Analyzing the impact of COVID-19 Pandemic on broadband across the country

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1.1 Introduction

The novel coronavirus disease arose in December 2019 in Wuhan, China and spread across the globe. In March 2020, many states in the United States began mandating statewide lockdowns because the virus was very contagious. Public spaces, offices, schools, and universities were closed, forcing individuals to adapt to life within their homes. Normal life was completely uprooted as people socially distanced from others to avoid the spread of COVID-19 and instead depended on the Internet for school, work, and social interactions.

Internet performance has become extremely important during the COVID-19 pandemic because of how dependent people are on broadband Internet. Broadband provides access to entertainment, information about COVID-19, school, work, and essential goods/services. For people in areas with lockdowns, broadband serves as a lifeline to the world one's home. Understanding how performance of Internet networks has changed is relevant to ISPs who face disgruntled customers when there are speed degradations.

Policymakers recognize how important broadband is for a productive society and should be informed of how broadband performance is changing for different groups. To address how internet performance has changed, this report answers questions about how internet speed changed on the national scale, day of week, state, COVID-related factors, and demographics such as income, poverty, race. To understand how COVID-19 impacted the internet, speed tests are an important metric to quantitatively describe the quality of the internet with increased traffic. Section 1.2 discusses our current understanding of COVID-19's impact on broadband by looking at various news articles. Section 1.3 explains our methods, including an introduction to speed tests, our data sources, and key metrics. Section 1.4 is about our results, and Section 1.5 is our conclusions.

1.2 Current Understanding of COVID-19's impact on Broadband

There are various articles about the impact of the coronavirus pandemic on Internet performance. These sources use different data sources and come to different conclusions.

Fastly is a cloud computing services provider. In "How COVID-19 is affecting internet performance," Bergman and Iyengar from Fastly sampled TCP connections from Fastly's servers (Bergman and Iyengar 1). They report that Internet traffic increased gradually as institutions closed and lockdown orders began. In "Decoding the digital divide," Bergman and Iyengar show that Internet performance is better for those in higher income groups (Bergman and Iyengar 2).

Sascha Meinrath, cofounder of Measurement Lab (M-Lab) expressed in an opinion piece that "...our internet is breaking. And it's not breaking equitably" (Meinrath). Gigi Sohn, a former senior staff member at the Federal Communications Commision and Sasha Meinrath "have testified that the digital divide was exacerbating disparities in the US, but it's the coronavirus outbreak which has brought these concerns to the forefront." (Holpuch).

Richard Bennett counters some of Meinrath's claims in a piece entitled "The internet isn't breaking." (Bennett). Bennett challenges Meinrath's conclusions by stating that M-Lab "has been regularly proven wrong in its critiques of internet infrastructure" and that there has been "virtually no degradation of service" (Bennet). He backs this idea by explaining that SamKnows data shows less than a 1% decrease in speed (Bennett).

We will discuss how our results relate to these findings in section 1.5.

1.3 Methods

1.3.1 Introduction to Speed Tests

The simplest way to measure internet performance is through third party speed tests. Some factors that impact a speed test include device or browser used and physical distance to the server (the third-party test provider's machine). Download and upload speed is commonly measured in Megabits per second (Mbps), the number of bits transferred per second over an internet connection ("What's the Difference between Mbps and MBps?"). Download speed measures how many Megabits of data that your device downloads per second and upload speed measures how many Megabits of data that your device uploads per second, aka sends to another device or server (George). Download speeds are important for listening to music online, streaming entertainment, or downloading content (George). Upload speeds are important for sending emails, working on something like Google Docs, and video calls (George). The infographic below shows the minimum download speeds a user needs to do the following activities.

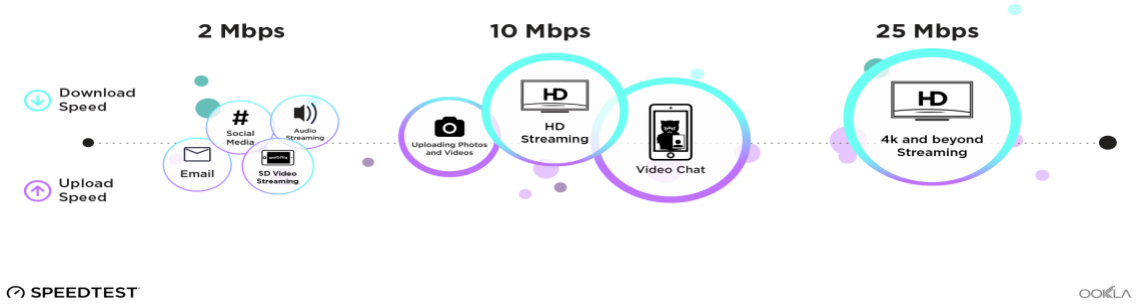


Figure 1.3.1.1 Possible Activities at 2, 10, 25 Mbps Download Speeds ("What's the Difference between Mbps and MBps?")

RTT is the time it takes a network request to go from a starting point to a destination and back to the starting point measured in milliseconds (ms) (“What Is Round Trip Time?”). To understand Internet performance through speed tests, we used two major sources: Measurement Lab (M-Lab) and SamKnows.

1.3.2 Introduction to Measurement Lab (M-Lab)

Measurement Lab (M-Lab) offers free Internet speed test data (“Open Internet Measurement.”). We primarily accessed the unified_uploads and unified_downloads speed test information through Google BigQuery. This information is from the Network Diagnostic Test (NDT) which is a “single stream performance measurement of a connection’s capacity for “bulk transport” (“NDT (Network Diagnostic Tool).”). We used the unified_upload and unified_download speed tests because they provide M-Lab’s best understanding of data by filtering for tests that meet their research quality requirements (“NDT (Network Diagnostic Tool).”). We used the field ‘MeanThroughputMbps’ to measure speed. Figure 1.3.2.1 illustrates the rise in M-Lab speed tests conducted during the pandemic, which may reflect internet users experiencing slower speeds and running speed tests to confirm their suspicions.

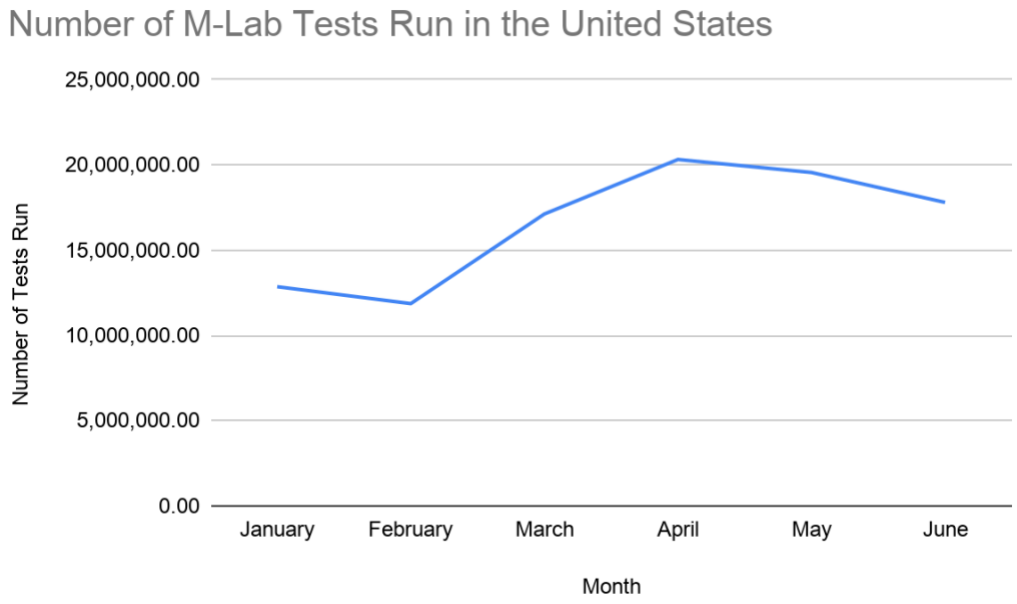


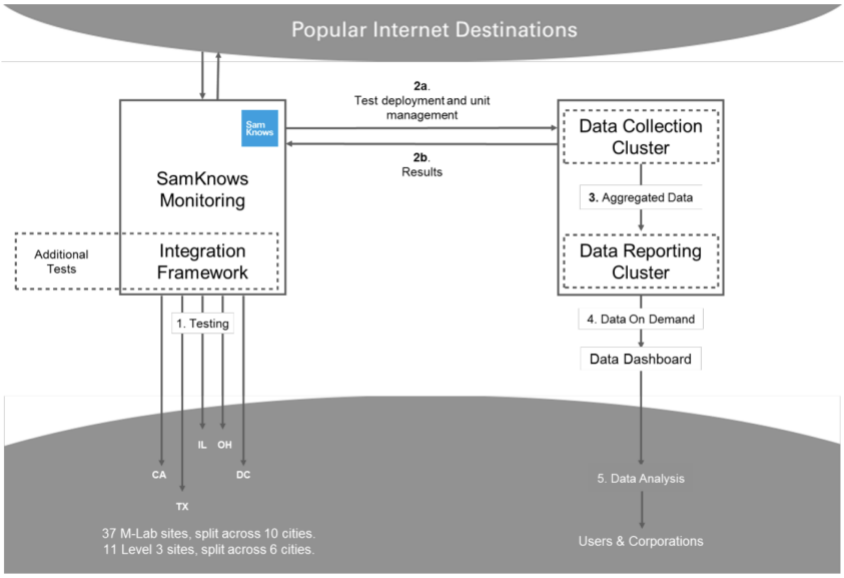
Figure 1.3.2.1 Number of M-Lab Tests Run in the United States

1.3.3 Introduction to SamKnows

SamKnows provides a way to measure broadband performance for users using the SamKnows Whitebox and a dashboard that keeps a track of all the performance metrics for the broadband

performance such as the download speed, upload speeds, jitter, delays, packet loss, and others. Figure 1.3.3.1 shows the SamKnows Testing Architecture.

SamKnows provides multiple tests such as the download speed test, upload speed test, UDP



latency test, UDP packet loss test, DNS resolution test, and others to measure the various metrics mentioned before. For the purpose of this report, we have focused on the Upload Speed test and Download Speed tests.

1.3.3.1 Download and Upload Speed Tests

The download and upload speed tests measure the performance of the internet connection by using 10 seconds fixed-duration tests.

1.3.4 M-Lab vs. SamKnows

We used two data sources for the analysis of internet speed in this section of the report - one from M-Lab (Section 1.3.2) and the other from SamKnows (Section 1.3.3). Both of these are reputed sources of broadband speeds measurement. The key similarities and differences in these two speed test measurements are highlighted below -

1. M-Lab speed tests use a software-based approach. It is a web-based speed test that runs on the user's browser to conduct speed tests. On the other hand, a SamKnows speed test measures the performance of the internet connection at the router.
2. The M-Lab speed tests are conducted manually by the user at any time of the day. Since a user may run the tests only when they are facing issues with the network or when they are setting up a new network, the results from these tests can be biased (from selection

bias) and skewed. The SamKnows whitebox is pre-programmed to conduct tests throughout the day.

3. Wi-Fi is the primary source of internet connectivity in households in the US (">75% of U.S. households use WiFi for in-home connectivity"). For the tests conducted over Wi-Fi, even the location of the device in the room while performing a speed test can be one of the factors that affect the performance of the tests. For the SamKnows speed tests, since the data is collected directly from the router, this scenario does not exist.
4. The M-Lab NDT (Network Diagnostic Tests) speed tests use a single TCP connection for conducting speed tests. SamKnows speed tests for download and uploads use 3 to 8 concurrent TCP connections for their tests.

The difference in their method to gather data leads to different datasets, which we will analyze in further sections.

1.3.5 Census Data

We used United States 2018 Census Bureau data collected by the American Community Survey (ACS) from Google Cloud Platform ("American Community Survey (ACS)"). It provides crucial information related to demographics and we focused on the total population, median income, poverty level, specific race populations, and school status data that was given by zip code. It may be worrying that this census data is collected by surveys from a sample of housing addresses. As an example, for the accuracy of this data, the percent margin of error from 2015 census data in Colorado ranged from +/-0.2% to +/-0.5%. Assuming the error is similar in 2018, it is not statistically significant enough to impact our conclusions.

1.3.6 Rural Classification

For part of our analysis, we investigated how results in rural locations changed as compared to non-rural locations. These groups have different relationships with broadband Internet, one example being having access to different broadband technologies. To identify which zip codes are classified as rural, we used the Federal Office of Rural Health Policy (FORHP)'s data files from the Health Resources and Services Administration

1.3.7 Metrics

To analyze the data across this report, we used the statistical measures of percentiles. The kth percentile is where k% of the data falls below that point. Percentiles help report relative standing. The 50th percentile explains what happens at the middle and is also known as the median. Percentiles can be better measures than mean for understanding internet performance because there are a lot of outliers in speed test data sets. Extremely high or low values skew the mean towards one direction and can provide a less accurate understanding. We used January and

February as a pre-COVID period, March as a transition month, and April and May as post-COVID months.

1.4 Results

1.4.1 Nationwide Changes by Percentile

Understanding how performance changed at different percentiles helps us see how performance for various groups changed. The median (50%) tells us what occurred at the middle, but the lower and higher percentiles represent how people who have the worst and best Internet experienced shifts. Figures 1.4.1.1 and 1.4.1.2 show the nationwide download and Figures 1.4.1.3 and 1.4.1.4 show the nationwide upload speeds for various percentiles by month in 2020.

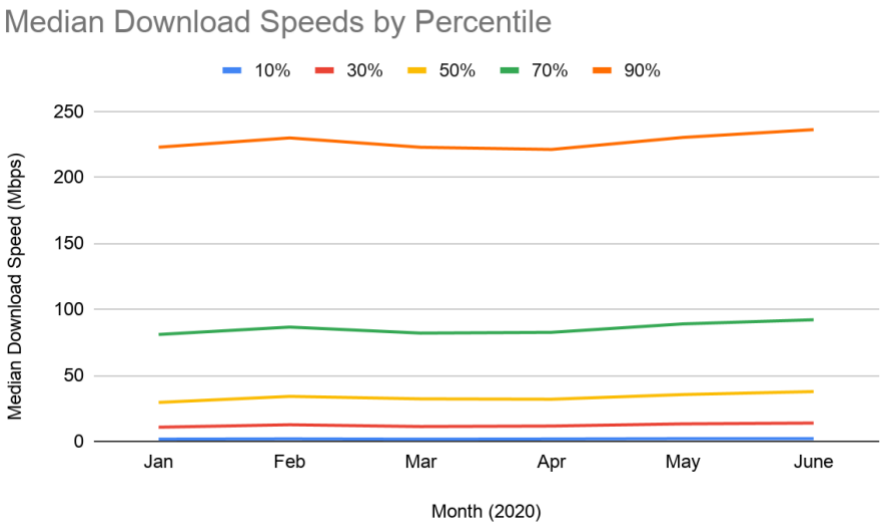


Figure 1.4.1.1 Graph of Median Download Speed by Percentile (January-June)

	10%	**30%**	**50%**	**70%**	**90%**
Jan	1.68	10.68	29.47	80.95	222.85
Feb	1.88	12.56	34.04	86.55	229.86
Mar	1.64	11.20	32.18	81.98	222.78
Apr	1.79	11.59	31.89	82.57	221.13
May	2.03	13.23	35.42	88.95	230.22
June	2.06	13.84	37.70	92.09	236.15

Figure 1.4.1.2 Table of Median Download Speed by Percentile (January-June)

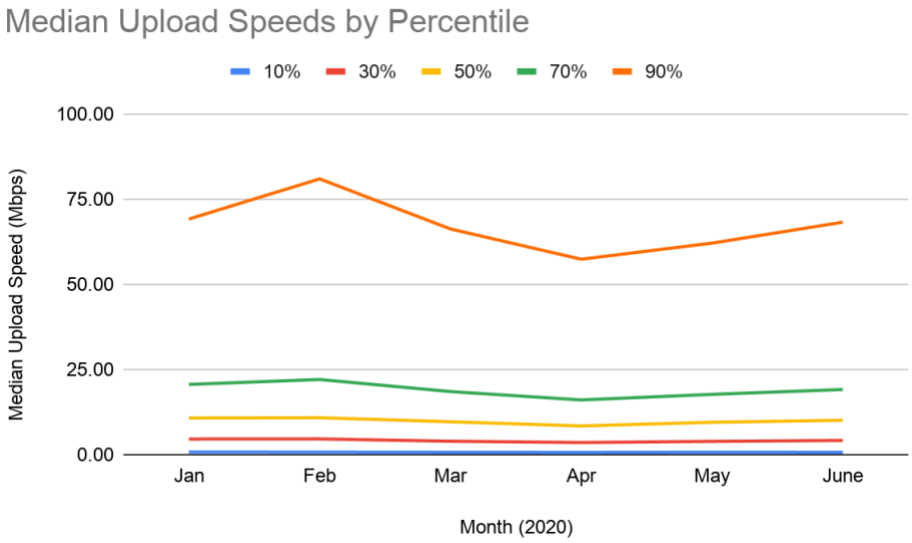


Figure 3.4.1.3 Graph of Median Upload Speed by Percentile (January-June)

	10%	**30%**	**50%**	**70%**	**90%**
Jan	0.80	4.60	10.78	20.62	69.15
Feb	0.76	4.63	10.85	22.07	80.92
Mar	0.71	3.96	9.67	18.52	66.24
Apr	0.67	3.58	8.44	16.07	57.36
May	0.73	3.92	9.52	17.71	62.08
June	0.70	4.19	10.10	19.13	68.22

Figure 1.4.1.4 Table of Median Upload Speed by Percentile (January-June)

There is a decrease in download and upload speeds from February to April and an increase from April to June. It was expected that speeds would drop in March and April because most states went into some form of government mandated lockdown, but it is surprising that performance improved (better than pre-COVID levels for downloads) in May and June.

Taking the average median speed for January and February as the Baseline, we compared this to speeds for March, April, and May. Figures 1.4.1.5 shows results for download speeds and 1.4.1.4 shows results for upload speeds.

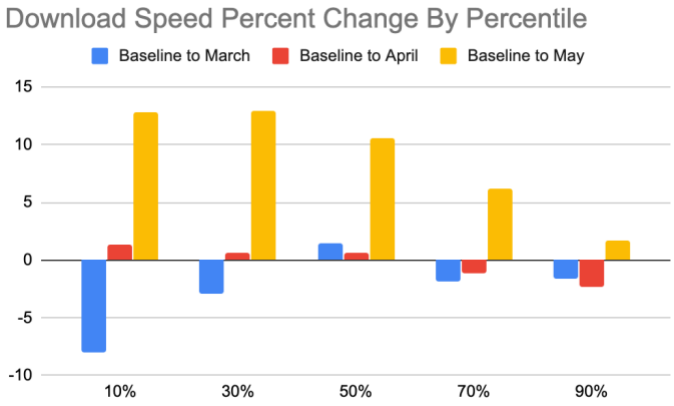


Figure 1.4.1.5 Download Percent Change by Percentile

For download speeds, the 10th percentile experienced an 8% decrease from Baseline to March. Across the other percentiles, there is no significant change to March or April. However, there was an increase in speeds in May. The increase is greater for lower percentiles and smaller for higher percentiles. The 10th and 30th percentiles experienced about a 13% increase in download speeds in May, while the 90th percentile experienced about a 2% increase. People who had poor Internet saw a greater increase in relative download performance than people who had better Internet.

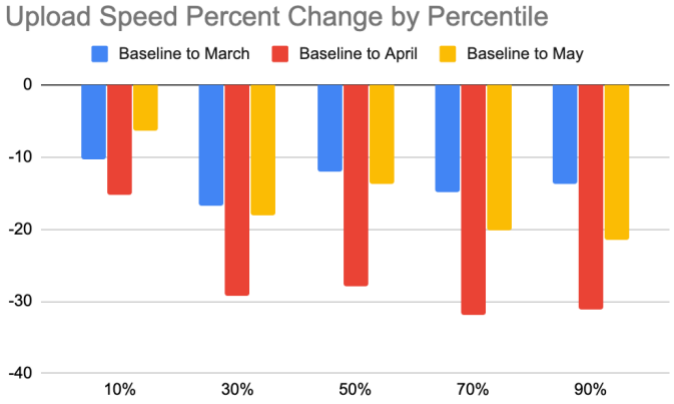


Figure 1.4.1.6 Upload Percent Change by Percentile

For upload speeds, there is a decrease for March, April, and May. The greatest change is from Baseline to April, when most states were officially under lockdown. The 10th percentile saw less of a decrease than other percentiles. The individuals who already had low upload speeds were not as impacted by speed degradations because they already had such low speeds. This is the opposite trend we saw for download speeds where people at lower percentiles experienced a greater increase in download speeds in May than other groups. Overall, upload speeds took a

greater hit than download speeds. This may be partially attributed to the rise in upload-heavy usage like video conferencing, combined with the fact that some broadband networks, such as cable systems and wireless systems, are currently designed asymmetrically to support much greater downstream traffic than upstream.

1.4.2 Maps of States by Changes in Speed

The following graphs display the percent change in median download speed (Figure 1.4.5) and upload speed (Figure 1.4.6) from the pre-COVID baseline of January and February to the post-COVID period of April and May for the states in the continental United States. The deeper blue represents a greater percent increase in median speed and the deeper orange represents a greater percent decrease in median speed.

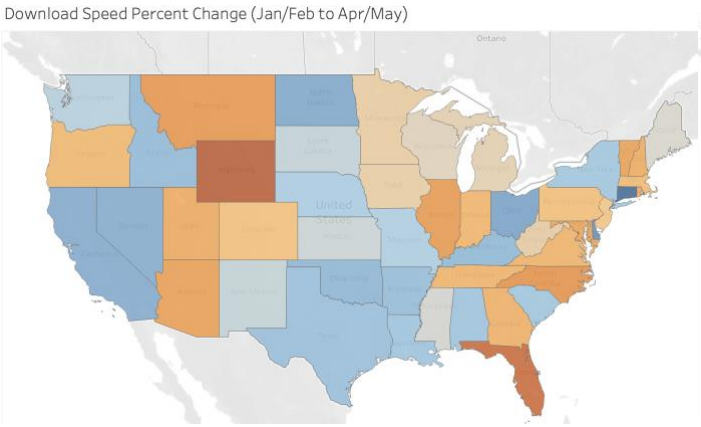


Figure 1.4.2.1 Download Change Map

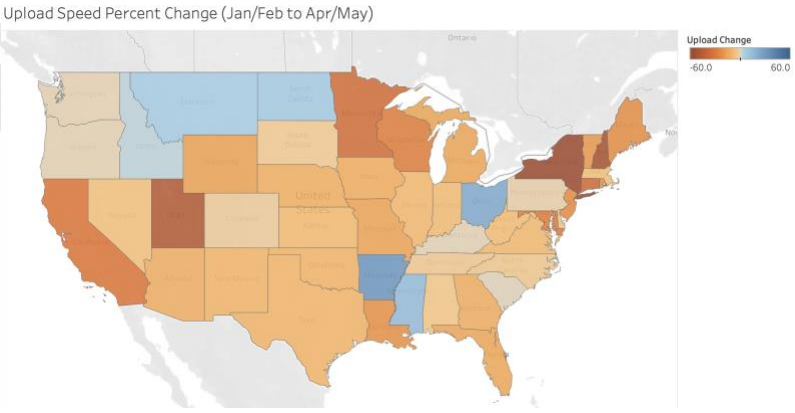


Figure 1.4.2.2 Upload Change Map

States were impacted in very different ways. Upload speeds experienced a greater percent decrease than download speeds for the majority of states, as displayed by the larger number of orange states on the graph on the right. DC, Florida, Montana, North Carolina, and Wyoming experienced the greatest download speed decreases and Connecticut, DC, New Hampshire, New York, and Utah experienced the greatest upload speed decreases. 27 states out of 51 (including DC) experienced a decrease in download speeds while a whopping 44 states experienced an decrease in upload speeds between these two periods. The correlation coefficient between change in download speed and change in upload speeds for states is 0.15. It is surprising to see that these two factors are not related.

1.4.3 Rural/Non-Rural

Understanding the changes in performance for zip codes deemed rural vs. otherwise is interesting because there are different technologies and uses between these two groups. We

used the rural definition from the Federal Office of Rural Health Policy Rural as described in Section 1.3.6. Rural locations have historically experienced lower Internet speeds and struggled with access to broadband. The following graphs display the monthly median download and upload speeds for months leading up to and including the pandemic period.

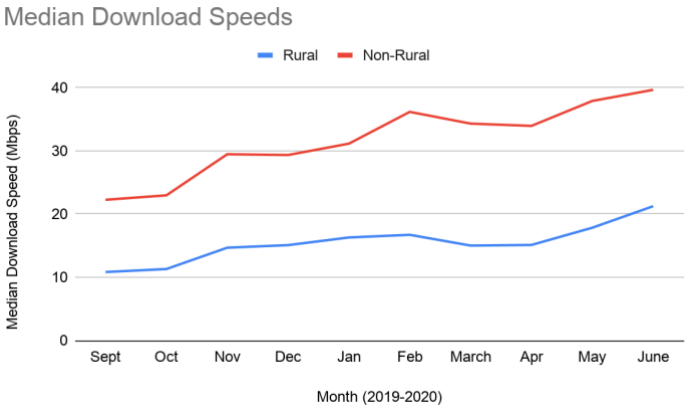


Figure 1.4.3.1 Download Speed by Rural Status

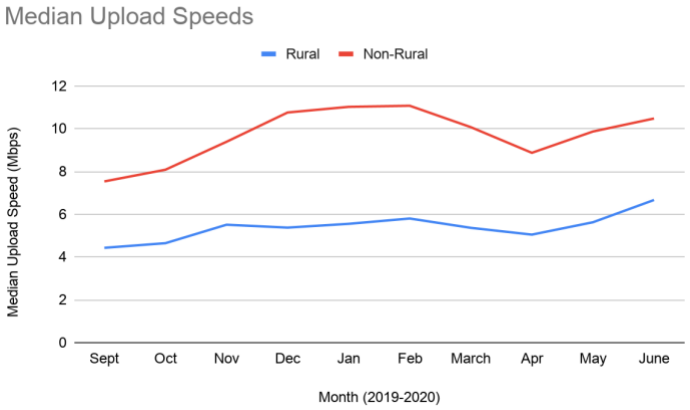


Figure 1.4.3.2 Upload Speed by Rural Status

Figures 1.4.3.1 and 1.4.3.2 show that the variations in download and upload speeds seem to follow a similar pattern for rural and non-rural locations. It is interesting to note that speeds were increasing in the months leading up to the pandemic and dropped in March when COVID-19 hit. In both graphs, there is a decrease from February to April and then an increase from April to June. As with the national graphs, the Internet begins "recovering" in May.

Figure 1.4.3.3 displays changes in download and upload speeds for rural and non-rural locations by comparing Pre-COVID (January & February) and Post-COVID (April/May) periods.

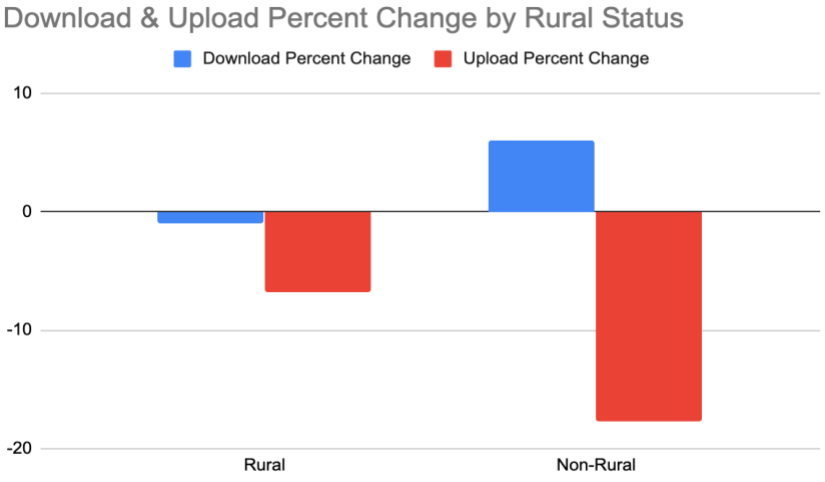


Figure1.4.5.3 Change in Upload/Download by Rural Status

Non-rural populations experienced a 17.7% decrease in upload speed, a much larger decrease than the 6.8% decrease for rural populations. The decrease was greater for non-rural populations potentially because rural populations already had low speeds and they stayed fairly low and non-rural population. Some of this difference can probably be attributed to differences in technology.

1.4.4 Income

Examining the median speeds each income bracket gets and the effects of a pandemic on these speeds could shed light on the digital divide of our nation. We used the U.S. Census Bureau income brackets (see Appendix 7.2.1) to produce the graphs below. Overall, higher income groups have higher speeds, which is expected -- households with higher income would have more disposable income to spend on more expensive and faster internet plans. The $140,000-$150,000 bracket is an exception; its range is exceptionally small and its curve could be due to random fluctuations, as it shows higher median download speeds than the $150,000-$200,000 group. The most interesting feature of these graphs is how lower income groups seem to have continuous low internet speeds and higher income groups show a drop in median speeds after February.

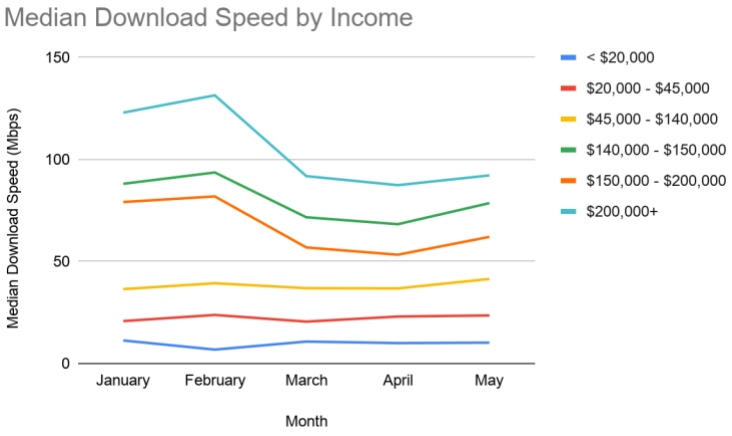


Figure 1.4.4.1 Median Download Speed by Income

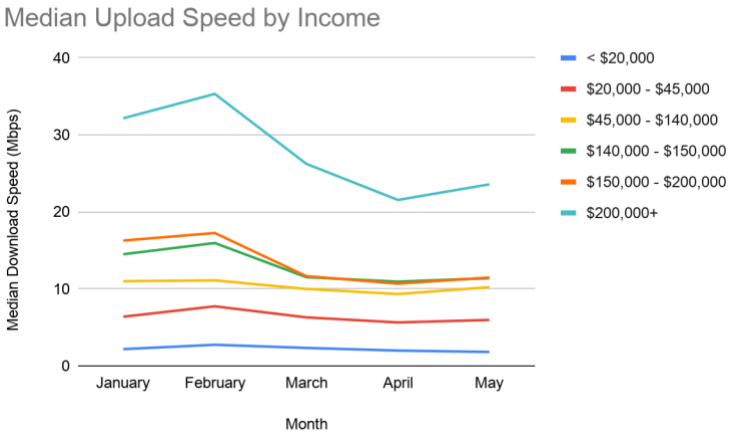


Figure 1.4.4.2 Median Upload Speed by Income

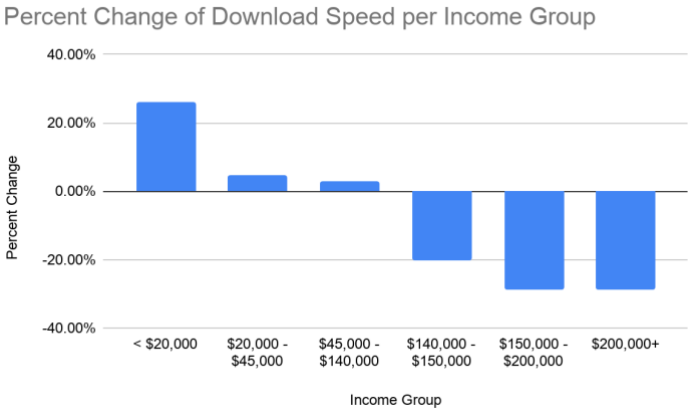


Figure 1.4.4.3 Change in Download Speed

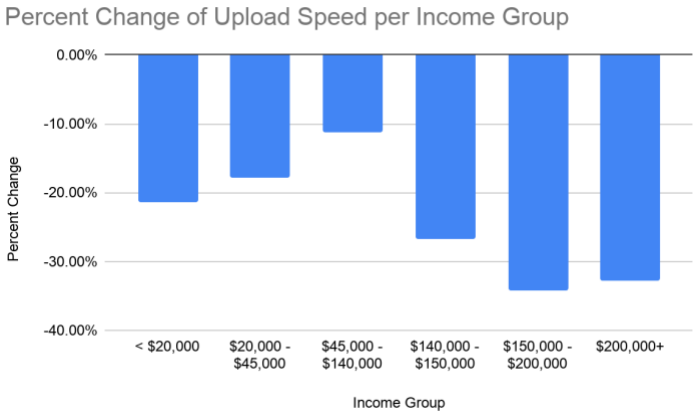
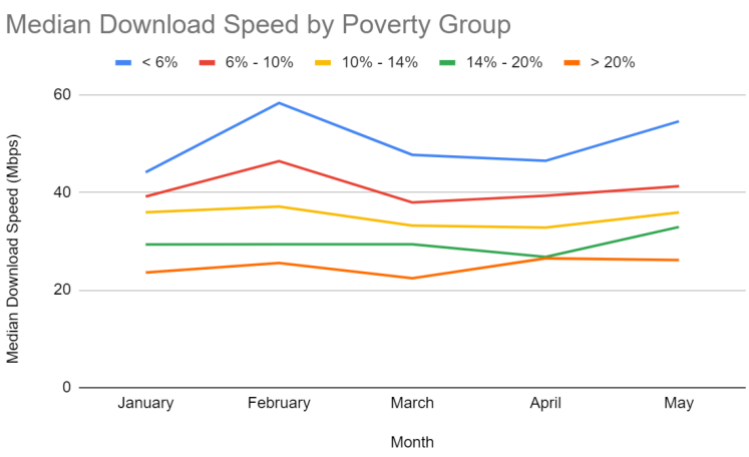


Figure 1.4.4.4 Change in Upload Speed

Figures 1.4.4.3 and 1.4.4.4 show the percent change in median download and upload speed per income group respectively from pre-COVID (median of April and May) to post-COVID (median of January and February). The raw difference of speeds for lower income groups are reflected by greater percentage differences because the median speeds for lower income groups are much smaller than those with higher speeds. This would be reflected in real life when a user with 8 Mbps cannot join a video call but can at 10 Mbps versus a user with 100 Mbps who can do the same as someone with 102 Mbps. We compare the percentage change and difference graphs in Appendix 7.2.2. We found most of the bars to be negative and increasing in magnitude as income increased, as reflected in the difference graphs in the appendix. The median download speed for lower income groups increases very slightly from pre-COVID to post-COVID, but these values can be attributed to random fluctuations. The remainder of the download speeds graph and the entire upload speed graph shows that in general, higher income groups had greater degradations in speed.

1.4.5 Poverty

The poverty groups were determined by the number of zip codes available for each (see Appendix 7.2.3). The following figures display the median download and upload download speed by poverty group respectively. The download speeds align with what we expected: groups with a smaller poverty rate have higher speeds than groups with higher percentages of poverty. There seems to be a bigger dip in speed for the group of less than 6% poverty between February and March, which is a common theme with income groups; those who got higher speeds before saw a more dramatic decrease in their speed after the pandemic struck.



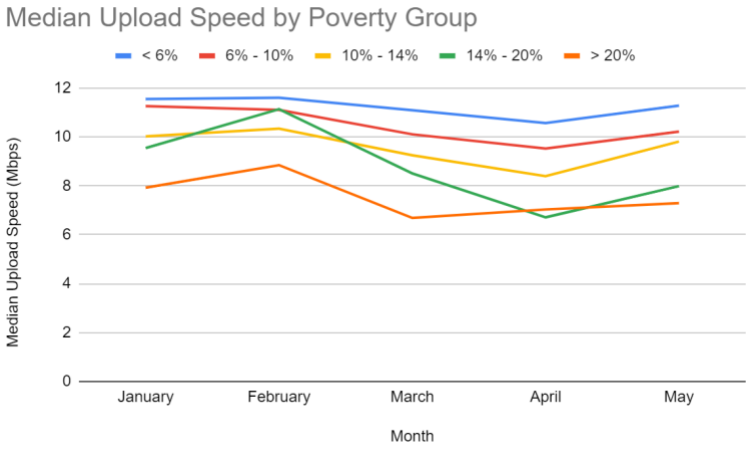


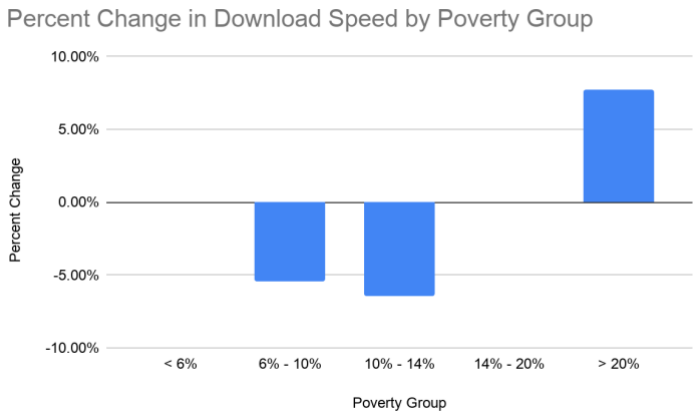
Figure 1.4.5.1 Median Download Speed & Poverty

Figure 1.4.5.2 Median Upload Speed & Poverty

Overall, the median upload speed graph to the right is similar to the download speed graph on the left with the exception of the 14%-20% poverty group getting better speeds than the 10%-14% poverty group in February and worse speeds than the >20% poverty group in April. We believe there is a confounding variable in the 14%-20% group that creates this anomaly. Otherwise, the shape of the upload graph would be the same as the download speed graph.

Contrary to what we expected, the percent change in download speed graphs from pre-COVID to post-COVID show very little change in the group with lowest poverty. We predicted that this group would have the greatest negative change, since this group typically has greater download speeds and groups with higher download speeds usually decreased the most from pre- to post-COVID. What is even more surprising is the nearly 8% increase for the group with highest poverty. We are unsure of what could cause these inconsistencies and believe there are confounding factors that are hidden within this data.

The percent change in upload speeds show all groups decreasing, which is what we expected, but the trend seems to show that groups with higher poverty have a greater decrease in speed. As mentioned earlier, we expected lower poverty groups have greater decreases in speed, but there must be some other factors influencing the data.



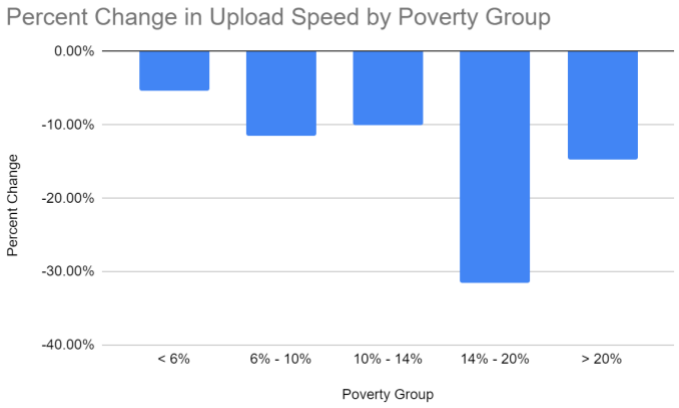


Figure 1.4.5.3 Percent Change in Download Speed Figure 1.4.5.4 Percent Change in Upload Speed

The pandemic did not significantly impact poverty groups differently. For two groups, there was no change at all, two other groups saw about a 5% decrease in speeds, while positively impacted the group with greater than 20% poverty. Upload speeds were all negatively impacted by the pandemic across all poverty groups, with the 14%-20% group having the greatest percent change.

1.4.6 Race

The following graphs relate the race of two minority groups (Hispanic people and Black people) with Median Download Speed in order to understand how the pandemic may have impacted the Internet performance for different races. The groups were determined by dividing the total population into roughly equal groups by the proportion of Hispanic or Black people in a zip code (refer to Appendix for total population in each group). Figures 1.4.6.1 and 1.4.6.2 display Median Download Speeds and Figures 1.4.6.3 and 1.4.6.4 display Median Upload Speeds.

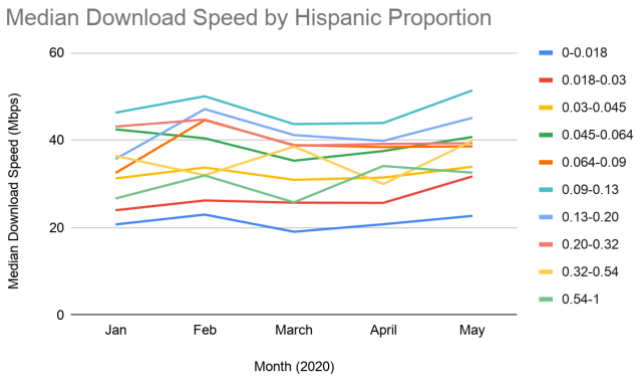


Figure 1.4.6.1 Download by Hispanic Proportion

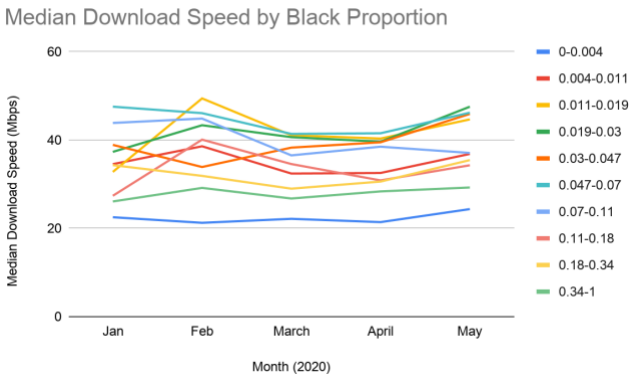


Figure 1.4.6.2 Download by Black Proportion

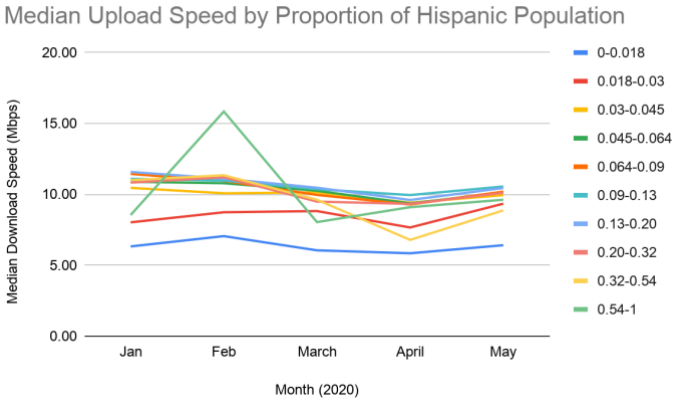


Figure 1.4.6.3 Upload by Hispanic Proportion

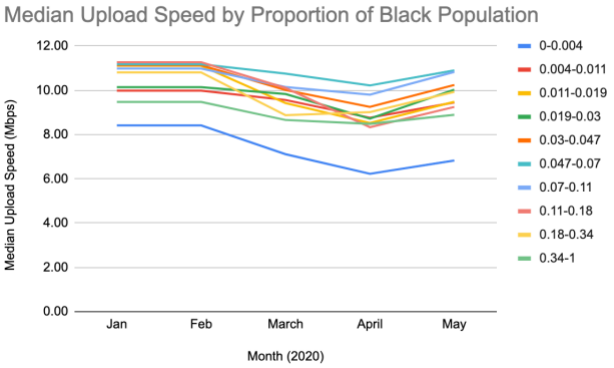


Figure 1.4.6.4 Upload by Black Proportion

The number of complaints is not dependent on the proportion of either minority. Figure 1.4.6.4 and 1.4.6.5 show percent change from pre-COVID (January & February) to post-COVID (April & May).

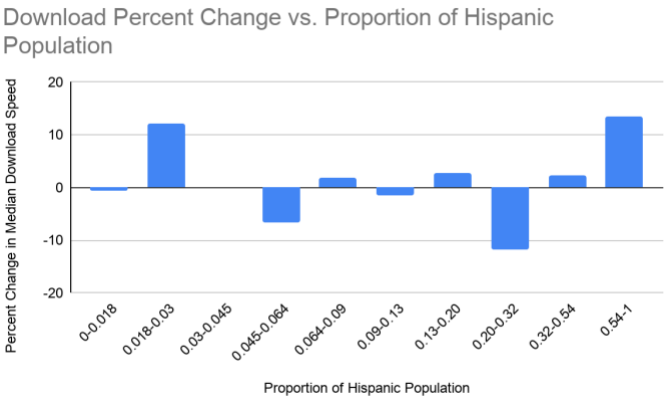


Figure 1.4.6.4 Change by Hispanic Proportion

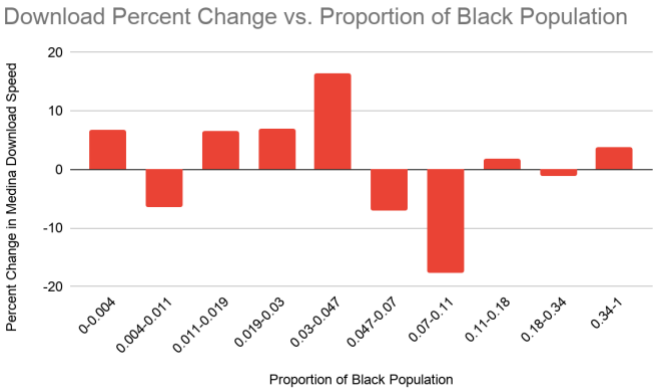


Figure 1.4.6.5 Change by Black Proportion

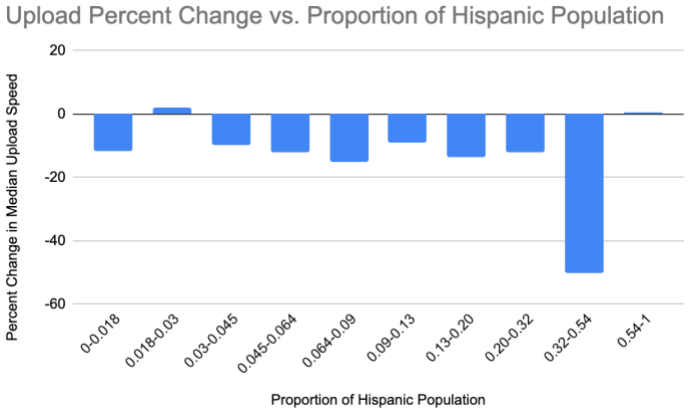


Figure 1.4.6.6 Change by Hispanic Proportion

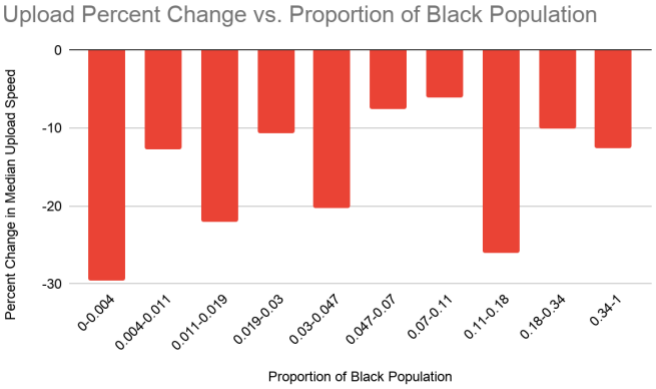


Figure 1.4.6.7 Change by Black Proportion

These fluctuations between brackets are random and cannot be attributed to the proportion of a minority population.

1.4.7 Day of Week Analysis

Even before COVID, there were noticeably slower speeds during a phenomenon known as "internet rush hour." "Internet rush hour" is not limited to certain times of day, but days of the week too- many internet connections seem to slow down on Saturdays and Sundays (Dilley). Surprisingly, the M-Lab data somewhat disagrees with this claim. For download speeds, the difference between the minimum and maximum median speed of day of week for all months is 2 Mbps. For upload speeds, this difference is 1 Mbps.

The figure below shows the median download speed by day of the week and has relatively flat lines for download speeds across the week for all months except for slight increases on weekends for March, April, and May. January and February do not show substantial decreases on weekends that we expected from days considered as "internet rush hour." Furthermore, download speed seemed to be better, not worse, on weekends than weekdays.

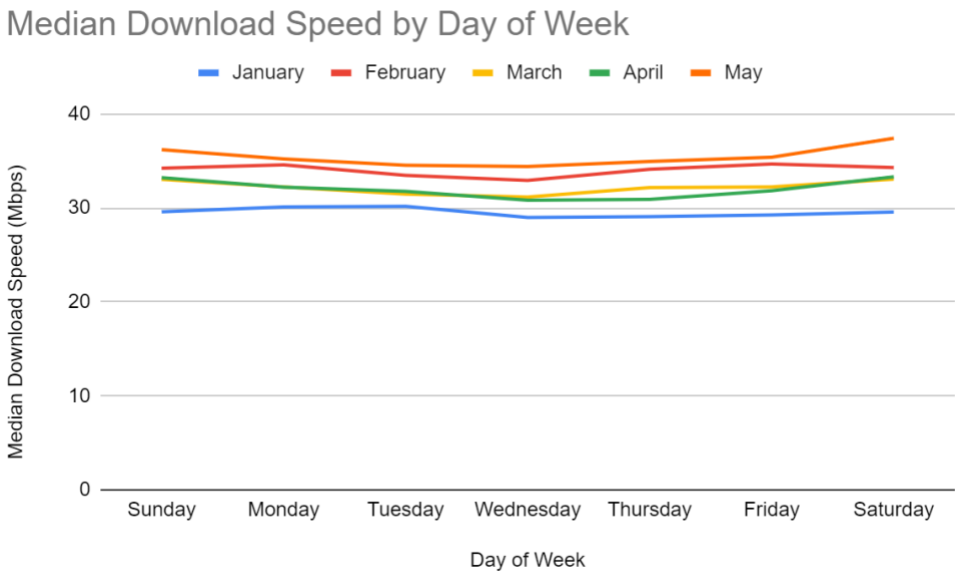


Figure 1.4.7.1 Median Download Speed by Day of Week

The figure below shows the median upload speed by day of the week. January and February weekends reflect slower upload speeds, as expected from "internet rush hour," while March, April, and May weekends had faster upload speeds.

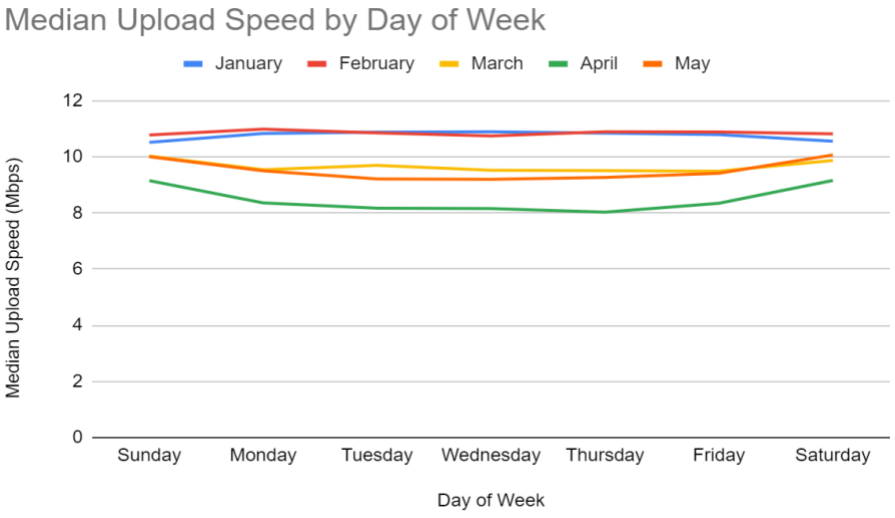


Figure 1.4.7.2 Median Upload Speed by Day of Week

We quantified the differences in weekdays versus weekends by calculating the percent change from the average of weekend medians to the average of weekday medians (their difference divided by the average of weekday medians). The percent change for download speeds is shown in the figure below. As noted earlier, January and February showed little difference; contrary to the "internet rush hour" belief, the results show weekend download speeds being slightly faster than weekday (at least, for January and February) pre-COVID. March through May show a greater increase in download speeds on weekends than weekdays (4-6% percent change).

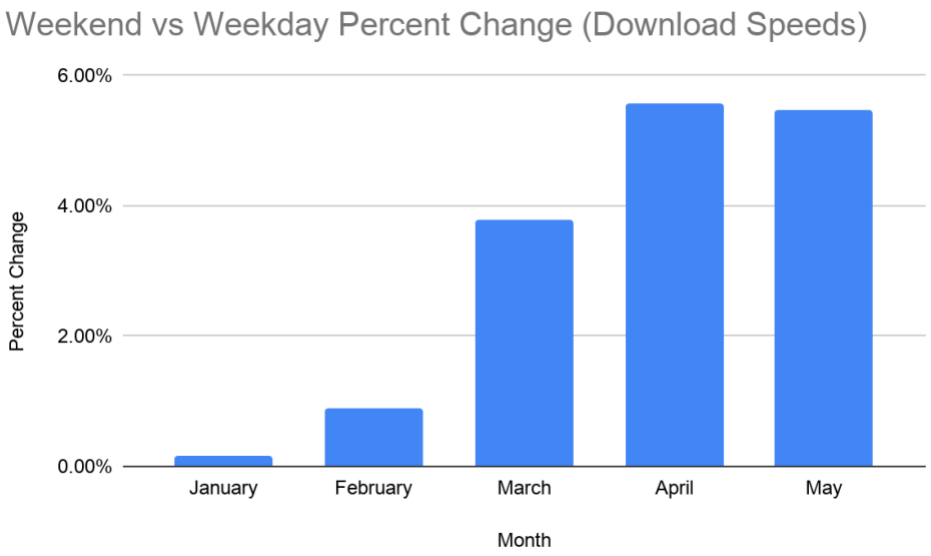


Figure 1.4.7.3 Weekend vs Weekday Percent Change for Download Speeds

We see in the figure below that for upload speeds, January and February represent what we expect from "internet rush hour," slower speeds on weekends versus weekdays. However, similar to download speeds, post-COVID months show much better speeds on weekends compared to weekdays. The most notable month, April, had an 11.46% increase in upload speed on weekends compared to weekdays.

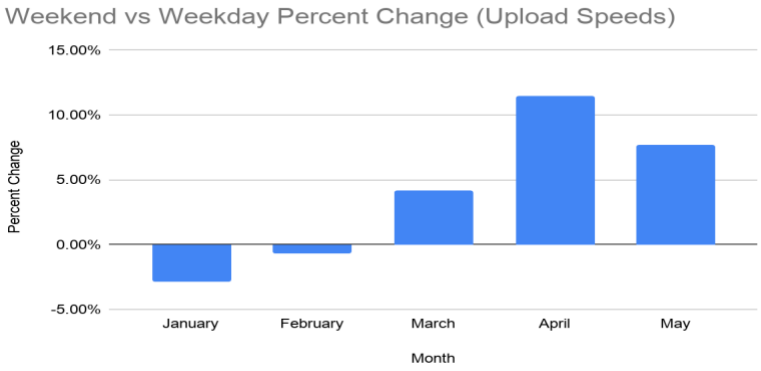


Figure 1.4.7.4 Weekend vs Weekday Percent Change for Upload Speeds

Our data shows about the same (download) or slightly worse (upload) speeds on weekends during the pre-COVID months and much slower download and upload speeds on weekdays compared to weekends during post-COVID months. Slower internet speed performance on weekdays after COVID-19 spread could be attributed to the high amount of traffic during the weekdays caused by students and adults working from home, using platforms like Zoom and Skype to communicate during the day in addition to Youtube and Netflix for recreation at night.

1.5 Conclusion

At a nationwide level, COVID-19 did have an impact on internet performance. Download speeds did not change much, but upload speeds experienced notable degradations. Internet performance got considerably worse in April and began improving in May and June. The nationwide median download speed barely changed in March and April but increased by 10% in May from the median for January/February. The median upload speed decreased by 12% in March, 28% in April, and 18% in May from January/February. These changes were seen on a monthly basis according to the M-Lab dataset. When analyzing pre-COVID (December 30, 2019 to March 29, 2020) and post-COVID (March 30, 2020 to June 28, 2020), we found that there is a statistically significant difference between upload and download speeds for these two periods. The COVID-19 pandemic did have a significant impact on speed when analyzing on a larger timeline. When comparing the last week of February and the last week of March for both the M-Lab and SamKnows datasets, we recognized that there was virtually no change in median download speeds and the median upload speeds. At that point, not all states were under lockdown and it took some time for speeds to change significantly.

When changes occurred, they mostly occurred across all percentiles irrespective of race and poverty level. However, in Section 1.4.4 we learn that zip codes with higher median income levels experienced greater decreases in speed. In Section 1.4.1 we see that higher percentiles of speed had smaller improvements in speed in May than lower percentiles. Assuming that those of higher income have higher speeds in general (by paying for faster, more expensive internet plans and hardware), locations with better Internet saw performance decrease more and recover less. This trend continues to rural vs. non-rural, which we explored in Section 1.4.5. Non-rural locations have faster internet speeds than rural, yet non-rural groups saw a greater percent decrease in upload speeds (17.7% vs 6.8%). The places that had better Internet to begin with experienced greater degradations than others.

In general, not all degradations occurred consistently. For example, some states saw a 60% decrease in download and upload speeds from while others saw a 60% increase from January/February to April/May. Geography played an important role in determining changes in

network performance. The good news is that the Internet “recovered” in May from the upload speed decrease experienced during the onset of lockdowns in March and April.

There is not a degradation in the download performance for speed tests when comparing the performance for the last week of February and the last week of March. For the upload speeds too, there is not a change in performance when we compared the median speeds for the last weeks of February and the last week of March. However, when we look at the broader picture, the upload speed has certainly been affected by the lockdown. These effects are not visible when comparing the last weeks of February and the last week of March.

However, the “internet rush hour” has changed by day of week -- Section 1.4.3 shows better speeds on weekends instead of worse, most likely due to massive traffic from communicating for work or school on weekdays.

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