Trends in Local Telecommunication Switch Resiliency

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***Abstract*— This paper presents a time series analysis of outage causality trends for local telecommunication switches in the United States. Additionally, the resiliency of local switches is assessed by examining changes in severity of outages over time by causality. Almost 13,000 Public Switched Telephone Network (PSTN) switch outages are examined over a 14-year period. Causality trends were examined from both resiliency and reliability perspectives, for scheduled outages, and failure induced cause categories such as procedural errors, design errors, random hardware failures, and external events. Examples of reliability growth, constancy, and deterioration are noted among these casual categories. Likewise, examples of increasing, constant and decreasing impact trends are also noted. To examine resiliency, a novel severity index metric is introduced that is not only intuitive, but also robust, given the long tailed distribution of outage impact. The new index allows time series comparison between causality reliability and outage impact trends. Interestingly, in some instances causality reliability trends were different from the corresponding impact trends. For example, when all outage causes are combined, a reliability growth trend is indicated while outage impact is constant. To get a good perspective on resiliency, both reliability and outage impact trends must be examined. Trends are assessed both graphically and analytically, and conclusions are reached with strong statistical inference.**

Keywords- reliability growth; resiliency, outage index; homogeneous poisson process (HPP), non-homogeneous poisson process (NHPP), Laplace trend test, time series of events, fault management.

I. INTRODUCTION

Telecommunication switches are an important subsystem of the Public Switched Telephone Network (PSTN). Along with the transmission and signaling subsystems, these switches provide end to end connections to subscribers. Although the PSTN in the U.S. is used predominantly for landline voice services, many wireless calls use many of the same facilities, especially for regional calls. Additionally, PSTN and wireless switches are often different models of the same switch vendor product line, as the switching functions are very similar. So wireline switches, besides serving millions of subscribers and deserving of study in their own right, are also good proxies for wireless mobile switching centers [1]. The PSTN is certainly migrating to voice over internet protocol (VoIP), but this migration will take many years, and local switches are likely remain in service for years to come [2]. At the beginning of 2011, there were 117 million subscribers connected over local loops to circuit switched local switches, and 32 million VoIP subscribers [3].

Additionally, local switches are access nodes, and access nodes, be they in a circuit or a packet switch networks, are very important as they represent the gateway to network services for users. For instance, the methods presented in this paper, and the types of insights that can be gleaned from failure and outage data are as relevant for local PSTN switches, as they are for Internet Service Provider (ISP) access nodes.

Trends are important in the dependability of systems, subsystems, and components. Statisticians identify trends – engineers endeavor to embrace favorable trends and influence for the better negative trends. A key to understanding reliability trends is to recognize and identify the hazards in which the item, system or service operates. Additionally, management must make reliability programs a priority [4]. In order to change a trend, we look for approaches offering insights into why failures are occurring. Telecommunication switch reliability results from complex interaction between software, hardware, operators, traffic load, and many environmental factors. By knowing failure causes and trends, switch vendors and service providers may take actions to change trends. Barnard argues that reliability engineering must endeavor to continually improve systems and products before and during the operational phase, using such techniques as the Failure Reporting, Analysis and Corrective Action System (FRACAS) [5]. In network management, this is a fault management function.

Additionally, all outages are not equal, as some might affect hundreds for long periods, while others might affect hundreds of thousands for short periods. Outages represent resiliency deficits, and trends in resiliency are as important as trends in reliability. This paper endeavors to examine reliability and resiliency trends, as they relate to outage causality. In this way, we can not only arrive at an overall assessment, but also assessments segregated by cause.

This study uses local switch outage data reported to the Federal Communications Commission (FCC) representing individual switch outage incidents of at least two minutes in duration from 1996 through 2009, collected from [6]. Unfortunately, after 2009, the FCC no longer required carriers to report this data. As each reported switch outage includes date, time, and outage cause, a time series by cause was created by us to assess causality trends. In addition, as the reports also included the size of each switch out (in

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access lines) and duration, time series outage impact trends could also be assessed. The reporting Carrier classified each incident using one of fifteen different cause codes. We further aggregated the fifteen causes into six outage causality categories. Causality trends are of paramount interest if the objective is to understand failure and outage patterns. This way, remedial action plans can be taken by network operators to improve network performance.

Section II presents a literature review of outage impact, local switch reliability, and reliability of repairable systems. Section III introduces the specific research questions being addressed in this paper while Section IV overviews the time series methods used to assess local switch reliability and resiliency, including a new resiliency metric. Section V presents the causality trends in graphical and tabular form, including reliability ad resiliency comparisons. Section VI summarizes conclusions while Section VII addresses research limitations and suggests future research directions.

II. LITERATURE REVIEW

A. Outage Impact

A system is resilient when it has "the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must." [7]. The role of modeling in understanding and promoting the resilience of critical infrastructures, including wireline and wireless telecommunications, has been argued. Before these processes can be modeled, they need to be characterized and understood. [8].

Large-scale telecommunication outages can result in heavy losses to business and society at large. Also, colocation and the resulting concentration of telecommunications assets represent "serious risk posed to small and mid-sized businesses from disruptions in telecommunications service." [9]. Local switches are in end offices that can represent concentrations. Additionally, although end offices are susceptible to power loss, they are typically protected by generator and battery backup power sources. However, damages to the AC power grid are common in hurricane prone areas, which causes outages to "wire-line networks, wireless networks, transmission links, cable TV grids, and TV and radio facilities...". The major causes of telecommunication outages from hurricane Katrina was found to be power loss because of fuel supply disruptions, flooding and security in low-lying areas [10].

Recently, Lyons, et al empirically assessed the economic impact of telecommunication outages [11]. In that paper, the economic costs of telecommunication outages, for fixed line networks, is estimated for both a complete sector outage and local exchange outages. The costs estimates are based on actual business and residential demographics, including service and manufacturing areas. For seven local exchange outages in Ireland, these costs ranged from €370,000 to €1.1 million per day. Unfortunately, the number of lines for local switch in each of the exchanges are not given.

The User Lost Erlang (*ULE*) was introduced by McDonald in [12] as an impact metric for large-scale outages. The *ULE* is the logarithm of the magnitude of an outage, or $ULE = log_{10}(Magnitude)$, where magnitude is the number of users impacted. For instance, the impact of an outage affecting 10,000 lines would be *4 ULE*. Because of the range of outages could be many orders of magnitude, McDonald thought such a metric would be easy to use and understandable by the public, much like the logarithmic Richter scale for earthquake intensity. Of course, the disadvantage of the *ULE* is that although size is taken into account, the duration of the outage is not. So an outage has both size and duration as variables. The Federal Communication System used the Lost Line Hour (*LLH*) metric, the product of the number of lines out times the duration in hours. For instance, a 10,000 line switch out for 2 hours would be an equivalent outage of 20,000 *LLH*, or 20,000 lines out for an hour. Although the *LLH* incorporates both the time and duration of an outage, it does not capture blocked calls. Additionally, the *LLH* has no logarithmic transformation to tame outliers in size or duration of outages. Committee T1 in the US, published an American National Standards Institute (ANSI) sponsored metric called the Outage Index (*OI*). This metric included the product of two weightings, one for size, and another for duration. Additionally, given the long tailed distributions of size and duration, each weight included logarithmic transformations. However, further analysis of the *OI* indicated a network administrator perspective rather than a subscriber perspective, in that the index was insensitive to long duration outages and very sensitive to large size outages [13]. For instance, assume a local switch with 10,000 lines experiences an outage: if a 1 day outage the *OI* is 0.519 while if an 8 day outage the *OI* is 0.532 [14]. This discounting of duration masked significant impact of outages below a regulatory reporting threshold, which according to the *OI* impact metric was minimal [15].

More recently, in [16], resiliency was defined as the percentage of users deriving successful service over time. Although a reasonable metric, the number of users impacted is not provided by this metric.

B. Local Switch Reliability

In the late 90s, Kuhn reported on the sources of major outages in the PSTN, including local switches, tandem switches, signaling, and transmission facilities. However, this work assessed but a few years of outages, and only those outages that exceeded impacting 30,000 or more subscribers for at least 30 minutes or more [17].

Time series analysis on local switch outages lasting 2 minutes or more was first reported by Snow in [18], examining trends, causes and impact of outages occurring from 1992 to 1995. In [19], Snow noted that some individual switches seemed to experience many outages. Recently, local switch outages were examined by Snow, et al in [1], from 1996 to 2009, extending the work in [18] but

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with the primary focus on switches suffering more frequent outages. Although summary statistics for causality and survivability were presented, causality trends, and the corresponding outage impact trends, were not investigated.

C. Reliability Assessments of Repairable Systems

A system is reliable when it carries out its intended functions over a specified period of time, without failure. The probability of this happening is the definition of reliability. Said another way, reliability is the probability a system will perform its intended function, in the intended environment and at a particular level of performance. Thresholds are very commonly used to declare a system as in either an “operational” or “degraded” mode [20]. Others define reliability as “conformance to specifications over time” [21].

As pointed out by Louit, et al. [22], reliability of systems are best assessed by time to failure (*ttf*) models and analysis. Because local switches are repairable systems, stochastic point processes must be applied, since the *ttfs* can be systemically changing over time. Said another way, the failure arrival process might be non-stationary, so *ttfs* cannot simply be fitted to a distribution unless they can be shown to be a renewal process (RP, independent and identically distributed) or a special case of renewal process, the homogeneous Poisson process (HHP, independent and identically exponentially distributed). So, the presence of trends are of paramount interest as they indicate improvement or deterioration.

Additionally, Louit, et al. [22], point out that methods for trend analysis are graphical and analytical. Graphical methods culminate in visual assessments of cumulative plots of outages versus time. Straight lines represent constancy, or no trend. Where the curve that bends up, represents an upward trend, and where a curve bends down, represents a downward trend of failures over time. Analytic trends are indicated when the visual trend evidence from the graph is slight, or to assess the strength of the trends. The Laplace trend test is well known, having a null hypothesis of HPP and an alternative hypothesis of a non-homogeneous Poisson process (NHPP). For no trend, renewal processes are often used, as it is hoped the system is made “good as new” through modular replacement. However, switches involve software and hardware changes, wherein some repairs result in a slightly different switch. This means that failures are not independent or identically distributed. The NHPP, is the most popular nonstationary model used in reliability for monotonically increasing or decreasing trends.

The Laplace statistic is zero for the null hypothesis of no trend. A statistic less than zero is a decreasing trend (reliability growth) while a statistic greater than 0 indicates an increasing trend (reliability deterioration). The Laplace score (L) asymptotically approaches a normal score, so if one chooses a critical value of 0.05, L is non-zero, representing a statistically significant trend, if -1.96 ≥ L ≥ +1.96. The Laplace score for a truncated time series of events is:

$$L = \frac{\sum_{i=1}^{n} t_i - \left(\frac{1}{2}\right) nT}{\sqrt{nT/12}} \qquad (1)$$

where t_i is the time of the i^{th} failure, n is the number of failures over the time observed time period T.

Lastly, Louit, et al. [22], point out that in cases as this study, where failures are from thousands of different local switches of different manufacturer and models, the superposition of many processes tend to converge to a Poisson process, either homogeneous or nonhomogeneous.

III. RESEARCH QUESTIONS

This research addresses the following questions regarding telecommunication local switch outage causality trends over a 14 year period:

- Are failure trends the same or different for different causal categories?
- Can causality failure processes be characterized as HPP or NHPP?
- Can a new impact metric be devised to provide insights into resiliency trends?
- For each causal category, are resiliency trends discernable from reliability and outage impact trends?

In this work, the PSTN is viewed as a single system, made up of switching, signaling and transmission segments. The switching segment is made up of the tandem and local switch subsystems. The purpose of this paper is to investigate the reliability and resiliency trends of the local exchange switching subsystem as a whole, by investigating the pooled failures of all individual local switches in the PSTN. There are a large number of different manufacturers and models of local switches in this infrastructure. Even the same model switch varies substantially from serial to serial because of differences in customers served and features offered. By pooling failures from different switches, we may assess the resiliency and reliability of local switching as a whole, rather than the reliability of a single switch. Then, failures and outages can be subdivided by causality and examined further for trends.

IV. TIME SERIES ANALYSIS METHODS

Two different time series methods are used. The first is the aforementioned graphical and analytical time-to-failure techniques, of Louit, et al. [22]. The second consists of methods developed for this paper: graphical plots of outage resiliency and linear regression, where indicated by visual assessment.

A. Causal Trend Analysis of Events

By combing similar cause codes reported to the FCC into categories, we reduced the fifteen causes reported to the FCC down to six causality codes:

- Scheduled outage: An intentional outage for maintenance purposes.

- Procedural error: Procedural errors made in installation, maintenance or other activities by Telco employees, contractors, switch vendors, or other vendors.
- Design error: Software or hardware design errors made by the switch vendor prior to installation.
- Hardware error: A random hardware failure, which causes the switch to fail.
- External circumstances: An event not directly associated with the switch, which causes it to fail or be isolated from the PSTN.
- Other/unknown: A failure for which the cause was not ascertained by the carrier.

These categories, their composition, and the distribution of failures to each category are shown in Table I. For each of these processes, time series were created for study over a 14 year period.

B. Causal Resiliency Trend Analysis

Manifold shortcomings of the aforementioned outage index indicate a different resiliency metric is needed for this analysis. Given the long tailed distribution of both switch lines and outage duration, *LLH* ranges from very small to very large, indicating a logarithmic transformation is desirable. However, a major problem with the outage index is a non-intuitive lack of reference and insensitivity to long duration outages, while a major advantage of *LLH* is that it represents switch size and duration equally.

TABLE I. LOCAL SWITCH OUTAGE CAUSE CATEGORY DISTRIBUTION

Outage Category	No.	%
Scheduled	3,885	30%
Procedural Error	1,394	11%
Design Error	1,214	9%
Random HW Failure	2,951	23%
Ext. Circumstances	2,900	23%
Other/Unknown	516	4%
Total	12,860	100%

To develop a new metric, we borrow from the field of communications engineering, where power is represented by decibels, referenced to a power level of interest. For instance, *dBm* is power in decibels referenced to one milliwatt (mW), while *dbW* is power represented to one watt. For example:

$$dBm = 10log_{10}\frac{P}{1\,mw} \qquad (2)$$

The nice feature about the *dBm* is that 0 *dBm* is 1 mW (the reference power), and a *10 dB* increase/decrease is a tenfold increase/decrease, and a *3 dB* increase/decrease represents a doubling /halving.

The new metric used here is as follows:

$$OI_{dBK} = 10log_{10}\frac{LLH}{1000} \qquad (3)$$

This new metric is called an outage index, referenced to *1,000 LLH*. So now, an OI_{dBk} of *20* represents two orders of magnitude above *1,000 LLH*, or *100,000 LLH*, while an OI_{dBK} of *23* represents a doubling above *20*, or *200,000 LLH*. Also, -3 OI_{dBK} represents *500 LLH* while -6 OI_{dBK} represents *250 LLH*. This new metric should "tame" the wide swings of *LLH*, and give an intuitive reference when doing time series plots and regression of outage resilience over time. Of course, if desirable, we can also have OI_{dBM} which references the severity to one million *LLH*.

V. RESULTS

Here we present tabular, graphical, and analytic results to assess reliability and resiliency and causal trends. First, the cumulative outage plot for all outages is seen in Figure 1. This is not a monotonic trend, as the failure rate (failures per unit time, the derivative of the cumulative graph) represents a "bathtub" curve: a region of high failure rate, followed by a region of lower failure rate, then an increasing failure trend.

A. Causal Reliability Trends

A summary of causal trend analysis is provided in Table II, while sample casual trend graphic results are shown in Figures 2 through 4 show sample cumulative plots. In Table II, we see three cause categories that show overall improvement and three that overall show deterioration.

Figure 1. Cumulative Outage Plot: All Outages

TABLE II. OUTAGE FREQUENCY TRENDS BY CAUSE

Cause Category	L	p-Value	Trend	Type
Scheduled	-58.41	0.0000	Decreasing	Monotonic
Procedural Errors	-14.42	0.0000	Decreasing	Monotonic
Design Errors	-27.61	0.0000	Decreasing	Monotonic
Random HW Fail.	3.0	0.0012	Increasing	Bathtub
External Circum.	28.33	0.0000	Increasing	Monotonic
Unknown/Other	3.34	0.0004	Increasing	Bathtub

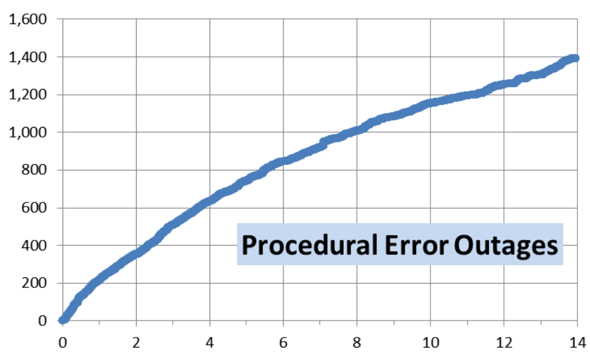

Figure 2. Cumulative Outage Plot: Procedural Outages

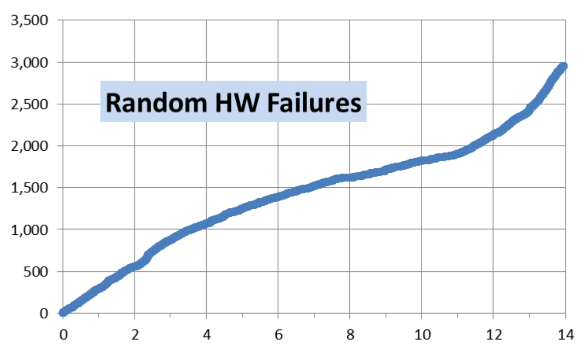

Figure 3. Cumulative Outage Plot: Random HW Failures

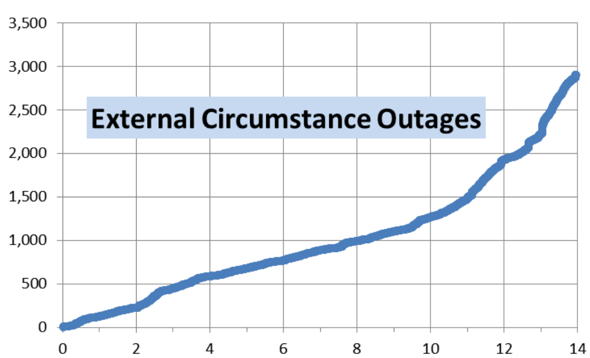

Figure 4. Cumulative Outage Plot: External Circumstance Outages

These trends are statistically very strong, as evidenced by the p-values. Several categories showed monotonic trends, good candidates for NHPP. Two showed bathtub type failure rates, and could be examined in a piecewise linear fashion. Interestingly, none showed promise of a renewal process, for which distributions could be fitted, as all six processes are nonstationary over the 14-year study period.

B. *Causal Impact Trends*

A summary of causal impact trends is shown in Table III, where we observe instances of increasing, constant and decreasing outage impact. The trends were determined by linear regression models, which were all statistically significant at the *0.05* critical value, for each model's F-test and coefficient t-tests. The trend constant and slope are provided for each model. Several observations can be made from this table. First, note that since the scheduled outage constant is about *3 dBK* higher than design error constant, on average, scheduled outage severity is about double that of design error. Secondly, however, using the regression constant, note that over 14-years, scheduled outage resiliency improved *17 dBK* while design error resiliency improved *13.2 dBK*. So by the end of the period, the aforementioned *3 dBK* difference evaporated. Lastly, note that over the 14-year period, external circumstance resiliency worsened by *7.4 dBK*, meaning its worsening more than quadrupled (*6 dB*).

TABLE III. OUTAGE IMPACT TRENDS BY CAUSE

Cause Category	Impact Trend	Regression Const.	OI_{dbk}/Yr	OI_{dbk}/14Yr
Scheduled	Decreasing	26.3 OI_{dbk}	–1.22 OI_{dbk}	OI_{dbk}
Procedural Errors	No	NA	NA	NA
Design Errors	Decreasing	23.4 OI_{dbk}	–0.94 OI_{dbk}	OI_{dbk}
Random HW Fail.	No	NA	NA	NA
External Circum.	Increasing	24.9 OI_{dbk}	0.53 OI_{dbk}	OI_{dbk}
Unknown/Other	No	NA	NA	NA

Next, we show the impact charts (OI_{dBK} quarterly plots), Figures 5 through 8, corresponding to the four cumulative outage plots, followed by an example *LLH* plot for outages due to external circumstances (Figure 9). The *LLH* plot in Figure 9 not only demonstrates the difficulty in determining trends, but also that *LLH* is a poor resiliency impact metric, compared to Figure 8.

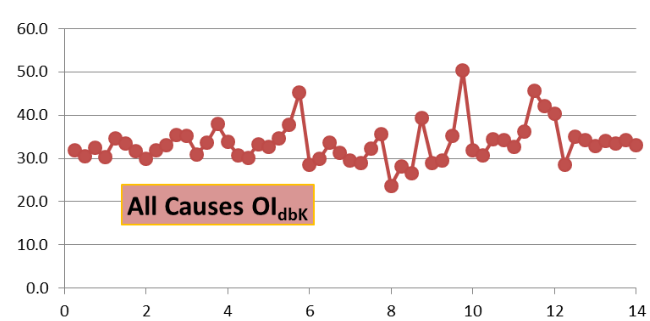

Figure 5. Outage Impact Plot: All Outages

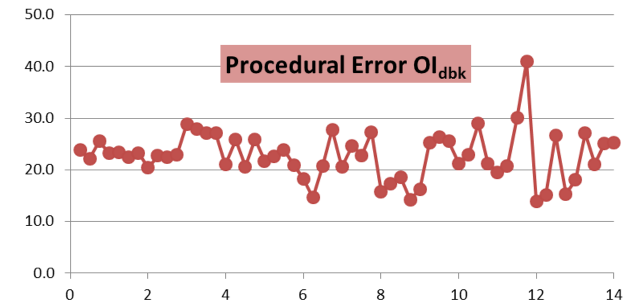

Figure 6. Outage Impact Plot for Procedural Error Outages

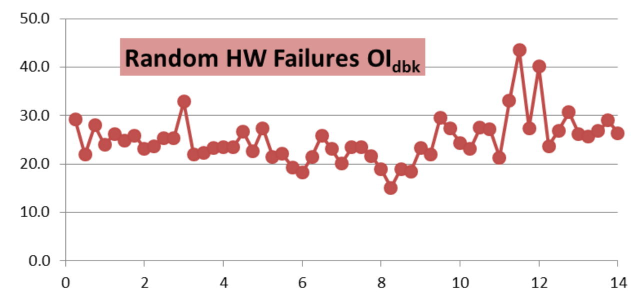

Figure 7. Outage Impact Plot: Random HW Failures

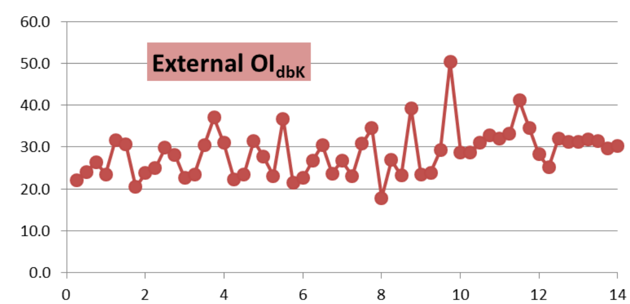

Figure 8. Outage Impact Plot: External Circumstance Outages

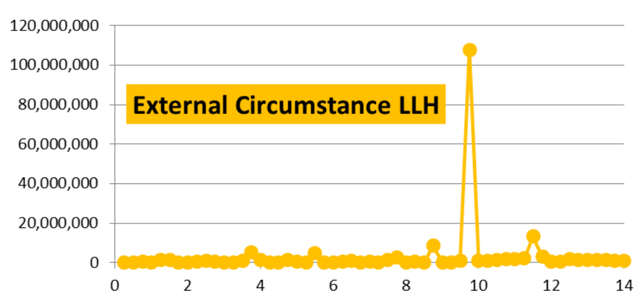

Figure 9. LLH Plot for External Circumstance Outages

VI. Summary Of Findings

The research questions listed in Section III are addressed here in turn.

A. *Are outage/failure trends the same or different for different causal categories?*

All failure/outage trends were markedly different. However, three causality trends were found to be decreasing over the study period, indicating reliability growth. Likewise, three other causality trends were found to be increasing, indicating reliability deterioration. In addition, some of the trends were monotonically increasing or decreasing, and others indicated bathtub processes, which indicate deterioration towards the end of the study period.

B. *Can causality failure processes be characterized as either HPP or NHPP?*

None of the six processes studied passed the test for HPP as all showed strong visual signs of nonstationary processes. The monotonically increasing and decreasing trends looked like good candidates for the power law model. The causality trends exhibiting bathtub characteristics are candidates for investigating piecewise linearity, or piecewise HPP.

C. *Can a new impact metric be devised to provide insights into resiliency trends?*

The new impact metric, the OI_{dBK}, showed promise as it controlled outliers through a logarithmic transformation and easily allowed trend analysis for resiliency. Also, it is referenced to a benchmark loss of *1,000 LLH*, making it intuitive. This metric overcomes shortcomings in both the *LLH* and the ANSI outage index metrics. Unlike the ANSI outage index, it is not insensitive to long duration outages, giving equal weight to both outage magnitude and duration. Unlike the *LLH*, it does not have extreme range of values.

D. *For each causal category, are failure/outage trends and impact trends in agreement?*

For scheduled and design error outage categories, both impact and outage trends decreased (deterioration in both) while for external circumstance outages, both trends increased (improvement in both). Interestingly, although procedural error outages decreased, there was no improvement in outage impact. In addition, random hardware failures and unknown/other outages increased (deterioration), with no concomitant deterioration outage impact.

VII. Conclusions

This work shows that to assess resiliency, both reliability and outage impact offers valuable insights. It also indicates the importance of posterior perspectives of these dependability attributes, as an important part of the fault management aspect of the network management function.

More research can be performed to gain additional perspectives. For instance, besides investigating the trends for the casual categories here, all fifteen cause codes can be examined for resiliency trends. Preliminary investigations indicates presence of possible renewal processes, including HPP. For those cases, event independence can be investigated using the coefficient of variation and presence of significant first order autocorrelation coefficients. Additionally, piecewise linear and power law modeling could be used to further characterize these causal processes.

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