analytics process descriptions in section 2.2.3, data collection methods will be discussed in section 2.2.4. Finally, web performance will be explained in 3.1, which leads the way to the

research questions.

2.2.1 Introduction

What is *Web Analytics*? Reviewing the literature, it is clear that there are several definitions:

Nakatani et al. state that "Web analytics is used to understand online customers and their behaviors, design actions influential to them, and ultimately foster behaviors beneficial to the business and achieve the organization's goal." [NC11] According to this definition, web analytics is about getting insights of the users using the system, not only who or what they are, but also how they interact with the system. Additionally, the definition emphasizes that the underlying motivation of web analytics is to achieve business goals.

Singal et al. provide a more technical definition by pointing out that "Web Analytics is the objective tracking, collection, measurement, reporting and analysis of quantitative internet data to optimize websites and web marketing initiatives." [SKS14] Again, the ultimate goal is to drive business, but supported by data science methods and tools such as tracking, collecting and analysing massive amounts of data.

Bekavac et al. provide a similar definition by pointing out that web analytics is "the analysis of qualitative and quantitative data on the website in order to continuously improve the online experience of visitors, which leads to more efficient and effective realization of the company's planned goals." [BGP15]

Summarizing the above definitions, it is noticeable that web analytics consists of two important elements: a data-driven, information-oriented and technical element of collecting and analysing data about users and a commercial and business-driven element that provides the main motivation for collecting the data primarily by setting business goals.

Moving from definitions to the practical realm, Zheng et al. describe four main use cases for web analytics [ZP15]:

- Improving the overall design and usability, for example of the navigation or layout of the website.
- Optimize for your business goals: Whatever goals the business is trying to achieve, generating conversions is the goal.
- Monitor campaigns: Understand and measure the success of advertising campaigns.
- Improve performance by examining metrics such as page load time. This is discussed further in chapter 3.1.

Web analytics is also difficult and there are some obstacles and challenges to overcome. Kumar et al. describe some of the hurdles as follows [KO20]: The analysis and interpretation of the data and the goals and measures derived from it are reactive rather than

anticipatory, since "predictive modelling applications" for web analytics are not yet on the market.

Big data, that is the volume, variety and velocity of data collected, can be challenging to manage, for example, important insights can be lost or overlooked.

Privacy and the information collected from visitors and customers can be another challenge in terms of inappropriate use of data and GDPR compliance.

2.2.2 Brief History of Web Analytics

The history of web analytics can be described as a transformation from an IT domain and a technical log file analysis tool to a sophisticated, polymorphic tool for marketers.

Each time a user requests an HTML file or other resource from a web server, the server makes an entry in a special log file [SKS14]. The first log entries followed the *Common Log Format* (CLF) which provides rudimentary information such as the date, the HTTP status code or the number of bytes transmitted. In 1996, the *Extended Log Format* (ELF) was introduced with more flexibility and information in mind. Thanks to the standardized format of the log files, it was possible to create software that evaluates the log files and presents them to users in a readable form. *GetStats* was one of the first tools which generated statistics and user friendly output for analysts [CP09]. In 1995, Dr. Stephen Turner developed *Analog*, the first free software for analysing log files [ZP15]. Log file analysis will be further discussed in chapter 2.2.4.

What was initially mainly interesting for maintenance and IT staff, who for example answered the question of how many 404s occurred on the server, developed into an interesting website information pool for marketers.

As the available information increased, it became clear that the data could be used for more than just analyzing server behavior. But log file analysis was not enough to provide details about how users interact with the site. Web analytics underwent a transformation from log analysis to user data tracking, analysis, and reporting.

Croll describes the move of analytics from IT to marketing with three steps: [CP09]

1. JavaScript eliminated the need for log files and enabled marketers to maintain and deploy their analytics solutions themselves, making them less dependent on IT.
2. The introduced advertising economy of search engines like Google led to a new focus of analysts on user attraction and conversion rates.
3. New cost models allowed marketers to pay for the analytics service based on website traffic, rather than paying upfront for hardware and software. Analytics spend was thus linked to website traffic and, ideally, revenue.

In 1990 the WWW started and in 1993 one of the first widely used browsers *Mosaic* was launched. At the same time *WebTrends* developed and released one of the first analytics

software. A lot more services followed, such as *WebSideStory* in 1996 [CP09] or *Quantified* by Urchin in the same year [CP09].

Page tagging made it possible to collect not only technical data, but also business-relevant information. Visitors and their behaviour were the focus, shaping questions like: How is this user behaviour related to a purchase? If a user buys shoes, will he also buy socks? The development and implementation of cookies enabled the identification of unique users. Not only business-relevant questions were asked and answered, but also studies on performance and usability [CP09]. More details about page tagging can be found in chapter 2.2.4.

In 2003, Edwards, Eisenberg and Sterne founded the *Web Analytics Association* (WAA). The WAA brings together and supports all the players in web analytics such as users, marketers and IT specialists on an international stage. Due to digitalization and its all-encompassing effects, the WAA has renamed itself *Digital Analytics Association* (DAA) in 2012 because the web is not the only area where users leave their digital footprint [SKS14].

As described in the section above, participant and user numbers on the Internet continue to rise and now all Fortune 500 companies operate websites, with web analytics a key marketing tool [KO20].

Some of the most established tools today are *Google Analytics*, *Adobe SiteCatalyst*, *Webtrekk* and *Piwik* [Hei20]. Google Analytics will be further discussed in chapter ??.

Looking ahead, Zheng et al. identify several trends for web analytics, such as mobile web and application-specific analytics like video, search, learning, or social media analytics [ZP15].

2.2.3 Web Analytics Process

Web analytics can be described as a process in which the main goal is usually to increase sales. The literature cites two main ideas and processes, the first from the Web Analytics Association and the second from industry best practices. They are briefly described in this section.

Both processes have in common that they are aimed at improving the website and thus increasing business revenue.

Key Performance Indicators (KPIs) are the ideal tool for the instrumentation of web analytics and help to identify areas and potential for improvement. They are an integral part and play an important role in any web analytics process as they provide a "in-depth picture of visitor behavior on a site" [Jan09].

KPIs can differ depending on the business in which they operate. For commercial domains, common KPIs are conversion rates, average order or visit value, customer loyalty, bounce rate, etc. [SKS14].

Defining the right KPIs and aligning them with business goals is a critical step in any web analytics process.

WAA Process Guide

The Web Analytics Association offers a web analytics guide that consists of nine steps. They are: [Jan09]

1. Identify key stake holders
2. Define primary goals of website and prioritize them
3. Identify most important site visitors
4. Determine key performance indicators
5. Identify and implement the right solution
6. Use multiple technologies and methods
7. Make improvements iteratively
8. Hire and empower a full-time analyst
9. Establish a process of continuous improvement

Industries Best Practices

On the contrary, Waisberg and Kaushik derive a five-step process from industry best practices with the main goal of improving the website and increasing sales [WK09]:

- Define Goals
- Build KPIs
- Collect Data
- Analyse Data
- Implement Changes
- Repeat last two steps

When comparing the two proposed processes, it becomes clear that both focus on identifying and being aware of the most important business goals. The WAA process is a finer-grained and more practical approach, with Waisberg and Kaushik abstracting the main activities.

2.2.4 Data Collection: Log File Analysis and Page Tagging

There are four main methods of collecting data for web analytics: through log file analysis, JavaScript page tagging, web beacons, and packet sniffing [WK09].

As already mentioned in chapter 2.2.2, the two most important methods of data collection are log file analysis and page tagging. In this section I will briefly describe and compare both mechanisms.

Log File Analysis

As already described, the log file analysis is about gaining knowledge from the log file records of the web server. Log file analysis is considered to be the traditional and original approach to web analytics [Mar15], [ZP15]. As soon as the user types a URL into the browser and presses the enter key, the request arrives at a web server. The server then creates an entry in a log file and sends the requested page or resource back to the client in response [WK09]. The information within the log entry can vary depending on the log format, usually IP, browser, time stamp, time required, transferred bytes, whether a cache hit occurs and the referrer is specified [WK09]. The standardized Common Log Format provides host, ident, authuser, date, request, status, bytes, as can be seen in listing 2.1.¹¹

Listing 2.1: CLF

```
127.0.0.1 user-identifier frank [10/Oct/2000:13:55:36 -0700] "GET_/apache_pb.gif_HTTP/1.0" 200 2326
```

Standard formats of log files and entries enable log file analysis software to process, evaluate and report valuable statistics such as *Analog*, *Webalizer* or *AWStats* to users [ZP15].

Below are a few points that describe the pros and cons of log file analysis. The advantages of log file analysis are ([WK09], [NC11], [SKS14], [ZP15]):

- JavaScript and cookies are not required on the client side
- Maintainer of the website and server owns the data
- Bots and web crawler requests are also logged
- History of data is available
- Log entries are reliable
- The standard format of log files enables easy switching of analysis tools
- The web server also logs failed requests
- No modification on the web page needed
- Does not demand more bandwidth

Some disadvantages of log file analysis are ([Mar15], [ZP15]):

- Log entries provide mainly technical information, which may not be very useful for user behaviour analysis. Business related metrics such as bounce rates are not available.

¹¹<https://www.w3.org/Daemon/User/Config/Logging.html#common-logfile-format>
[03.06.2021]

- Only direct requests from the client to the web server are logged: Any user interaction in the web browser that does not trigger a request is not logged. Responses from caches and proxies are also not visible in the web server's log file. Only interactions with the web server are logged.

Page Tagging

In a nutshell, page tagging describes the analysis method used to incorporate JavaScript into the website, which collects data and sends it to an analysis server [Mar15]. To do this, JavaScript must be integrated on every page to be analysed [WK09]. Page tagging is the most important method in web analytics today [ZP15].

Croll provides a illustration (figure 2.1) of the page tagging process which is explained below [CP09].

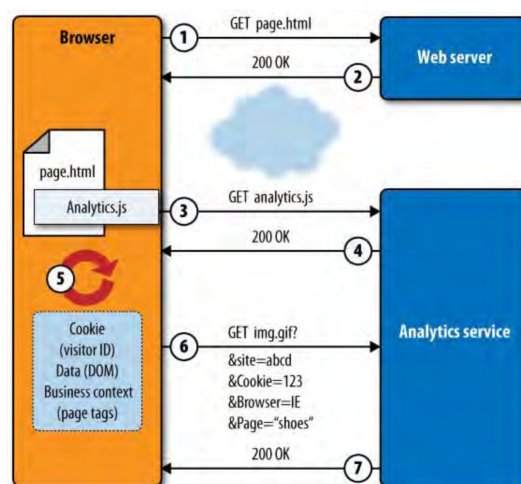


Figure 2.1: Page Tagging

The client (browser) requests a page from the web server (1, 2). Within the HTML file an external JavaScript resource, the analytics code, is linked and received from the analytics server (3, 4). The analytics script tracks and measures the user behaviour and eventually sends the data back to the analytics server (5, 6, 7).

The data collected can also be stored in cookies, which contain data beyond a session and enable the user to be identified, e.g. the next time he visits the page [KO20].

The advantages and disadvantages of page tagging are as follows, starting with the pros ([WK09], [NC11], [Mar15], [SKS14], [ZP15]):

- Every page visit is counted
- The analytics service is outsourced, which includes the storage of the data, but also the data analysis and reporting

- Page tagging is rather easy to implement and favourable when the analyst does not have access to the web server
- Highly customizable: Everything that JavaScript enables to measure, collect, and track is available. This also includes information about the client such as screen size, device used or color depth.
- Ability to track events and actions such as mouse clicks that do not send requests to the web server. This is especially important for single-page or progressive web applications that do not generate requests as often.
- Mechanics of cookies provide identification of unique and repeat visitors
- Real time reporting is possible

Some drawbacks are mainly privacy concerns and the permission to collect data by the user, that the analysis process relies on the use of JavaScript and cookies that can be disabled by the user [Mar15], that every page that is supposed to collect data must contain the analytics script and due to the use of a third party analytics service it is pretty difficult to switch tools [SKS14].

2.2.5 Web Analytics Metrics

[Introduction to Metrics]

In this thesis, two kinds of metrics occur: Web Analytics metrics and Web Performance metrics. Web Analytics metrics are metrics which reflect and quantify any business related aspect of the website. I use the term "business" or "non-performance" metrics to draw a line between metrics mainly concerned with a websites performance and metrics reflecting other web analytics aspects. I will use the terms "business", "non-performance" and "web analytics" metrics interchangeably. Business metrics are not directly responsible to capture performance data such as loading speed of a website. Performance metrics on the other hand are mainly related to website performance, for example site speed, as discussed in section X.

The selection of any kind of metrics and especially their relevance for the websites business enhancement is crucial. It is important to measure what is important and relevant for the users and reaching business goals, while "each business has its own definitions of success". Hence, metrics are ideally tailored and custom to the website and they should track if "your business benefited in some way from their [the users] visits." Just as each website is unique and serves a different purpose, so should metrics be, which quantify the website. As for each specific business question or use case, metrics can be made up, an unlimited amount of metrics exist.

Metrics are only helpful when they are useful. That implies that the collection and measurement of metrics should be consistent and their representation should be user-friendly and understandable. Kumar states that ideally, good metrics are uncomplex,

relevant, timely, and instantly useful.

In this section, I will describe metrics which are more likely correlated and mapped to business topics, such as conversion or bounce rate. In literature, a core corpus of web analytics metrics can be found and multiple ideas of structuring and categorizing those metrics exist. The different possibilities of categorizations are discussed next. Afterwards, one approach of categorization is then used to list a selection of common web analytics metrics.

Web Analytics Metrics Categorizations

Categories help to better grasp and comprehend metrics, and they can provide structure and order. Following are some examples of business metrics categorizations as they are presented in literature.

Peterson arguments from a marketing perspective and categorizes the metrics according to the customer life cycle, which includes the phases reach, acquisition, conversion, and retention.

Metrics for measuring *Reach* are for example number or percentage of new visitor. *Acquisition* contains metrics such as average number of visits per visitor or average pages viewed per visitor. The category *Conversion* includes metrics such as conversion or abandonment rates. And the last category *Retention* includes metrics such as the number of returning visitors. This proposed categorization is highly customer-related and customer-centric and from a marketers perspective.

The Web Analytics Association defines three types and accordingly categories of metrics: *Counts*, *Ratios* and *KPIs*, Where counts are metrics which are single numbers like the number of visits, ratios consist of counts divided by other counts, such as page views per visit. KPIs are counts or ratios with a specific meaning and importance for the specific business.

Jansen defines four categories for web analytics metrics: *Site Usage*, which encompasses metrics such as demographics and system statistics, but also visitor length and type, *Referrers*, that are metrics describing the referring URL, *Site Content Analysis*, which includes metrics such as top pages or visitor paths, and *Quality Assurance* with metrics reflecting errors or other quality aspects of the measured system.

Croll arguments that all metrics answer at least one of four user-centric questions: *What did they do?*, *How did they do it?*, *Why did they do it?*, and *Could they do it?*. Accordingly, the metrics are categorised by the question they answer.

Bekavac organizes the metric according to what they describe: *Visits*, such as entry or exit page, *Visitors*, such as the metrics capturing new or returning visitors, metrics such as page exit ratio or bounce rate which describe *Visitor Engagement*, and metrics describing *Conversions* as the conversion rate.

Hassler proposes a classification which is close and similar to the WAA proposed cate-

gorisation. The metrics are ordered by their type: *Counts* are absolute values like visitors or total sales, *Relations* put counts into relation for example as percentages, such as page views per visitor, and *Values* include non-numerical metrics such as referrer or search term.

Gessert et al. propose a semantic categorization of metrics, they structure the metrics according to their meaning and their domain membership. The categories are *Performance*, which includes performance metrics such as Time to First Byte or First Input Delay (see section X.), *User Engagement* metrics such as the session length or the bounce rate, *Business KPIs* such as the cart size or the amount of transaction, but also conversion rates and revenue, and *QA Metadata* which subsumes technical metrics like JS errors or the browser distribution.

Value-Driven	{Counts, Ratios, KPIs}, {Counts, Relations, Values}
Semantic-Driven	{Performance, User Engagement, Business KPIs, QA Metadata}, {Site Usage, Referres, Site Content Analysis, Quality Assurance}
Marketing-Driven	{Reach, Acquisition, Conversion, Retention}, {Visits, Visitors, Visitor Engagement, Conversions}

Table 2.2: Business Metrics Categorizations

As described above, multiple categorizations of metrics are proposed in literature. While some authors group the metrics by their type of value, e.g. if they count something or represent a ratio, others use a more semantic approach and group the metrics by their meaning, with some extreme examples by authors which group only through a marketing perspective.

In the following, I will list some metrics and provide brief explanations, following the categorization of counts, ratios and values. After that, i will take a look at metrics which are specific for performance.

Web Analytics Metrics Examples

Table X provides web analytics metrics which are not directly concerned with performance. The categories used to structure the metrics are *Counts*, *Ratios* and *Non-Numerical Values*, like they are already defined by Hassler or WAA in the section above.

Counts	
Hits	Represent amount of requests to the server.
Visits or Sessions	Count how many users view the website
Session Length	How long the session endures
Page Views	How often a page has been viewed
Single Page Visits	Sessions where one page has been viewed
New / Unique / Repeat / Return Visitors	...

2 Introduction to E-Commerce and Web Analytics

JS Errors	How many JS errors occurred
Cart Size	...
Conversions	... (business specific)
<i>etc.</i>	
Ratios	
Conversion Rate	...
Bounce Rate	...
Abandonment Rate	...
Page Views per Visitor	...
New Visitors Percentage	...
Visits per Visitor	...
Page Exit Ratio	...
Click Through Rate (CTR)	...
<i>etc.</i>	
Non-Numerical Values	
Demographics	...
Referrer	...
<i>etc.</i>	

Table 2.3: Business Metrics Examples

The table X provides a selection of common business metrics, following the proposed categorization of counts, ratios and non-numerical values and is not complete. In the next section, I will discuss web performance and accordingly web performance metrics, which are designed to directly capture performance related data.

[Transition to Web Performance]

3 Web Performance

[tbd]

[Last chapter]

[This chapter]

[Relevance of this chapter for research question]

[Next chapter]

[Outline of this chapter]

3.1 Introduction

As already described in chapter 2.1.3, web performance plays a role that cannot be neglected for user satisfaction and business success. The cited studies show that increasing website performance also increases sales, or as Google states it: "Performance plays a major role in the success of any online venture".¹

The MDN Web Docs identify multiple areas of web performance:²

- Reducing overall load time
- Making the site usable as soon as possible
- Smoothness and interactivity
- Perceived performance
- Performance measurements

Reducing load time In order to understand how load times emerge, the technical aspect of how websites are being loaded and presented to the user by the browser, needs to be comprehend. This question is covered in chapter X.

Concrete optimization steps and techniques to reduce load times are not focus of this thesis.

¹<https://web.dev/why-speed-matters/> [03.06.2021]

²https://developer.mozilla.org/en-US/docs/Learn/Performance/What_is_web_performance [03.06.2021]

3 Web Performance

Usability and interactivity As I will describe in chapter X, there are several metrics available that attempt to reflect areas of performance such as load time, smoothness, and interactivity, and specific metrics are available as well as for differentiating between technical and user-perceived performance.

Performance perception The perception of performance is generally subjective. As already seen in chapter 2.1.3, there are some quantifiable time intervals that correlate with human psychology regarding the received performance. Table 3.1 contains "unofficial rule of thumb" for delay thresholds [Gri13].

Delay	User Perception
0-100 ms	Instant
100-300 ms	Small perceptible delay
300-1000 ms	Machine is working
> 1 s	Likely mental context switch
> 10 s	Task is abandoned

Table 3.1: Rule of thumbs for delay

If one interprets the numbers from the table, one can make the statement that it is desirable to keep loading times below one second. Thresholds for certain performance metrics and the psychological rationale for setting them are discussed in chapter X.

Performance measurements There are several methods of measuring performance. *Synthetic monitoring* is discussed in chapter X. *Real User Monitoring* (RUM) is covered in chapter X.

3.2 The Website Loading Process

In order to understand web performance metrics and the methods to measure them, it is crucial to have a basic understanding of the technical aspect of the loading of a website into the browser. This process includes establishing a connection between a client and a server, which will be discussed in section X, and the task of the browser to transform the received data from the server into a readable ready-to-use website, which will be discussed in section X.

It is possible to divide the website loading process into three entities. In his code talk 2016, Witt identifies three main areas of the website loading process: The Front End, the Back End, and the Network. The Front End is everything the user sees on the screen, client, UI, browser, sends requests to a back end, etc. The Back End is the logic, server, also data base, handles requests and sends responses to a front end Network is what connects clients and servers, FE and BE, infrastructure element composed of routers, cables, wireless connections etc.

The main steps can be divided into networking, that is, establishing a connection with DNS etc., backend processing, e.g. data base queries etc., and the rendering in the front end, as seen in image X. The last part of this process is when browser receives finally the HTML / Document. How the browser transfers the HTML into an interactive website is part of the next section.



Figure 3.1: Timing Overview

- BE is not discussed (server time, data base, etc.) - Section X is about Network - Section X is about Front end: how browser works, crp, - How to optimise websites is not part of this thesis

Focus and perspective is performance, like in overall thesis. Also when explaining the technical background, I will keep the aspect of performance in mind.

Once I discussed the processes in the network and the front end, I will move on to the question of how to measure the performance of those processes, and which metrics are available to quantify the performance.

3.2.1 The Website Loading Process in the Network

[tbd]

The network is... Starting from hardware, ISP, routers, switches etc and the cables connecting them. But also communication protocols such as the Internet protocol suite.

Regarding performance, latency and bandwidth come into mind, and we will see that latency has a bigger impact on performance than bandwidth in section X.

After discussing this issue, i will continue by describing the process or navigation steps which happen once the user enters a URL into the browser, up until he sees pixels on his screen and can use the website.

Latency and Bandwidth

There are two important attributes when discussing network performance: Latency and Bandwidth. The important thing to say here is that Latency is bottleneck for performance, and not bandwidth.

Bandwidth is the "maximum throughput of a logical or physical communication path". In other words, bandwidth describes the amount of data which can be sent in parallel from one node in a network to another. Physical communication paths are most likely

3 Web Performance

cables such as metal wires or fiber-optic cables, where fiber-optic cables have less signal loss, and lower lifetime maintenance costs. With methods such as wavelength-division multiplexing (WDM), it is possible to transmit up to 70 Tbit/s over a fiber-optic connection. This high technology stuff is only used in the backbone infrastructure, e.g. for connecting Europe with America. For the end user, bandwidth is much lower, and the average was in late 2015 just 5.1 Mbps. A high bandwidth is useful for bulk or large data transfer such as streaming of video or audio. But for loading a website, or any browser activity that depends on many requests that fetch data from many different locations around the globe, the performance bottleneck is latency.

Latency is "the time from the source sending a packet to the destination receiving it". Latency is measured in seconds and can be the time spent for one-way, or more common, how long it takes for the transmitted data package for the round-trip time (RTT), from source to destination and back. In other words, latency "describes the amount of delay on a network or Internet connection". For the very first request when establishing a connection, latency is longer due to protocols such as DNS lookup, TCP and TLS handshakes. Those will be discussed in section X.

To get an idea about how the two aspects, bandwidth and latency, impact web performance, Mike Belshe launched a study. Once setup has a fixed latency and bandwidth is variable, and vice versa. He and compared the performance of the two experiments using the Page Load Time metric. (cf. X for this metric)

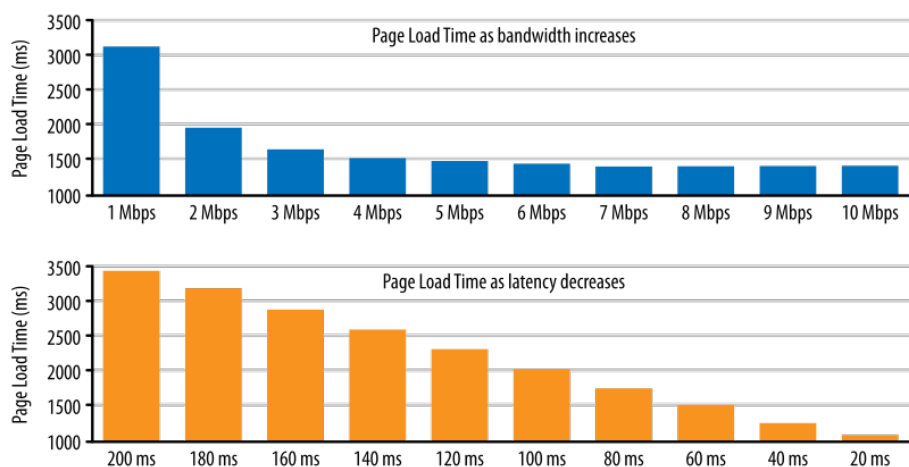


Figure 3.2: Latency vs Bandwidth

We can see that the impact of bandwidth is trivial: if the available bandwidth is doubled, e.g. from 5 to 10 Mbps, there is no change in performance load time. For Latency on the other hand, the picture is different: If the latency can be decreased by half, e.g. from 120 ms to 60 ms, the page load time also sinkt um die hälfte. Or as Belshe states it, "[reducing] cross-atlantic RTTs from 150ms to 100ms [...] would have a larger effect on the speed of the internet than increasing a user's bandwidth from 3.9Mbps to 10Mbps or even 1Gbps."

This observations can be explained with the many short, small connections and requests are made when browsing websites and the contrary underlying structure of the communication protocols, which are "optimized for long-lived connections and bulk data transfers. " But just simply decreasing the latency is not straightforward: The speed of data transfer is already at a 2/3 of light, but the physical constraint is the limiting factor, e.g. there is a minimum distance between London and New York which can not be further "optimized".

Another aspect of latency is that for wireless connections and therefore mobile devices, latency is even higher, "making networking optimization a critical priority for the mobile web." This is due to the infrastructure of mobile nets, latency is high for mobile users. cf. Why are mobile latencies so high? in Grigorik

As latency is a important factor, what happens on the front end is still important. And again for this thesis metrics measuring performance in the front end are the focus.

Before i will discuss what happens in the browser once the website data arrived, i will briefly describe the preceding steps of establishing a connection between the browser (client) and the server, which can be considered to be still a part of the network.

Network Navigation Steps

[tbd]

I will explain briefly the main navigation steps: It begins when the user is submitting a URL in the browser and ends when he received website data.

"To start, it is important to recognize that every HTTP request is composed of a number of separate stages (Figure 10-3): DNS resolution, TCP connection handshake, TLS negotiation (if required), dispatch of the HTTP request, followed by content download."

DNS Lookup When the requested resource can not be loaded from the browsers cache, the first step to establish a connection is a DNS Lookup (or DNS Resolution).

This step is about translate URL to IP address. Must be done for each unknown URL, e.g. when linked images within a website are from different server, for each unique URL DNS Lookup has to be done. The mapping of URL to IP can be cached by browser, which makes repeated views faster.

Avg. time is 20 and 120 ms

TCP Handshake Once a connection between a client and a server is established, the TCP 3-way-Handshake comes into play.

The goal of TCP is to establish a reliable connection within an unreliable network. TCP "guaranteed that all bytes sent will be identical with bytes received and that they will arrive in the same order to the client. " Regarding performance, the handshake adds two more round trips, which is bad for performance as we have seen because of latency.

3 Web Performance

Many algorithms and techniques to get optimal data transfer and also avoid congestion are existing, such as Slow-Start. Slow-Start is an algorithm that determines the maximum bandwidth that can be used by gradually increasing the amount of data sent. Slow start prevents that the full capacity of the network is being used from the beginning, which in performance terms adds again more round trips and latency.

For a detailed discussion of "Building Blocks of TCP" in 2013 Grigorik

TLS Negotiation TLS is another protocol which has the goal to establish a secure connection in terms of data encryption. Data transmitted over the network has to be encrypted so that aussenstehende can not read or manipulate the data. For encryption, a cipher to be used needs to be established, which will be shared between client and server during the TLS Negotiation.

TLS again adds more round trips which is bad for performance.

for a detailed discussion see Transport Layer Security (TLS) in 2013 Grigorik

HTTP Request and Response Now that a secure connection is established, the client fetches the first resources via HTTP GET request. Most often, the server will respond by sending back the index.html file, which then can be used by the browser to build the website.

The time when this first response containing the first byte for building the web site is reflected in the metric TTFB which is discussed in section X.

Usually, many more resources are requested by the browser to complete the build of the web site. As of today, the median value is about 70 requests per web site.

A request is not the same as a connection. Once the connection is established via the above described procedures such as DNS lookup, TCP and TLS handshakes, multiple requests can be transmitted over the same connection. Usually, the number of requests is much higher than the number of connections to load a website, as the browser persist connections, keep them open for multiple requests. Median connections for a web site today is about 13. Modern browsers like Chrome enable up to six open connections in parallel.

At this point, the browser has received the first data about the web site and he can start with rendering the page. How this exactly happens, is explained in the next section.

3.2.2 The Website Loading Process in the Frontend: Critical Rendering Path

This section explains what happens after the first bytes of the web sites arrived in the browser. The following processes are typically subsumed under the term *Critical Rendering Path* (CRP). The CRP is the last part of the navigation process as seen in image X.

The CRP is the minimum steps that the browser has to take from the moment it receives the first byte of HTML to the moment that it renders pixels on the screen for the first time.

The rendering is critical as it is the very first render, the first visible content the user will see on the screen. The resources that are needed for the first render of the page are considered to be critical. Without the critical resources, the browser can not display content on the screen. An example of a critical resource is the first HTML file the browser receives, as without it, nothing is visible on the screen. Non-critical resources on the other hand will not stop the browser from displaying the first content on the screen.

There are a sequence of steps the browser goes through to render the page. The basic idea is to convert HTML, CSS and JS to actual pixels on the screen.

Image X visualizes the flow of the CRP: Once the HTML is received, the browser starts with parsing the HTML and translate it into the DOM. The content of the CSS files will be parsed to the CSSOM. JavaScript needs to be fetched and executed. Once DOM and CSSOM are available, the Render Tree is being created. When the Render Tree is available, Layout is happening. Finally, pixels can be printed on the screen.

In the following, the individual steps will be discussed in more detail.

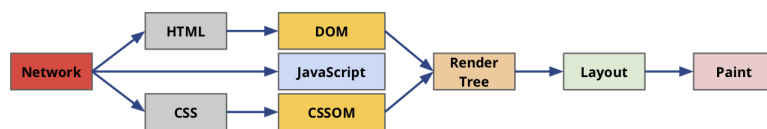


Figure 3.3: Critical Rendering Path

DOM Construction from HTML Once the browser received the first bytes of the HTML file, it starts to parse it into the *Document Object Model* (DOM). The DOM construction is the first step the browser performs when receiving data. The DOM is a tree structure and internal representation of the HTML for the browser. The general parsing process consists of translating from bytes to characters, to tokens, to nodes and finally to the object model. The specification of the DOM is maintained by the WHATWG living standard.

The DOM tree contains information about the content of the document, but not its style. The styling is defined in the CSS. Once HTML and CSS are transmitted and processed by the browser, the *Render Tree* can be created, which reflects the actual information and its styling the browser can display. Within this context, it is possible to categorise resources into render blocking and non-render blocking. A render blocking resource is a resource that prevents the browser from rendering content to the screen. HTML and CSS are render blocking resources, as the parsing process of those files blocks the browser of displaying the page to the screen.

As soon as the first data packages of HTML arrive at the browser, the parsing process starts. The DOM is created incrementally, this means that the browser can begin to process the HTML before all of its content is transmitted over the network.

3 Web Performance

Usually, within the HTML, external resources are linked which are necessary for the website to be complete, such as CSS or JavaScript. While parsing the HTML incrementally, eventually a reference to such an external resource will be encountered. How the external resources CSS and JavaScript are being handled by the browser is discussed below.

CSSOM Construction from CSS The CSS resource contains all information about the styling of the page. As with the HTML, CSS is converted from bytes to characters, to tokens, to nodes, and finally to the *CSS Object Model* (CSSOM). CSSOM construction is usually very fast. CSSOM is standardized here

As opposed to the HTML parsing process, CSS can not be translated to the CSSOM incrementally. Cause it the cascading nature of style sheets, which has the potential that the styling rules defined at the top of the file may be overridden by rules defined at the very end of the CSS file. A partial CSSOM is therefore not possible. Hence the browser needs the entire CSS file before he can create the CSSOM.

As soon as the parser encounters a reference to an external style sheet such as

```
<link rel="stylesheet" href="styles.css">
```

it requests the resource and continues with parsing the HTML. CSS is not a parser blocking resource. When the CSS arrived at the browser, the CSSOM construction starts.

While CSSOM creation is not parser blocking, it is render blocking. The browser blocks the page rendering until it received and parsed all of the CSS. Rendering content to the screen is only possible when CSSOM and therefore CSS is available.

Once the DOM and CSSOM are created, they can be merged together into the render tree, which will be layout and painted to the screen. Before I describe this process, I will discuss how JavaScript is being handled.

JavaScript in the Critical Rendering Path JavaScript (JS) resources add functionality and interactivity to a web site. When the browser encounters a script tag such as

```
<script src="myScript.js"></script>
```

it will stop its current task of parsing, fetch immediately the resource and execute its content, and only then proceed with the creation of the DOM. See image X.

JS can manipulate and query the DOM tree and directly change the HTML file. As the HTML file is the input stream for the parser, the parser stops until the JS is downloaded and executed. Hence JS is parser blocking. JS fetching and execution stops the parsing of the HTML and the construction of the DOM. Only after the script finished execution, HTML parsing will continue.

Implicitly, because JS execution blocks DOM creation, and HTML processing itself is render blocking, JS is also render blocking.

The behaviour is the same for an external references JS file and a script directly added within in the HTML.

As JS can also manipulate the styling of the page, its execution is blocked until the CSSOM is available. This means that the execution of the JS is on hold until the CSSOM is ready. To summarize, while JS blocks the parsing of the HTML to the DOM, JS execution itself is blocked by the creation of the CSSOM. CSSOM blocks JS, and JS blocks DOM construction.

Several attributes on the script tag can change the behaviour of the browser. *Async* and *defer* are options to counter the blocking nature of the script tag. They will be discussed now.

With the *async* (asynchronous) attribute, the browser downloads the JS in the background while continuing with the parsing of the HTML. The parsing is not blocked and the browser can continue with his task. As soon as the JS is downloaded and available, it is parser blocking: the browser stops the parsing and executes the JS.

The order of all the *async* scripts within the document is not maintained any more. Whenever a script is downloaded and available, it will be executed. It does not matter if an *async* script was included at the top or bottom of the HTML document.

Like with *async*, scripts with the *defer* attribute enable the browser to download the script in parallel while continuing with the parsing of the HTML. Contrary to *async*, *defer* scripts will only be executed after the parsing of the page is complete and the DOM tree is fully constructed, and the order of the scripts will be maintained.



Figure 3.4: Scripts

The *async* and *defer* attributes not applicable on inline scripts. The HTML standard states that "scripts may specify *defer* or *async*, but must not specify either unless the *src* attribute is present. " As inline scripts do not contain a *src* attribute, as the source of the script is within the script tags and not external, the *async* and *defer* attributes are not applicable.

Building the Render Tree As already described above, HTML and CSS are both render blocking, as they prohibit the rendering of the page. Rendering can happen once the *Render Tree* is available. The render tree is the combination of the DOM and CSSOM and captures all visible content with its styles which will be displayed on the screen. If an element has a CSS property such as `display: none;` it will not occur in the render tree.

The computed render tree is then used to layout the content to the page.

3 Web Performance

Layout In the layout process, the position and size of the nodes from the render tree are calculated. New layout calculations or reflows are triggered as soon as the screen area changes, e.g. by device rotation or window resizing, or on modifications of the DOM and render tree.

Once the layout is resolved, the browser continues with painting pixels on the screen.

Paint Finally, the browser can paint the content on the screen. If some content changes, browsers are optimized to only repaint areas on the screen affected.

3.2.3 Technical Background Conclusion

[tbd]

Network, BE and FE. Network: Latency and Bandwidth, Navigation steps FE: CRP

[Link to next section] Why was this section important for research question? How is it connected to measurement methods and metrics?

3.3 Measurement Methods

[tbd]

Last section: At this point we have an understanding of how web sites are being loaded into the browser and displayed to the user. Some of the steps are more important for performance than others. In this section, I will describe how to measure the performance of a website.

[Link to Research Question]

Multiple methods for measuring website performance exist. The prominent ones are synthetic monitoring and real user monitoring. They will be discussed below.

Some other methods are mentioned in the last section.

After discussing measurement methods, I can finally discuss the metrics we want to measure.

3.3.1 Synthetic Monitoring

The "Synthetic" Aspect in Synthetic Monitoring

As the name already suggests, synthetic monitoring is a measurement method performed in an artificial, laboratory-like, synthetic environment. Test agents simulate real users and are configured to run a browser, load the web site under observation while capturing performance data. Synthetic monitoring does not take real user traffic into account.

Performance data can be captured using common performance APIs as described in section X. Additionally, through video recording and analysis, user centric metrics such as Speed Index can be computed (see section X.)

In synthetic monitoring, many possible configurations and variables of the test agent (client) are under control, such as the location (geography), network conditions, device type, browser version, and so on. Hence, the tester has control over many variables that impact performance.

The controlled environment makes it possible to capture performance data for a specific set up of configurations, such as the test agents location or browser version, which may help to identify issues regarding certain user segments. For example., a test could check the performance of all users using Firefox running on macOS in Germany.

Apart from defining the technical configuration such as browser version or network condition, the tester can also define artificial user journeys to simulate real user behaviour.

A characteristic of the controlled environment is that measured data and test results are rather consistent with low variability and can therefore provide a performance base line for the web site under observation and facilitate performance tuning.

Synthetic Monitoring is not about Real Users Synthetic monitoring does not capture data of real users as the web sites traffic is generated artificially. Real user behaviour is approximated through simulation of users by for example predefining user paths. The measured performance data does not necessarily reflect actual real user experience and the tester should not assume that "synthetic results are like real-user metrics".

Capturing the wide variety and diversity of real-world users such as which pages they visits,, the general configuration of the users machine such as the CPU, GPU and memory performance, what data stores the browser cache and which browser version is being used, the screen size, the operating system, and the network connection to name a few, is difficult to represent in synthetic monitoring. The selected test configuration in synthetic monitoring only reflects one special use case and can only approximate what a user with a similar set up may experience. In short, synthetic monitoring test results "are synthetic and therefore not representative for actual user data".

The "Monitoring" Aspect in Synthetic Monitoring

Synthetic monitoring can be automated and used to monitor a systems performance in real time while generating up to date reports for the systems maintainer. Monitoring enables to check the availability of the web site around the globe, to identify performance issues before real users are aware of them. and is in general helpful for continuous "health checks" of the running system.

As any web site can be tested synthetically, it is possible to compare performance data across multiple competitors.

Many synthetic monitoring tools exists (For a list of tools, see for example 2016 Kaur or some online resources here). WebPageTest is one of them and will be discussed in section X.

3 Web Performance

Coming back to e-commerce context, as discussed in section X. a online shops performance correlates with the revenue. Synthetic monitoring allows to capture performance metrics independent of real user behaviour. Real user behaviour is not measured in synthetic monitoring. As only real users are capable of generating revenue, synthetic monitoring can not identify correlations between user satisfaction and performance (as described in section X.).

In order to do this, RUM is needed. Real-User Monitoring (RUM) enables to capture data of each individual real user . RUM will be discussed next.

3.3.2 WebPageTest

Overview

[tbd]

Configuration

[tbd]

Private Instances

[tbd]

3.3.3 Real-User Monitoring

As the name suggests, Real-User Monitoring (RUM) is about collecting and measuring data from real users visiting the web site. As opposed to synthetic monitoring, where web site traffic is generated artificially and performance experience from real users is only approximated, RUM data relies on real user traffic and captures data directly from each users browser. RUM measures the performance as experienced by the users.

The Page Tagging Technique in RUM

As already described in section X. Page Tagging is a technique to instrument the users browser in order to collect data and report it back to an analytics server. RUM is based on page tagging, in terms of that it relies on a JS code snippet (tracking or code) which will be loaded into the users browser. Once this JS code is loaded and executed in the browser, it collects data and sends it back to an analytics service. If the user blocks JS, or the script can not be downloaded due to other reasons, RUM will not work. Once the data arrives at an analytics service, it has to be stored and an interface for the analyst has to be provided in order that he can query the data and get insights, for example by providing a dashboard.

As RUM relies on the JS code, the very first opportunity to measure data is when this JS code has been downloaded and executed. Anything what happens before this step is not

visible for the tracking script and therefore the analyst. Meenan states that approximately 20 % of the loading process lies outside of the RUM measurement scope and "getting a reliable start time for measurements from the real world has been the biggest barrier to using RUM".

Another facet of RUM is that ideally the measuring of data has as little as possible impact on the web sites rendering process and that network capacity should not be occupied by RUM scripts and block resources of the CRP (see section X.) If RUM, as a page tagging technique, is slowing down the web site under observation, is one research question of this thesis. The evaluation of the controlled experiment tackling this questions states that RUM...., as discussed in great detail in section X.

RUM is independent of the users set up or environment and collects data for all active users: Regardless of the device, the browser, the network condition or the geographical location of the user, as long as the measurement script is downloaded into the users browser, RUM collects data. Hence, RUM data represents each individual user experience.

Through the diversity of users and the unique environment of each user, RUM data tends to be more diverse and heterogeneous than data collected by synthetic monitoring.

RUM Measures Behaviour of Real Users

As discussed in section X, a web sites performance and user satisfaction are directly correlated. A critical part of RUM is to not only capture performance metrics, but also measure user behaviour, for example how the user interacts with the web site and where he clicks. In an e-commerce context, user behaviour questions of interest are for example if a new campaign changes user behaviour as expected or where users leave the check out process.

RUM facilitates the combination of collected metrics with user behaviour and business KPIs and can answer questions such as if and how the performance of the web site affects the user behaviour, for example if users buy more or less depending on the web sites speed. Thus RUM is not only important for understanding user behaviour, but also for optimizing the web site and to increase revenue. With techniques such as cookies (see section X.), it is also possible to track user behaviour not only for one page load but over a series of web site visits, leading to even more detailed insights about the visitor.

Multiple RUM tools and JS libraries exists, such as Boomerang by Akamai.³ The main player Google Analytics will be discussed in greater detail in section X.

Google collects RUM and browser data of chrome users agreed to do so. The data is accessible through the Chrome User Experience Report (CrUX) and will be discussed next.

³<https://github.com/akamai/boomerang> [23.06.2021]

Chrome User Experience Report (CrUX)

The Chrome User Experience Report (CrUX) is a RUM method implemented by Google which collects real user data of Chrome users. As soon as the Chrome user gives his consent, data collection can start and does not need any more set up.

The CrUX only captures data from Chrome users and is therefore not an exhaustive sample of the web users population, as data by users browsing the web with for example Firefox or Safari is not collected.

The collected data is available via Googles PageSpeed Insights, the CrUX Dashboard or the BigQuery and CrUX API.

3.3.4 Google Analytics

[tbd]

The Tracking Script

[tbd]

Real World Examples

[tbd]

3.3.5 Log Files and Surveys

[tbd]

Other methods are surveys and log file analysis.

3.3.6 Measurement Methods Conclusion

Multiple methods to measure performance of a web site exist. Two main complementary techniques exist, Synthetic Monitoring and Real-User Monitoring.

Synthetic Monitoring measures a web sites performance in a controlled environment using test agents and is especially useful to find a performance base line of the web site and for continuous monitoring and health checks. Performance as end users may experience it can only be approximated it is not captured by synthetic monitoring.

RUM collects data from each user visiting the web site and reports it back to an analytics server. RUM is especially useful when combining multiple metrics together such as performance and business metrics in order to analyse user behaviour. On the other hand, when no user is visiting the web site, RUM is not collecting any data.

Other performance measurement methods such as CrUX and surveys provide browser specific or quality data and complement the analysts tool box.

Metrics are critical in order to map performance to some sort of value or number. Through metrics, performance is quantifiable to some extent and therefore comparable.

Synthetic Monitoring	RUM
Artificial test agents	Real users
Controlled configuration	No control over configuration
Approximates real user data	Collects real user data
For monitoring	Links user behaviour to business KPIs

Table 3.2: Synthetic Monitoring and RUM

As already described, measurement methods such as synthetic monitoring or RUM can measure metrics such as "performance" or "business" metrics. What are does metrics exactly? What do they reflect? How can they be measured?

Those questions will be addressed in the next section.

3.4 Web Performance Metrics

[tbd]

[Link to Research Question]

As discussed in section X., web analytics, or business or non-performance metrics, track data about many different aspects of an online venture, for example, how many visitors the website has, or what the conversion rate is. For measuring performance, for example site speed and how users perceive the performance of the website, a set of special metrics is needed. Performance metrics are established to measure various performance aspects of a website and will be discussed in this section.

Through performance metrics, performance is quantifiable, as the metrics reflect performance as numbers. Once performance is mapped to numbers, they can be compared with each other, for example over time, after a change in the measured application, or with numbers of a competitor. Through their performance quantification, metrics facilitate the analysis of website traffic. Specific metric values can be used as a target for goal achievement and are therefore a critical instrument for improving websites. Ideally, metrics are precise and serve as objective criteria for the evaluation of the measured website.

As with web analytics metrics, multiple ways exist to structure and categorize performance metrics. One way to bring order to performance metrics is to differentiate between performance timing metrics, which measure elapsed time for concrete processes and navigation steps from the CRP, and user-centric performance metrics, which approximate user perceived performance by visual analysis. Both classes of metrics will be discussed in the following. Beforehand I will discuss page weight, a metric which characterizes the size of a website. The benefits of custom metrics and why they are important concludes the section about performance metrics.

3.4.1 Page Weight

A naive approach of quantifying a website is measuring its size and the amount of resources needed to build the website. Page weight can be used as a performance metric as the performance of a website depends on its size, especially in conjunction with the network condition, like download speed and latency. The more bytes have to be transmitted over the network, the longer it takes for the website to get constructed and the longer the waiting time for the user is. Similar for requests, the more requests are needed, more connections need to be established, which takes more time.

A website consists of multiple resources, such as HTML files, fonts, script files or images (cf. table X). Page weight describes the number of bytes fetched and requests made for each resource type.

HTML	CSS	JS	Fonts
Images	Videos	Others	(Total)

Page weight is a first assessment for a website regarding performance. It is mainly useful for comparison with median values or other websites, but has little to nothing expressiveness and significance for evaluating a websites performance. To get more useful insights about a websites performance, other metrics are in need, such as navigation timing metrics, which will be discussed in the next section. As described in section X, the idea of page weight is used to construct a test site with a median page weight values.

3.4.2 Navigation Timing Metrics

Navigation timing metrics depict elapsed time within the website loading process such as navigation and CRP (cf. section X). They are calculated and derived from a set of standardized Web APIs. In the following, I will briefly explain the nature of web standards and recommendations. Then, performance relevant specifications and the metrics they expose are discussed.

Web Standards

Web Standards are documents describing the technology used to build the WWW. Those documents, also called specifications, are maintained by different groups and organizations. Multiple organizations exist to provide and maintain standards for different areas and technologies of the web. Such organisations are for example the WHATWG, which maintains the HTML living standard⁴, or Ecma International, providing the specification for JS.⁵

⁴<https://whatwg.org/> [11.07.2021]

⁵<https://www.ecma-international.org/> [11.07.2021]

The World Wide Web Consortium (W3C) is an organization which maintains different standards for the WWW, including specifications for performance measurement⁶, and will be discussed next.

W3C The W3C was founded in 1994 by Tim Berners-Lee, with the goal to bring together "representatives from many different technology companies to work together on the creation of web technology specifications". The W3C maintains and publishes documents that describe and define web technologies such as DOM, SVG or CSS.

The document, or specification creation, follows a "recommendation track", which describes the hurdles a document needs to overcome in order to turn from an idea into a final recommendation and web standard, which browser vendors implement as concrete APIs. The phases in the recommendation track are described by "maturity levels" of the document and are as follows: First Public Working Draft (FPWD) → Working Draft (WD) → Candidate Recommendations (CR) → Proposed Recommendation (PR) → W3C Recommendation (REC). W3C Recommendations are considered to be web standards.

Web Performance Working Group Within the W3C, several groups exist, each one concerned with a specific topic within the WWW universe. The Web Performance Working Group, founded in 2010, is a group responsible "to provide methods to measure aspects of application performance of user agent features and APIs"⁷.

The Web Performance Working Group publishes and maintains a variety of documents concerned with performance measurement, such as High Resolution Time, Navigation Timing or Page Visibility. The released publications especially important for performance metrics are discussed next.

High Resolution Time Two versions of High Resolution Time exist. High Resolution Time Level 2 has the maturity level of a W3C Recommendation and was released in November 2019. The newer specification, simply High Resolution Time, is a Working Draft from June 2021. The High Resolution Time specification does not expose or define performance metrics directly, but serves as a basis for other specifications regarding measuring and capturing time values.

Before High Resolution Time, time values were calculated with ECMAScripts Date object, which represents time in milliseconds since 1 January 1970 UTC. This definition of time is imprecise in terms of clock skew and system clock adjustments. It is possible that the time values derived from the Date object are not monotonically increasing, or sometimes even decreasing.

High Resolution Time solves those issues and provides monotonically increasing time values, a resolution of sub-milliseconds and an start value which is relative to the web-

⁶<https://www.w3.org/> [11.07.2021]

⁷<https://www.w3.org/webperf/> [11.07.2021]

3 Web Performance

sites start of the navigation process, instead of the year 1970, which makes it more feasible to understand and calculate time stamps and intervals. The following specifications use the precise timing information provided by High Resolution Time.

Navigation Timing Two versions of Navigation Timing exist. A W3C Recommendation "Navigation Timing" (Level 1) from December 2012 and "Navigation Timing Level 2", a Working Draft from March 2021. Level 1, still in use for backwards compatibility, uses the more imprecise time measurement starting from 1 January 1970. Level 2 replaces Level 1 and relies on the exact high resolution time as described above. A summary of improvements from Level 1 to Level 2 is listed in

Navigation Timing exposes time stamps of events which occur during the navigation and loading process of a website. All relevant timing information from the document loading process are accessible through Navigation Timing. The navigation or loading process depicts the conversion of the received HTML document and other resources to a working website and happens in the browser, as described in section X.

Navigation Timing only captures time values from the main HTML document. Within the main document, requests to other linked resources are made. The timing information for those linked resources are gathered and exposed via Resource Timing, as described in section X.

The exposed timing events are represented in figure X and described in table X. Metrics directly calculated with Navigation Timing (and Resource Timing), are listed in table X.

Navigation Timing timestamps are exposed via the PerformanceNavigationTiming interface and can be retrieved via `window.performance.getEntriesByType("navigation")`, as seen in figure X.

Resource Timing Two versions of Resource Timing exist. A Candidate Recommendation, Resource Timing Level 1, from March 2017, and Resource Timing Level 2, a Working Draft from April 2021.

As described above, while Navigation Timing exposes timing information for the main document, Resource Timing exposes timing information for all other resources the main document requests, and also resources other resources request. Other resources may be CSS, JS, other HTML documents, images, and so on.

The exposed time stamps from Resource Timing are mainly network related timing values (see table X.) For example, the time it takes to download a specific resource.

The values are exposed by the PerformanceResourceTiming interface and can be retrieved via `window.performance.getEntriesByType("resource")`.

Navigation and Resource Timing go hand in hand. With Navigation and Resource Timing, all relevant timing information for all resources of the website are available. The Waterfall Chart (see section X.) is a picturesque example of a visualization of the exposed attributes by both specifications.

```

> performance.getEntriesByType("navigation");
< [PerformanceNavigationTiming] 1
  0: PerformanceNavigationTiming
    connectEnd: 24.30000001192093
    connectStart: 24.30000001192093
    decodedBodySize: 0
    domComplete: 730.3999999761581
    domContentLoadedEventEnd: 567.5
    domContentLoadedEventStart: 567.5
    domInteractive: 413.39999997615814
    domainLookupEnd: 24.30000001192093
    domainLookupStart: 24.30000001192093
    duration: 732
    encodedBodySize: 0
    entryType: "navigation"
    fetchStart: 24.30000001192093
    initiatorType: "navigation"
    loadEventEnd: 732
    loadEventStart: 730.3999999761581
    name: "https://www.baqend.com/"
    nextHopProtocol: ""
    redirectCount: 0
    redirectEnd: 0
    redirectStart: 0
    requestStart: 24.30000001192093
    responseEnd: 246.5
    responseStart: 220.80000001192093
    secureConnectionStart: 24.30000001192093
    serverTiming: []
    startTime: 0
    transferSize: 0
    type: "navigate"
    unloadEventEnd: 0
    unloadEventStart: 0
    workerStart: 9.099999964237213
    __proto__: PerformanceNavigationTiming
  length: 1
  __proto__: Array(0)

```

Figure 3.5: Navigation Timings

Figure X. depicts the values exposed by Navigation and Resource Timing. Those attributes will be discussed next.

Navigation and Resource Timing Attributes All timing values, or attributes, relevant for the navigation process and exposed by Navigation and Resource Timing Level 2, are listed in table X and figure X. The black coloured time stamps assigned to the blue boxes in figure X. are captured by Navigation Timing. The yellow time stamps are exposed by Resource Timing. All attributes are retrievable via `performance.getEntriesByType("navigation")`.⁸ Figure X. does not include all defined and available values from the specification definitions, but only those important within the navigation process. For documents from different origins, the attributes in parenthesis may not be available.

Table X gives a short explanation for each time stamp. The definitions are taken directly from the W3C specifications or MDN Web Docs, if not stated otherwise. These time stamps are used to calculate performance metrics, as described in the next section.

Navigation Timings Level 2

⁸They are exposed to navigation due to interface inheritance. For more details cf.

3 Web Performance

startTime (= navigationStart)	Start time of the navigation process. Is set to 0. Navigation Timeline Level 1 exposes "navigationStart" which is set to the "time immediately after the user agent finishes prompting to unload the previous document." ⁹ As some metric calculations still rely on navigationStart as seen below, it is mentioned here.
unloadEventStart	Set to 0 if there is no previous document. Otherwise, value is set to time when previous documents unload event gets fired by the user agent.
unloadEventEnd	Set to 0 if there is no previous document. Otherwise, value is set to time when previous documents unload event ends.
domInteractive	Time value equal to the time immediately before the user agent sets the current document readiness of the current document to "interactive".
domContentLoadedEventStart	Time value equal to the time immediately before the user agent fires the DOMContentLoaded event at the current document.
domContentLoadedEventEnd	Time value equal to the time immediately after the current document's DOMContentLoaded event completes.
domComplete	Time value equal to the time immediately before the user agent sets the current document readiness of the current document to "complete".
loadEventStart	Time value equal to the time immediately before the load event (window.onload ??) of the current document is fired. Returns 0 if event has not been fired.
loadEventEnd	Time value equal to the time when the load event of the current document is completed. Returns 0 if event has not been fired or is not completed.
Resource Timings Level 2	
redirectStart	Start time of the fetch which initiates the redirect.
redirectEnd	Marks timestamp which occurs immediately after receiving the last byte of the response of the last redirect.
fetchStart	Marks when the browser starts to fetch a resource. Does not mark when the browser makes a network request for a resource, but rather when it begins checking caches to see if a network request is even necessary.
domainLookupStart	Returns the timestamp immediately before the browser starts the domain name lookup for the resource.
domainLookupEnd	Returns the timestamp immediately after the browser finishes the domain name lookup for the resource.

⁹<https://www.w3.org/TR/navigation-timing/> [15.07.2021]

connectStart	Returns the timestamp immediately before the user agent starts establishing the connection to the server to retrieve the resource.
secureConnectionStart	Returns a timestamp immediately before the browser starts the handshake process to secure the current connection.
connectEnd	Returns the timestamp immediately after the browser finishes establishing the connection to the server to retrieve the resource.
requestStart	When the browser issues the network request.
responseStart	Returns a timestamp immediately after the browser receives the first byte of the response from the server, cache, or local resource.
responseEnd	Returns a timestamp immediately after the browser receives the last byte of the resource or immediately before the transport connection is closed, whichever comes first.

Table 3.3: Navigation and Resource Timing Level 2 Attributes

The document states and events mentioned above, such as `DOMContentLoaded`, and when they are fired by the user agent, are defined in the HTML standard.

Metrics calculated with Navigation and Resource Timing The attributes exposed by Navigation and Resource Timing are used to calculate common navigation timing metrics. Table X. lists a selection of navigation timing metrics and how they are derived from the exposed attributes by Navigation and Resource Timing. Figure X. provides a graphical overview of the metrics and which intervals they are reflecting.

As with business metrics (section X.), there is not one source of truth or a set of definitions for navigation timing metrics. Still, when going through literature, a common set of navigation timings can be identified. Literature sources are for example MDN Glossary Google developers guides Other performance specialists blog posts Research papers Or documentation of common RUM tools

The sources mentioned above explain the idea of the metrics sometimes rather in an informal way. How exactly the metrics are implemented and calculated, e.g. which Navigation Timing attributes are used, is not all the time the clear and is the responsibility of the RUM tools vendors and can only be checked directly in the source code. It is therefore possible. due to the lack of metrics standardization and definition, that for the same metric, different calculations are being used.

3 Web Performance

Time to First Byte (TTFB)	$[responseStart - navigationStart]$ Indicates when the user agent received the first byte of the websites data. "Time it takes between the start of the request and the start of the response".
Page Load Time (PLT)	$[loadEventStart - navigationStart]$ The MDN Docs define PLT as the "time it takes for a page to load" and it is calculated as stated above. Across multiple authors, PLT is defined as the time from navigation start until the load event ¹⁰ has been fired. The load event is fired when the main document and its linked resources have been loaded. Grigorik states that PLT "has been the de facto metric of the web performance world", but is nowadays inaccurate due to the shift from static websites to dynamic web applications which load resources differently (cf also 2018 Netraveli) and
DNS Lookup Time	$[domainLookupEnd - domainLookupStart]$ Time it takes for a DNS lookup.
TCP Handshake	$[connectEnd - connectStart]$ "The time it takes for the TCP handshake."
TLS Handshake Time	Time it takes to secure connection with TLS. MDN Docs defines TLS time with $[requestStart - secureConnectionStart]$ Google defines TLS Time as $[connectEnd - secureConnectionStart]$
Request Time, Server Response Time	$[responseStart - requestStart]$ How long it takes for the request. Also called Server Response Time by Akamai
DOM Content Loaded,DOM Content Load	MDN defines DOM Content Loaded as $domContentLoadedEventEnd - domContentLoadedEventStart$, that is the DOMContentLoaded event duration. Akamai defines a "DOM Content Load" time which represents the time from navigation start until the DOMContentLoaded event has been fired, captured by domContentLoadedEventEnd.
Page Download Time, Receiving Time, Transfer Time	$[responseEnd - responseStart]$ How long it takes to download the page. Also called Transfer time by Akamai or Receiving Time by MDN
Latency	$[responseStart - fetchStart]$

¹⁰https://developer.mozilla.org/en-US/docs/Web/API/Window/load_event [16.07.2021]

	Latency is defined as the elapsed time from when the browser requests the resource until the first byte from it is received.
DOM Interactive	<i>[domInteractive – navigationStart]</i> When the "browser has completed parsing the entire HTML and constructed the DOM"

Table 3.4: Metrics

Apart from Navigation and Resource Timing, the Web Performance Working Group also maintains other performance related specifications. Some of them will be briefly discussed next.

User Timing User Timing Level 2 is a Recommendation from February 2019 and User Timing Level 3 is a Working Draft from July 2021. User Timing provides methods to create own, specific and unique high resolution timestamps, to query them and to calculate intervals and the elapsed time between those created timestamps. User Timing simplifies and facilitates the usage of custom metrics (see section X.)

Performance Timeline Performance Timeline is a Recommendation from December 2013 and Performance Timeline Level 2 is a Working Draft from June 2021.

In short, the Performance Timeline defines an API and methods which expose all timing values captured by other specifications such as Navigation or Resource Timing. Performance Timeline defines an interface to acquire a variety of performance measurements. As already described, it can be used to retrieve Navigation Timings with *performance.getEntriesByType('navigation')*.

Additionally, a PerformanceObserver interface is defined, which can be used to monitor the Performance Timeline and notify as soon as new measurements and recordings are available.

Long Tasks Long Tasks API 1 has been released as a First Public Working Draft in September 2017. The goal of the API is to detect "long tasks", these are tasks that occupy the main thread for more than 50ms. Long tasks are critical for performance as they block other critical tasks such as user input.

Long Tasks API is a basis to calculate metrics such as Time to Interactive (TTI) and Total Blocking Time (TBT). TTI and TBT will be discussed below.

Server Timing Server Timing is a Working Draft from June 2021. With specifications such as Navigation and Resource Timing, the user agent has access to a variety of different timings regarding the navigation process. Not visible nor available are measurement and timings within the server processing, e.g. database queries. Server Timing addresses

3 Web Performance

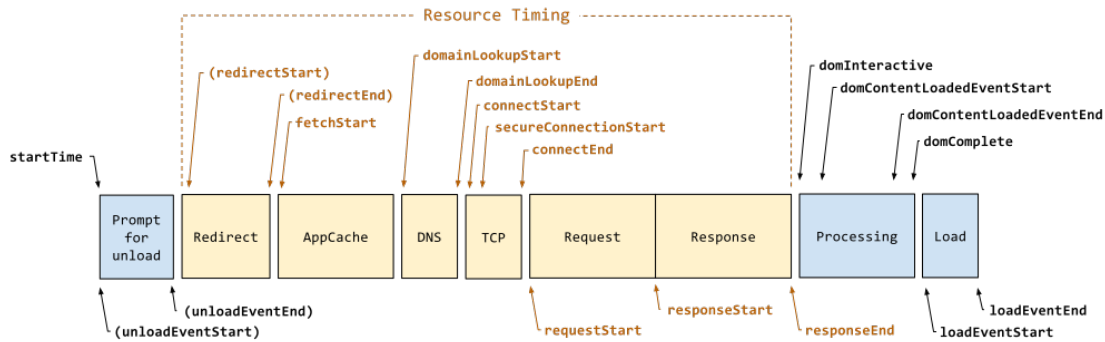


Figure 3.6: Timestamps from Navigation and Resource Timing

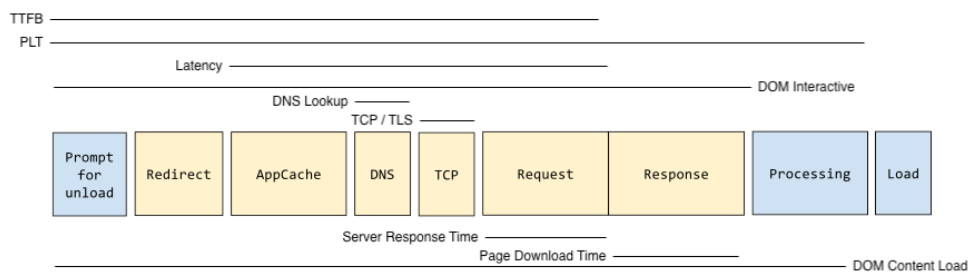


Figure 3.7: Navigation Timing Metrics

this problem by enabling a server to transfer and communicate performance related information to the user agent.

Paint Timing Paint Timing 1 has been released as a First Public Working Draft in September 2017. It specifies two "key moments" during the load process: First Paint (FP), and First Contentful Paint (FCP). Table X. provides explanations for the key moments as they are defined in the specification.

The metrics can be retrieved directly in the browser via `performance.getEntriesByType("paint")`. Hence, FP and FCP can be collected in RUM. Other visual metrics rely mostly on video analysis and need a synthetic monitoring setup, as described in the next section.

First Paint	Marks the point when the browser renders anything that is visually different from what was on the screen prior to navigation
First Contentful Paint	The point when the browser renders the first bit of content from the DOM, which may be text, an image, SVG, or even a canvas element

FP and FCP indicate when the user sees something different than the default white screen for the first time. If the visual change is important or useful for the user is not

reflected by FP or FCP.

As described below, FCP is part of Google's Web Vitals. For a more fine grained measurement, they enhance the default metric.

Element Timing API and Event Timing API Unofficial drafts

Element Timing used for LCP Event Timing used for FID

Navigation Timing Metrics Conclusion

[tbd]

We can measure time for different processes in the document loading process. W3C and the Performance Working Group especially maintain and define a set of specifications with the task to measure performance related data. The attributes exposed by there specifications are used to calculate performance or navigation timing metrics.

As the performance metrics are not officially defined by any authorizes party or institution, their meaning may diverge depending on the implementation.

Table X provides an overview of all discussed specifications, in which maturity level they are available and why they are important.

3 Web Performance

High Resolution Time	Level 2: REC November 2019 WD July 2021 Provides exact, stable and reliable time measures
Navigation Timing	Level 1: REC December 2021 Level 2: WD March 2021 Exposes navigation timing information of the main document
Resource Timing	Level 1: CR March 2017 Level 2: WD April 2021 Exposes timing information from requested resources and the resources they request.
Navigation and Resource Timing	Used to calculate a variety of metrics
User Timing	Level 2: REC February 2019 Level 3: WD July 2021 Mark and measure custom timestamps
Performance Timeline	REC December 2013 Level 2: WD June 2021 Subsumes gathered performance data from other specifications
Long Tasks	API 1: FPWD September 2017 Identifies tasks occupying main thread for more than 50ms Basis for TTI and TBT
Server Timing	WD June 2021 Standard to transmit performance related data from the server to the client
Paint Timing	FPWD September 2017 Exposes the "key moments" First Paint and First Contentful Paint

Paint Timing already shoots in a direction which tries to measure user perceived performance not just by measuring elapsed time between navigation events, but rather observe visual changes during the websites loading process. When navigation timings can help to identify eventual bottlenecks or other technical debts during the loading process, they do not reflect how the actual user is perceiving the performance of the websites loading process. As users consume websites mainly with the eyes, visual indicators are relevant and of crucial importance.

A variety of visual and user-centric performance metrics emerged in the last years, with Google promoting some of them. They will be discussed in the next section.

3.4.3 User-Centric Performance Metrics

[tbd]

Navigation Timings as described above are directly measured through a variety of Web APIs and are accessible within the browser. Metrics concerned with user-perceived per-

formance focus mainly on visual changes of the website and can thereby not be captured directly through Web APIs.

Perceived performance tackles the question how fast a website "feels" to a user. As already described in section X. different users feel performance differently, depending on factors such as gender, region or stress level. The perceived performance can diverge from actual loading times, and user-centric performance metrics are usually more difficult to measure than navigation timings, as visual or even video analysis is necessary to calculate the metrics.

I will describe user-centric performance metrics which are established among performance monitoring solution vendors. With Web Vitals, Google defines their own set of user-centric metrics and moves websites performance into focus. They will be discussed below.

Visual Metrics

[tbd]

Start Render, Time to First Paint (TTFP) The Start Render time is the time when the browser rendered the first pixel on the screen visible for the user. Start Render is calculated through video analysis instead of leveraging browser APIs such as Paint Timing.

Start Render is defined and exposed by a variety of synthetic monitoring solutions such as speedcurve or WebPageTest.

Netravali et al. use the term Time to First Paint (TTFP) for the very same metric, whereas for Enghardt et al. , TTFP is the same as FP, which is measured within the browser and not through video analysis.

This example reveals that the definitions of metrics is not clear and different authors use different definitions.

Above the Fold Time (AFT) The above-the-fold is the area of the website which is visible to the user without scrolling. The AFT metric measures how long it takes the browser to render all pixel within that above the fold area. AFT measurement needs to take into consideration visual dynamic areas of the website which are expected to change pixels frequently and static areas where pixel and color changes are not likely to happen.

AFT is measurable through synthetic monitoring and requires video recording and analysis.

The AFT is not standardized.

Speed Index (SI) The Speed Index (SI) is a metric invented by the founders of WebPageTest and aims to express user experience in a single number.

Like the AFT, the SI reflects the visual completeness of the website. Where as AFT only measures the single point in time when the viewport is fully rendered, SI also takes the

3 Web Performance

visual loading progress of the website into consideration and reflects "the average time at which visible parts of the page are displayed". SI is not directly measured, but calculated, and expressed in milliseconds.

Like AFT, SI is reliable for static websites and unreliable for websites with dynamic and changing visual content. The SI calculation details are covered in

Web Vitals

With the Web Vitals initiative, Google joins the web performance metrics discussion. Their goal is to "provide unified guidance for quality signals that are essential to delivering a great user experience on the web." The unified guidance consists of the Web Vitals, a set of performance metrics, focussing on how the users experience and perceive performance, contrary to the mere navigation timings as discussed in section X. With performance being a factor in Google search rankings, Web Vitals become automatically important for website operators.

The set and definitions of Web Vitals metrics are not set in stone, but are constantly evolving. The definitions, calculations, recommended thresholds, or even the metrics themselves may change over time, always adapted to the rapidly evolving technologies of the WWW and advances in web performance. While Web Vitals are currently primarily about web performance, other aspects of usability, such as security, privacy, or accessibility, will be included in the future.

Web Vitals and their definitions are derived from a set of key questions (table X.). The key questions reflect what users may (eventually unconsciously) ask while consuming a website. This user-centric framework guides and sets the agenda for creating and defining Web Vitals metrics. Contrary to navigation timing metrics, the Web Vitals focus are users and their perception, and each question is a perspective or facet of user experience. Web Vitals are "metrics relevant to users".

<i>Is it happening?</i>	Did the navigation start successfully? Has the server responded?
<i>Is it useful?</i>	Has enough content rendered that users can engage with it?
<i>Is it usable?</i>	Can users interact with the page, or is it busy?
<i>Is it delightful?</i>	Are the interactions smooth and natural, free of lag and jank?

In addition to the key questions, Google identifies different aspects or types of a website's performance. Like the key questions, these types provide a guide and framework to organize, classify, and integrate Web Vitals.

<i>Perceived load speed</i>	How quickly a page can load and render all of its visual elements to the screen.
<i>Load responsiveness</i>	How quickly a page can load and execute any required JavaScript code in order for components to respond quickly to user interaction.
<i>Runtime responsiveness</i>	After page load, how quickly can the page respond to user interaction.
<i>Visual stability</i>	Do elements on the page shift in ways that users don't expect and potentially interfere with their interactions?
<i>Smoothness</i>	Do transitions and animations render at a consistent frame rate and flow fluidly from one state to the next?

Web Vitals can be measured through synthetic monitoring or RUM. For example, RUM data is available through CrUX¹¹, synthetic data is available through Lighthouse¹². A custom JS library is available and can be integrated into any website to capture Web Vitals.¹³

In the following, I will describe common Web Vitals metrics. Afterwards, Core Web Vitals, Web Vitals that matter the most, will be discussed.

First Contentful Paint First Contentful Paint (FCP) tackles the question *Is it happening?* and is classified as the type *Perceived load speed*. This is the same FCP as exposed by Paint Timing (see section X.), and "marks the first point in the page load timeline where the user can see anything on the screen".

Google enhances the Paint Timing specification regarding FCP by only considering pages that are in the foreground all the time, by measuring FCP also if the page has been loaded from cache, and by exposing FCP for all frames, including cross-origin iframes. Implementation details are available within the web-vitals library.¹⁴

FCP is measured in seconds and retrievable in synthetic and real-user monitoring.

First Meaningful Paint First Meaningful Paint (FMP) is "the paint after which the biggest above-the-fold layout change has happened and web fonts have loaded".

Google states that FMP is deprecated, due to "inconsistent results" and the impossibility to measure it in all web browsers. The successor, Largest Contentful Paint, is discussed below. The replacement of FMP nicely illustrates the evolving nature of Web Vitals.

Time to Interactive and First CPU Idle Time to Interactive (TTI) is an indicator for *Load responsiveness* and gives insights to the question *Is it usable?* TTI measures the "time from when the page starts loading to when its main sub-resources have loaded and it is capable of reliably responding to user input quickly." Previously, TTI has been called *Time to Consistently Interactive*.

¹¹<https://developers.google.com/web/tools/chrome-user-experience-report> [22.07.2021]

¹²<https://developers.google.com/web/tools/lighthouse> [22.07.2021]

¹³<https://github.com/GoogleChrome/web-vitals> [22.07.2021]

¹⁴<https://github.com/GoogleChrome/web-vitals/blob/main/src/getFCP.ts> [22.07.2021]

3 Web Performance

For the calculation of TTI, other metrics and definitions are needed: FCP as the starting point and a "quiet window", that is a time interval where no long tasks (as defined by Long Tasks API, see section X.) and not more than two in-flight GET requests occur. The TTI is then the "end time of the last long task before the quiet window". The quiet window time interval is set to 5 seconds, and the starting point of the search of TTI is FCP (for details, cf. X).

Ideally, the time between FCP and TTI, that is when content is visible, but the website is not interactive, is short. To summarize, "TTI measures how long it takes a page to become fully interactive. " TTI can be measured through synthetic monitoring, and also RUM. The latter is not recommended, as user interaction may affect TTI, leading to unreliable results.

First CPU Idle is a metric closely related to TTI. Previously, First CPU Idle was called *First Interactive*. It indicates when the website is minimally interactive, contrary to TTI, which signals when the website is fully interactive. Google deprecated First CPU Idle, as "the difference [to TTI] isn't significant enough to justify maintaining two similar metrics".

Total Blocking Time Total Blocking Time (TBT) captures the aspect of *Load responsiveness* and gives hints to the question *Is it happening?*. According to the definition, TBT measures "the total amount of time between First Contentful Paint (FCP) and Time to Interactive (TTI) where the main thread was blocked for long enough to prevent input responsiveness." The starting point for the measurement is the point of FCP, as user input is not likely to happen before the UI got rendered. The end point of the measurement is the point of TTI.

The blocking of the main thread is characterized through long tasks, as they are defined in Long Tasks API (cf section X.) If the user interacts with the website while a long task is running, the browser can only respond to the user when he finished processing the long task. Therefore, the user has to wait. The blocking time of a long task is the full time of the task minus the defined long task time of 50ms. For example, a long task of 180ms has a blocking time of $180ms - 50ms = 130ms$. The sum of all those times, between FCP and TTI, is the TBT.

For some use cases, TBT can adjust and correct TTI, when TTI does not reflect available interactivity realistically: As TTI is framed around a quiet window of 5 seconds, TTI will likely be the same for (A) three long tasks of 51ms spread over 10 seconds, and (B) one 10 second task. (A) is expected to be more interactive, as in between the three long tasks, the main thread is able to react to user input. For (B) on the other hand, the main thread is blocked and user interactivity is prohibited. For use cases like this, TBT is a good indicator: For (A), TBT is 3ms, and for (B), TBT is 9950ms. The lower TBT value indicates a better interactivity and user experience.

As with TTI, Google recommends to measure TBT through synthetic monitoring rather

than RUM, as user input may affect and disturb measurement results.

Among the Web Vitals are three metrics that matter the most. The *Core Web Vitals* are discussed below.

Core Web Vitals

Within the set of Web Vitals, there is a group of metrics that matter the most: "Core Web Vitals are the subset of Web Vitals that apply to all web pages, should be measured by all site owners, and will be surfaced across all Google tools." The Core Web Vitals are structured around the performance aspects *Loading*, *Interactivity*, and *Visual Stability*. Each of three Core Web Vitals reflects one of those aspects (table X.).

The Core Web Vitals are relevant for all kinds of websites and can be measured with RUM. Contrary to the general evolving nature of Web Vitals, Core Web Vitals are rather stable in terms of definition and recommended benchmarks.

Core Web Vitals are collected by common Google performance assessment tools such as Crux or PageSpeed Insights.¹⁵ Additionally, Google provides a JS library for core web vitals measurements.¹⁶

<i>Largest Contentful Paint (LCP)</i>	Measures loading performance.
<i>First Input Delay (FID)</i>	Measures interactivity.
<i>Cumulative Layout Shift (CLS)</i>	Measures visual stability.

The three Core Web Vitals will be discussed in more detail below.

Largest Contentful Paint

First Input Delay "First Input Delay can only be measured if the user interacts with the page. Synthetic performance tools like Lighthouse don't involve any user interaction, and therefore use Total Blocking Time as a proxy metric."

Cumulative Layout Shift

Thresholds and Benchmarks for Core Web Vitals [tbd]

3.4.4 Custom Metrics

[tbd]

3.4.5 WebPageTest and Google Analytics Metrics

[tbd]

¹⁵<https://developers.google.com/speed/pagespeed/insights/> [23.07.2021]

¹⁶<https://github.com/GoogleChrome/web-vitals> [23.07.2021]

3 Web Performance

WebPageTest Metrics

[tbd]

Name	Description
Successful Tests	Amount of tests who completed successfully
Document Complete	...
Fully Loaded	...
First Byte	...
Start Render	...
Bytes In (Doc)	...
Requests (Doc)	...
Load Event Start	...
Speed Index	...
Last Visual Change	...
Visually Complete	...

Table 3.5: Your caption here

GA Site Speed Metrics

[tbd]

Name	Description
Page Load Sample	The number of pageviews that were sampled to calculate the average page-load time.
Speed Metrics Sample	The sample set (or count) of pageviews used to calculate the averages of site speed metrics. This metric is used in all site speed average calculations, including avgDomainLookupTime, avgPageDownloadTime, avgRedirectionTime, avgServerConnectionTime, and avgServerResponseTime.
DOM Latency Metrics Sample	Sample set (or count) of pageviews used to calculate the averages for site speed DOM metrics. This metric is used to calculate ga:avgDomContentLoadedTime and ga:avgDomInteractiveTime.
Page Load Time (sec)	The average amount of time (in seconds) it takes that page to load, from initiation of the pageview (e.g., click on a page link) to load completion in the browser.
Domain Lookup Time (sec)	The average amount of time spent in DNS lookup for the page.
Page Download Time (sec)	The time to download your page.
Redirection Time (sec)	The time spent in redirection before fetching the page. If there are no redirects, the value for this metric is expected to be 0.
Server Connection Time (sec)	The time needed for the user to connect to your server.
Server Response Time (sec)	The time for your server to respond to a user request, including the network time from the user's location to your server.
Document Interactive Time (sec)	The average time (in seconds) that the browser takes to parse the document (DOMInteractive), including the network time from the user's location to your server. At this time, the user can interact with the Document Object Model even though it is not fully loaded.
Document Content Loaded Time (sec)	The average time (in seconds) that the browser takes to parse the document and execute deferred and parser-inserted scripts (DOMContentLoaded), including the network time from the user's location to your server. Parsing of the document is finished, the Document Object Model is ready, but referenced style sheets, images, and subframes may not be finished loading. This event is often the starting point for javascript framework execution, e.g., JQuery's onready() callback, etc.

Comparison GA and WPT Metrics

[tbd]

Navigation Timing API	WPT	GA
loadEventStart - navigationStart	Document Complete, Load Event Start	pageLoadTime
domainLookupEnd - domainLookupStart	DNS lookup, dns_ms	domainLookupTime
connectEnd - connectStart	connect_ms	serverConnectionTime
responseStart - requestStart	..	serverResponseTime
responseEnd - responseStart	..	pageDownloadTime
fetchStart - navigationStart	..	redirectionTime
domInteractive - navigationStart	..	domInteractiveTime
domContentLoadedEventStart - navigationStart	domContentLoadedEventStart	domContentLoadedTime

3.4.6 Web Performance Metrics Conclusion

[tbd]

[summary table]

[Link to Research Question]

Observer Effect [tbd]

4 Related Work

- Last chapter...
- This chapter: Describe shortly all sections from this chapter
- In the next chapter...
- This chapter should list research which covers and explores questions relevant for this thesis, such as:
 - Metrics: New metrics, meaning of metrics, difficulties of defining metrics, etc.
 - Overview, evaluation and comparison of measurement tools and methods
 - If available: Impact of RUM on performance

4.1 Research

- Research exists about topics like:
- Here i will provide a list of in my eyes relevant papers, summaries them and discuss why this is important for my research

4.1.1 some title for first category

2014 Singal I. - Describes history of web analytics and tools - Provides definitions and taxonomy for metrics - Describes log file vs page tagging - Describes KPIs

II. - Lit. overview for KPIs and Web Metrics - Lit. overview for "Trust" - Lit. overview for "Fuzzy" -> What are does categories?

III. - Some other literature worth mentioning

IV. - Describes 8 open challenges for researchers

2015 Bekavac - Two parts: - 1: Some general overview of web analytics, tools and metrics, KPIs etc - 2: Empirical study about employees satisfaction of used web analytics tools

1: - 9 web business models and 5 common goals - Hypothesis: Web analytics tools track and improve a user's satisfaction with web-based business models. - Web analytics definition. Log files vs Site Tagging - Web Analytics process - Tools: 5 categories, Process

4 Related Work

of selecting tool, Table with features of different tools - Web metrics categories, Table with business models and their KPIs

2: - Which tools are used for which purpose / Activity - Users satisfaction

4.1.2 Research about Tools

Kaushik 2007 - Provides 3 questions which help to choose web analytics tools

2011 Nakatani - Gives some arguments why web analytics is important for business
- Provides different categorizations for web analytics tools - Gives pros and cons of log file analysis and page tagging - Provides tool selection method based on AHP (Analytic Hierarchy Process)

"Web analytics tools collect click-stream data, track users navigation paths, process and present the data as meaningful information. - Categorizations: 1: By 4 different data collection methods 2: SaaS vs in-house 3: mobile vs non-mobile 4: Time lag

2016 Kaur - free vs paid - real time vs long term - hosted vs in-house - data portability
- free / open source tools - proprietary tools - Service Hosted Software - GA most popular one

4.1.3 Research about Metrics

Categorizations as seen in section X.

- Dont know:

5 Approach

- Last chapter...
- This chapter: Describe shortly all sections from this chapter
- In the next chapter...
- In this chapter the practical work should be documented and explained
- Elaboration of how the practical work could help answer the research question
- Discussion of real-life setup and how experiments approach it

5.1 Empirical Research Methods

- Overview of methods
- reproduceability etc.
- validity
- Justification why following approaches are conducted as controlled experiments
- Change something: Delete this item again

5.1.1 Controlled Experiment

- Short overview about controlled experiments in computer science
- Design: Show test setup image: Independent and dependent variables
- Hypothesis testing

5.1.2 Test Setup

- What is test object (website)
- What are dependent variables: Performance metrics
- What are independent variables: Specific changes in test object (see next chapter)
- Kohavi 2016: Sample size, collect right metrics, track right users, randomization unit

5 Approach

Variable	Values
Position	top-head, bottom-head, bottom-body
Attribute	no attribute, async, defer
Other Script	false, true

Measure effects: Dependent Variables

- Performance metrics from Lab and Field, see terms and definitions
- But also quality of RUM data. Because we could have a nice performance but RUM will be of bad quality.

Test object / HTML Template

- Depending on different approaches / Ideas (see next chapter), template looks different
- But general structure stays the same and independent variables can be defined
- Here we show different independent variables and variants

Lab and Field

- I want to collect Lab and field data for dependent variables for comparison
- This setup is a special case because lab bots (e.g. WPT) simulate at the same time real users for RUM data

5.1.3 Independent Variables within template

- IV 1 POSITION: Position of included analytics script. Values: top-head, bottom-head, bottom-body
- IV 2 ATTRIBUTE: Attribute of included analytics script: no-attribute, async, defer
- IV 3 OTHER SCRIPT: Other tracking script included
- Other IVs not included but worth mentioning

I will compare the values from one independent variable only. Therefore, when comparing the values of one independent variable, I need to set a default value for the other independent variables. The default values are:

Position: top-head Attribute: no attribute Other Script: false

Listing 5.1: Position 1

```

<!DOCTYPE html>
<html>
  <head>
    <!-- Google Analytics -->
    <script></script>
    <!-- End Google Analytics -->

    <title>
    <meta>
    <link>
    <script>
  </head>

  <body>
    ...
  </body>
</html>

```

Listing 5.2: Position 2

```

<!DOCTYPE html>
<html>
  <head>
    <title>
    <meta>
    <link>
    <script>

    <!-- Google Analytics -->
    <script></script>
    <!-- End Google Analytics -->
  </head>

  <body>
    ...
  </body>
</html>

```

Listing 5.3: Position 3

```

<!DOCTYPE html>
<html>
  <head>
    <title>
    <meta>
    <link>
    <script>

  </head>

  <body>
    ...
    <!-- Google Analytics -->
    <script></script>
    <!-- End Google Analytics -->
  </body>
</html>

```

5 Approach

Other IVs not included but worth mentioning

- More or less infinite number of independent variables
- Again the big and important fact that each website is different

it looks like attribute on inline script is ignored... "Inline JavaScript script tags ignore the defer or async attribute" so those variables will not make any sense? Do i see this in the data? As i can see how the GA is included, it will create a async attribute to fetch the analytics.js

5.2 Test Object: HTML Template / Test website ideas

- Several ideas are proposed
- Each idea has pro and contra: each idea should be discussed of its usefulness, advantages and disadvantages

5.2.1 WordPress

- Show usage of WordPress with some statistics: Why is it so verbreitet
- Explain Plugin system
- Explain Setup on localhost with wocommerce and GA plugin
- Elaborate why this idea was not used

5.2.2 Plain / Skeletal Website

- Idea: Lab environment to have control over all and see effects of changing independent variables
- Problem: Too far away from reality
- Use this as the simplest test possible, not even POC (POC is http archive site)

5.2.3 HTTP Archive inspired website

- Idea: Get correct page weight
- POC: Show that changing independent variables X affect result

- Chart with changes on time: apps are growing

5.2.4 Mirroring a complete e-commerce website

- Which website / shop to clone? Show some statistics about biggest e-commerce websites in germany

Listing 5.4: Attribute 1

```

<!DOCTYPE html>
<html>
  <head>
    <!-- Google Analytics -->
    <script></script>
    <!-- End Google Analytics -->

    <title>
    <meta>
    <link>
    <script>
  </head>

  <body>
    ...
  </body>
</html>

```

Listing 5.5: Attribute 2

```

<!DOCTYPE html>
<html>
  <head>
    <!-- Google Analytics -->
    <script async></script>
    <!-- End Google Analytics -->

    <title>
    <meta>
    <link>
    <script>
  </head>

  <body>
    ...
  </body>
</html>

```

Listing 5.6: Attribute 3

```

<!DOCTYPE html>
<html>
  <head>
    <!-- Google Analytics -->
    <script defer></script>
    <!-- End Google Analytics -->

    <title>
    <meta>
    <link>
    <script>
  </head>

  <body>
    ...
  </body>
</html>

```

Listing 5.7: Other Script 1

```

<!DOCTYPE html>
<html>
  <head>
    <!-- Google Analytics -->
    <script></script>
    <!-- End Google Analytics -->

    <title>
    <meta>
    <link>
    <script>
  </head>

  <body>
    ...
  </body>
</html>

```

Listing 5.8: Other Script 2

```

<!DOCTYPE html>
<html>
  <head>
    <!-- Google Analytics -->
    <script></script>
    <!-- End Google Analytics -->

    <!-- Other Script -->
    <script></script>
    <!-- End Other Script -->

    <title>
    <meta>
    <link>
    <script>
  </head>

  <body>
    ...
  </body>
</html>

```

Otto Re-write this to otto start page clone chapter

Manual adjustments: - Move everything to test folder because top domain is /otto

What did not work (mostly 404s): - user-set-consent-id-cookie: Cookie with name consentId is not set, user-set-consent-id-cookie returns therefore 404 - subscribeToNewsletterSnippetContent: Change path did not work... - amount.json: Not found, also wl_miniWishlistAmount in local storage does not created - a_info: Mock a_info response json does not work...

- footer - userTiming

WPT RV is returning empty csv when 404s are encountered. Therefore i mock the missing ressources so that WPT can run bulk tests successfully.

- mock image sprite_all_1ba408b2.png

- create empty file called user-set-consent-id-cookie

- change path for subscribeToNewsletterSnippetContent: This will remove the cookie banner... but then WPT works

- Idea: Close to reality as possible
- Problems when mirroring a website
- Elaborate why this idea of mirroring complete website was not used
- I used mock of start page of otto, which works fine
- Compare original otto website with mock

Comparison to original webpage

- Remove GA again from mock, so that mock and original are as similar as possible
- Run the same lab test on both pages: WPT and maybe lighthouse
- Compare both results and explain differences

- Setup: Run WPT on mock and on original website - WPT config: - Browser: Chrome
- Number of test runs: 3 - FV and RV - Capture Video - Capture DevTools Timeline - Bulk testing: 100x

Diagrams with FV and RV for both cases:

Technical: - First Byte - Bytes In (Doc) - Requests (Doc)

Visual: - Document Complete - Speed Index

Problem with Repeat View - Problem with RV, Caching: Otto sets request headers to cache-control: no-cache which means that RV basically downloads all resources again. The mock is hosted on Github, where the cache-control header is set to ... It is not possible to change the github request headers. We can modify the http request headers via html, but this is not a clean solution. Therefore I use a different e-commerce website which does not shut down caching so that the RV results are more similar.

5 Approach

Ideally I would host the mock website on a similar infrastructure as the original site with the same webserver configuration. This is for a masters thesis not feasible.

Zalando Idea: It looks like zalando page does not has that many cache-control headers, therefore it may be easier to clone so that RVs are more similar.

Comparison Diagrams with fixed traffic shaping:

5.3 Test Runs

- This section covers all conducted test runs
- Explain test configuration: how many runs, dependent and independent variables, etc.

5.3.1 WPT Configurations

General Settings

Table 5.1: Test Runs [Sch99]

Configuration Setting	Options	GA
Test Location	Test Location	.
Browser	Firefox, Chrome	.
Connection	LAN	.
Number of Tests to Run	1 to 9	..
Repeat View	First View and Repeat View, First View Only	.
Capture Video	True or False	..
Keep Test Private	True or False	...
Label	Any String	...
Advanced Tab
Chromium Tab
Auth, Script, Block, SPOF, Custom Tabs
Bulk Testing Tab	List of URLs	...

Explanations First View: "First View refers to the cold cache setup in which nothing is served locally" Repeat View: "Repeat View refers to the warm cache containing everything instantiated by the first view" (2016 Using WPT p. 62)

Capture Video: ...

For one test, we have actually six times that the website gets loaded and tested. For e.g. 500 URLs in the bulk test list, we have a total of $500 \times 6 = 3000$ page hits.

Configuration 1

Configuration 2 Emulate Mobile Browser

Figure 5.1: Number of tests to run: 3, First View and Repeat View

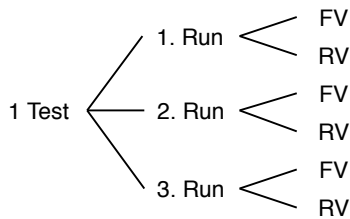


Table 5.2: Configuration 1

Configuration Setting	Option
Test Location	Test Location
Browser	Chrome
Connection	LAN
Desktop Browser Dimensions	default (1366x768)
Number of Tests to Run	1
Repeat View	First View and Repeat View
Capture Video	True
Keep Test Private	False
Label	none
Advanced Tab	Nothing selected
Chromium Tab	Capture Dev Tools Timeline selected
Auth, Script, Block, SPOF, Custom Tabs	Nothing
Bulk Testing Tab	Test URL x times according to test plan

Traffic Shaping

- Important to have stable and realistic network condition
- Chromes tool is not the best for this
- Private WPT Instance docker on mac does not allow traffic shaping functionality from WPT
- I use Network Link Conditioner from Apple to slow down the whole machine. See in same blogpost that Patrick highly recommends this
- WPT also slows down their whole machines
- IN general internet connection is very unstable. If i run network link conditioner with e.g. DSL each speedtest gives different results. And other test platforms such as fast.com gives also different result.
- as long as internet connection is stable along all tests, it should not make a big difference because i compare the different variants. Therefore internet connection will fall out of the equation

5 Approach

- i will use the durchschnitt in germany which seems to be 40 mbit per second. or actually i use LTE profile from network conditioner which is 50 mbit per second

5.3.2 Test Object (Website) Variations

as described before, i will compare the values within one independent variable. This is needed in order to compare the impact of the different values within one IV. For example, i want to measure if there is a difference in performance between the different script attributes. To measure this, i set the default values for the other IVs and vary the values for the IV attribute

Positions: 1: Top of head element 2: just before closing head element 3: just before closing body element

Variants

Variant	Position	Attribute	Other Scripts
Variant P1	top-head	none	no
Variant P2	bottom-head	none	no
Variant P3	bottom-body	none	no
Variant A1	top-head	none	no
Variant A2	top-head	async	no
Variant A3	top-head	defer	no
Variant OS1	top-head	none	no
Variant OS2	top-head	none	yes

Table 5.3: Your caption here

I will not compare variants which are not from the same subgroup, e.g. Variant A2 will not be compared to Variant OS2. Because the first row of the variants table also includes the default values for Attribute and Other Scripts, VP1 is equal to VA1 and VO1.

With the defined IVs and variants, I can create the test objects, that is the index.html files with the corresponding setup. Because its easier to differentiate i will create for the three equal variants nevertheless own index files.

For each test variant, I will create a concrete test artefact, which is a modified index.html. This index.html needs to be uploaded to the webserver before starting with the tests.

All variants will have the same name which is index.html. This is the default file which will be delivered by the webserver when accessing root path of webpage.

Variants to measure: _____

- Original website - Mock without GA - Position 1 - Position 2 - Position 3 - Attribute 1

- Attribute 2 - Attribute 3 - Other Script True - Other Script False

5.3.3 Test Plan. Generate the data

The Google Analytics code is more or less fixed and there are no configurations. It would be possible to change config of script, e.g. change sample rate, track other metrics etc. But it is not possible to change default tracking behaviour (?)

How the script is included into the file should be reflected with Website Variations

I will use only one WPT Configuration for all tests. Other WPT config can be used in future work, e.g. emulate mobile device.

Table 5.4: Test Runs [Sch99]

Variant	Traffic Shaping	Runs	Date
V-P1	DSL	500	2021-05-07
V-P2	DSL	500	2021-05-07
V-P3	DSL	500	2021-05-07
V-A1	DSL	500	2021-05-07
V-A2	DSL	500	2021-05-07
V-A3	DSL	500	2021-05-07
V-OS1	DSL	500	2021-05-07
V-OS1	DSL	500	2021-05-07

Pre-step: Compare Mock website with and without GA included The comparison between mock and original is part of chapter Test Object

5.3.4 Test Protocol

- Deploy variant of index.html by pushing to GitHub
- Start Network Link Conditioner with specified config on local machine
- Test internet speed with speedtest-cli
- Start local WPT server and agent
- Configure WPT according to specified setup and add list of urls to bulk test interface
- Run test
- When finished, download summary csv file
- On GA helper site, fetch and download data for the current day

5 Approach

5.3.5 Tool support for diagrams and data analysis

- python
- Matplotlib
- seaborn library

6 Evaluation



- Last chapter...
- This chapter: Describe shortly all sections from this chapter
- In the next chapter...

6.1 Test Results

6.1.1 Metrics for Evaluation

Page Weight: Measured by WPT: - bytes - bytes uncompressed - Requests

Technical Timings / API: Measured by WPT and GA: - page load time - domain lookup time - page download time - redirection time - server connection time - server response time - Dom interactive time - Dom content loaded time

Visual Metrics / Web Vitals: Measured by WPT TODO Measure also with GA / own script ??: - CLS - FCP - FMP - LCP - SI

6 Evaluation

- Visually complete ? - Time to Interactive ? Is this the same as DOM interactive time ?

Core Web Vital FID ?? -> Can not be measured without real users...

From WPT bulk section. Also include this somewhere for comparison ?: - Filmstrips ?

- Waterfall ? - Visual Progress ? - Layout Shifts ?

6.1.2 Original vs Mock Plain

6.1.3 Mock Plain vs Position 1 (which is default position of GA: Check this again!)

TODO rename this like with GA true false ?

6.1.4 Position 1 vs 2 vs 3

6.1.5 Attribute 1 vs 2 vs 3

6.1.6 Other script True vs False

6.2 General

- For each attempt, describe: Threats to validity, generalizability

generalizability: meine Daten zeige nur für Chrome, MacBook, diese Geschwindigkeit etc. Und auch nur für diese Test-Website Die Schwierigkeit der Generalisierbarkeit ist eines der grössten Probleme bei dieser Fragestellung

6.3 Plain / Skeletal Website

- Information gained from this experiment
- Limitations and questions which can not be answered with this approach

6.4 Mirroring

6.5 HTTP Archive inspired website

- Information gained from this experiment
- Meaning and interpretation of the collected data
- Limitations and questions which can not be answered with this approach

6.6 WebPageTest Bulk Tests

- Bulk testing is a feature for private instances only
- Misuse this feature to test the same website X times

6.6.1 Bulk Test Overview: Description of test result page

- Each test has Test ID: YYMMDD_random_random
- Test results after bulk test available under `http://localhost:4000/result/{testID}/`
- For each test run, following data is available:
 - Link to test results: Test result page as same as for single test run
 - Median load time (First view)
 - Median load time (Repeat view)
 - Median Speed Index (First View)
 - Raw page data (file: [TestID_summary.csv])
 - Raw object data (file: [TestID_details.csv])
 - Http archive (.har) (file: json)
- Average First View Load Time
- Average Repeat View Load Time
- Combined Raw: Page Data (file: [TestID_summary.csv])
- Combined Raw: Object Data (file: [TestID_details.csv]). For 100 test runs, this file is appr. 20 MB, 24432 rows, 76 columns.
- Aggregate Statistics (file: [TestID_aggregate.csv])

6.6.2 Summary File for one Test

- Contains 6 rows: 3 test runs: for each test runs 1x first view and 1x repeat view
- Rows 1, 3, 5 contain FV, rows 2, 4, 6 contain data for RV

6.6.3 Aggregate Statistics File

- Contains aggregated data from bulk test
- One row for each test run: For 100 URLs in bulk test will be 100 rows in csv
- Each metric is available with Median, Average, Standard Deviation, Min, Max

6 Evaluation

- Metrics are available once from FV and once for Repeat View
- Metrics:
 - Successful Tests
 - Document Complete
 - Fully Loaded
 - First Byte
 - Start Render
 - Bytes In (Doc)
 - Requests (Doc)
 - Load Event Start
 - Speed Index
 - Last Visual Change
 - Visually Complete
- => For metric details, see Terms and Definitions

6.6.4 Compare Section

WPT has a feature to compare multiple tests. Accessible under compare URL: `http://localhost:4000/video/compare.php?tests={TestID},{TestID},...`

The compare page contains:

- Film strip
- Waterfall diagram
- Visual Progress diagram
- Timings diagram:
 - Visually Complete (First View Visually Complete Median)
 - Last Visual Change
 - Load Time (onload)
 - ...
- Cumulative Layout Shift diagram
- Requests diagram
- Bytes diagram
- Visually complete

- Last Visual Change
- Load Time (onload)
- Load Time (Fully Loaded)
- DOM Content Loaded
- Speed Index
- Time to First Byte
- Time to Title
- Time to Start Render
- CPU Busy Time
- 85% Visually Complete
- 90% Visually Complete
- 95% Visually Complete
- 99% Visually Complete
- First Contentful Paint
- First Meaningful Paint
- Largest Contentful Paint
- Cumulative Layout Shift
- html Requests
- html Bytes
- js Requests
- js Bytes
- css Requests
- css Bytes
- image Requests
- image Bytes
- flash Requests
- flash Bytes

6 Evaluation

- font Requests
- font Bytes
- video Requests
- video Bytes
- other Requests
- other Bytes

6.7 Internal, external validity

- At this point, i have the data collected and can analyse it
- The quality and quantity of the data needs to be discussed
- Quality: There are chances that some data are malformed, e.g. because internet connection was bad, etc.
- Quantity: Is the amount of data sufficient to make the evaluation generalisable

7 Future Work

- Last chapter...
- This chapter: Describe shortly all sections from this chapter
- In the next chapter...

7.1 Limitations of this thesis

- Discussion of unobserved topics
- Discussion of possible next steps

7.2 Other measurement tools and metrics

- List of tools and metrics worth investigating

7.2.1 Google Analytics 4

7.3 Speed Kit

7.4 PWAs, AMPs, Service Workers, Caching, HTTP2 etc.

- Overview of other web technologies and how they could be relevant for further research

8 Conclusion

- Last chapter...
 - This chapter: Describe shortly all sections from this chapter
 - Scope and contribution of this thesis
 - Short summary of each chapter:
 - Problem statement and why it is worth to examine research question
 - Terms and definitions
 - (Related work)
 - Approach and evaluation of practical work
 - Future work
- Several topics wurden bearbeitet in this thesis, such like mocking a website for testing purposes, literature review, metrics taxonomy, and the main part which is an experiment

9 Appendix

9.1 WebPageTest Bulk Tests

9.1.1 Single Test Raw page data

WPT Metrics from summary file

Name	Description
minify_total	Total bytes of minifiable text static assets.
responses_200	The number of responses with HTTP status code of 200, OK.
testStartOffset	...
bytesOut	The total bytes sent from the browser to other servers.
gzip_savings	Total bytes of compressed responses.
requestsFull	...
start_epoch	...
connections	The number of connections used.
base_page_cdn	The CDN provider for the base page.
bytesOutDoc	Same as bytesOut but only includes bytes until the Document Complete event. Usually when all the page content has loaded (window.onload).
result	Test result code.
final_base_page_request_id	...
basePageSSLTime	...
docTime	Same as loadTime.
domContentLoadedEventEnd	Time in ms since navigation started until document DOMContentLoaded event finished.
image_savings	Total bytes of compressed images.
requestsDoc	The number of requests until Document Complete event.
firstMeaningfulPaint	...
score_cookies	WebPageTest performance review score for not using cookies on static assets.
firstPaint	RUM First Paint Time, the time in ms when browser first painted something on screen. It's calculated on the client for browsers that implement this method.
score_cdn	WebPageTest performance review score for using CDN for all static assets.
optimization_checked	Whether or not optimizations were checked.

9 Appendix

score_minify	WebPageTest performance review score for minifying text static assets.
gzip_total	Total bytes of compressible responses.
responses_404	The number of responses with HTTP status code of 404, not found.
loadTime	The total time taken to load the page (window.onload) in ms.
URL	The tested page URL.
score_combine	WebPageTest performance review score for bundling JavaScript and/or CSS assets.
firstContentfulPaint	...
image_total	Total bytes of images.
score_etags	WebPageTest performance review score for disabling *ETag*s.
loadEventStart	Time in ms since navigation started until window.onload event was triggered (from W3C Navigation Timing).
minify_savings	Total bytes of minified text static assets.
score_progressive_jpeg	WebPageTest performance review score for using progressive JPEG.
domInteractive	...
score_gzip	WebPageTest performance review score for using gzip compression for transferring compressable responses.
score_compress	WebPageTest performance review score for compressing images.
domContentLoadedEventStart	Time in ms since navigation started until document DOMContentLoaded event was triggered (from W3C Navigation Timing).
final_url	...
bytesInDoc	Same as byteIn but only includes bytes until Document Complete event.
firstImagePaint	...
score_keep-alive	WebPageTest performance review score for using persistent connections.
loadEventEnd	Time in ms since navigation started until window.onload event finished.
cached	0 for first view or 1 for repeat view.
score_cache	WebPageTest performance review score for leveraging browser caching of static assets.
responses_other	The number of responses with HTTPS status code different from 200 or 404.
main_frame	...
fullyLoaded	The time (in ms) the page took to be fully loaded — e.g., 2 seconds of no network activity after Document Complete. This will usually include any activity that is triggered by javascript after the main page loads.
requests	List of details of all requests on tested page.

final_base_page_request	...
TTFB	Time to first byte, which is the duration in ms from when the user first made the HTTP request to the very first byte of the page being received by the browser.
bytesIn	The amount of data that browser had to download in order to load the page. It is also commonly referred to as the page size.
osPlatform	...
test_run_time_ms	...
tester	The ID of tester that performed the page test.
browser_version	The browser version.
document_origin	...
document_URL	...
date	Time and date (number of seconds since Epoch) when test was complete.
PerformancePaintTiming.first-paint	...
osVersion	...
domElements	The total number of DOM elements.
browserVersion	The browser version.
fullyLoadedCPUms	CPU busy time in ms until page was fully loaded.
browser_name	The browser name.
PerformancePaintTiming.first-contentful-paint	...
base_page_cname	...
eventName	...
os_version	...
base_page_dns_server	...
fullyLoadedCPUpct	Average CPU utilization up until page is fully loaded.
domComplete	...
base_page_ip_ptr	...
document_hostname	...
lastVisualChange	Time in ms until the last visual changed occurred.
visualComplete	Time in ms when page was visually completed.
render	The first point in time (in ms) that something was displayed to the screen. Before that user was staring at a blank page. This does not necessarily mean the user saw the page content — it could just be something as simple as a background color — but it is the first indication of something happening for the user.
SpeedIndex	The SpeedIndex score.
visualComplete85	Time in ms when page was visually completed 85%.
visualComplete90	Time in ms when page was visually completed 90%.
visualComplete95	Time in ms when page was visually completed 95%.
visualComplete99	Time in ms when page was visually completed 99%.
LargestContentfulPaintType	...
LargestContentfulPaintNodeType	...

9 Appendix

chromeUserTiming.navigationStart	...
chromeUserTiming.fetchStart	...
chromeUserTiming.responseEnd	...
chromeUserTiming.domLoading	...
chromeUserTiming.markAsMainFrame	...
chromeUserTiming.domInteractive	...
chromeUserTiming.domContentLoadedEventStart	...
chromeUserTiming.domContentLoadedEventEnd	...
chromeUserTiming.firstPaint	...
chromeUserTiming.firstContentfulPaint	...
chromeUserTiming.firstImagePaint	...
chromeUserTiming.firstMeaningfulPaint	...
chromeUserTiming.firstMeaningfulPaintCandidate	...
chromeUserTiming.domComplete	...
chromeUserTiming.loadEventStart	...
chromeUserTiming.loadEventEnd	...
chromeUserTiming.LargestContentfulPaint	...
chromeUserTiming.LargestTextPaint	...
chromeUserTiming.CumulativeLayoutShift	...
run	The run number.
step	...
effectiveBps	Bytes per seconds, i.e.: total of bytes in / total time to load the page.
effectiveBpsDoc	Same as effectiveBps but until Document Complete event.
domTime	The total time in ms until a given DOM element (specified via domelement parameter when running a test) was found on the page.
aft	Above the Fold Time (no longer supported). The time taken to load everything in the viewport above the fold.
titleTime	Total time in ms until page title was set on browser.
domLoading	...
server_rtt	...
smallImageCount	...
bigImageCount	...
maybeCaptcha	...
bytes.html	...
requests.html	...
bytesUncompressed.html	...
bytes.js	...
requests.js	...
bytesUncompressed.js	...
bytes.css	...
requests.css	...
bytesUncompressed.css	...
bytes.image	...
requests.image	...

bytesUncompressed.image	...
bytes.flash	...
requests.flash	...
bytesUncompressed.flash	...
bytes.font	...
requests.font	...
bytesUncompressed.font	...
bytes.video	...
requests.video	...
bytesUncompressed.video	...
bytes.other	...
requests.other	...
bytesUncompressed.other	...
id	...
chromeUserTiming.InteractiveTime	...

Table 9.1: Your caption here

- 9.1.2 Single Test Raw object data
- 9.1.3 Single Test Http archive (.har)
- 9.1.4 Combined Test Raw page data
- 9.1.5 Combined Test Raw object data
- 9.1.6 Combined Test Aggregate data

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