Estimation of the relationship between FAVAD N1 and ILI values for flexible pipe material water systems using field data in South Africa

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ABSTRACT

The relationship between pressure and leakage rates in water distribution systems have been subject of many technical studies. However, it has been demonstrated that the most physically meaningful and "Best Practice" form of equation for representing pressure:leakage rate relationships is a simple Power Law (Thornton & Lambert, 2005) regulated by the FAVAD N1 value. So if pressure is reduced from P0 to P1, flow rates through existing leaks change from L0 to L1, and the variation depends on the exponent N1: L1/L0 = (P1/P0)N1. This N1 value differs for each single water system depending on the characteristics of the systems, and an interesting form of showing this variation is relating it with the Infrastructure Leakage Index (ILI). This paper analyses a new set of field data to test the mentioned pressure / leakage rate relationship, adding additional data for the comparison of the FAVAD N1 value with the ILI for flexible pipe materials water systems.

The analysis of more than 50 field tests on different Pressure Management Zones (PMZs) in South Africa enabled the achievement of the relationship between N1 and ILI values. The obtained curve has a logarithmic pattern, which shows that N1 varies between 1.5 and 1.0; tending to be 1.5 for systems with low ILI (ILI < 4) and 1.0 for systems with high ILI (ILI > 10). Finally a new method to analyze the leakage is presented, taking into account five variables: Length of Mains (Lm), Number of Connections (Nc), Average Zone Pressure (AZP), Night Day Factor (NDF), and Water Density.

KEYWORDS: Leakage, FAVAD N1 value, ILI.

INTRODUCTION

Many technical studies have proven that leakage flow rate (L) is proportional to the pressure (P) on the pipe, and the function relating these two variables is a power law: L varies with P^{N1}. Where N1 is the exponent FAVAD N1 Value (Fixed and Variable Area Discharges, this concept was proposed by John May in 1994). Then if we reduce the average pressure P0 to P1, the volume lost through leakage will decrease from L0 to L1 and the magnitude of this decrement depends on the exponent N1:

$$\frac{L_1}{L_0} = \left(\frac{P_1}{P_0}\right)^{N1} \qquad [1]$$

Field studies and laboratory tests have shown that the N1 value generally varies between 0.5 and 2.5, and the average is close to 1. Then the pressure effect on leakage is greater than the effect considered by the orifice theory which suggests that L is proportional to the square root of P. N1 differs for each single water system depending on the characteristics of the system; some of the factors which affect this exponent are: size and shape of the leaks' orifices, expanding capacity of the leaks, surrounding soil, and the flow and pressure conditions. The size, shape and expanding capacity depends on the pipe material; so the pipe material has a meaningful importance on the pressure:leakage relationship. The leakage is more sensitive to pressure variations on flexible pipes (i.e. plastic pipes) than on rigid pipes (i.e. steel pipes); generally N1 is assumed to be 1.5 for leakage on flexible pipes, 0.5 on rigid pipes, and 1 for large systems composed by different material types.

An interesting way of showing the N1 variation for different systems is relating it with the Infrastructure Leakage Index (ILI). The Pressure Management Team of the International Water Association (IWA) has developed and tested a method for predicting N1, using the Infrastructure Leakage Index (ILI) as a measure of leakage level and the percentage (p) of detectable real losses occurring on rigid pipe materials (mains and services) as a secondary parameter (Lambert, 2009). This is the most reliable practical method to predict the power law exponent in the absence of field data, and results are shown in Figure 1.

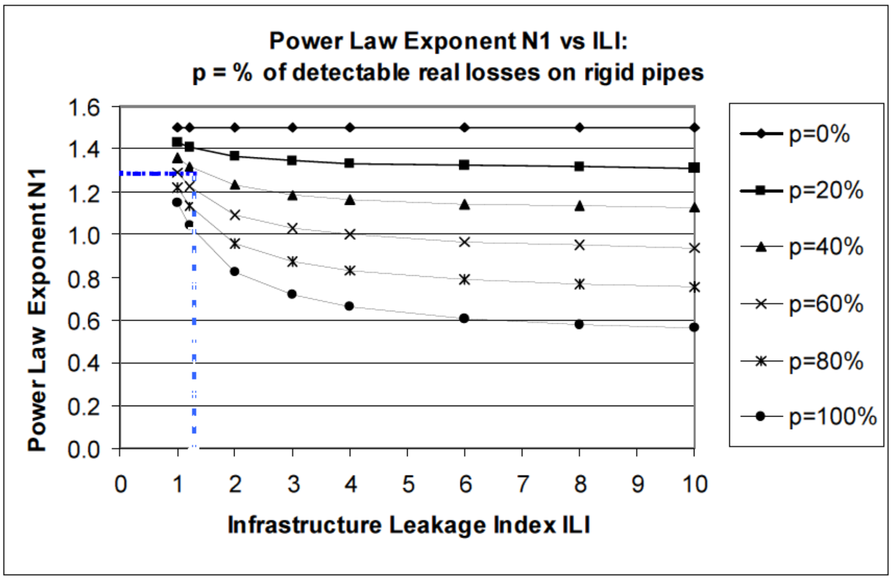

Figure 1. *Predicting the power law exponent using ILI and % of detectable real losses on rigid pipes (Lambert, 2009).*

This paper analyses a new set of field data to test the mentioned pressure / leakage rate relationship, adding additional data for the comparison of the FAVAD N1 value with the ILI for flexible pipe materials water systems. In order to provide significant experience and data from a number of Pressure Management projects in South Africa, N1 Tests were performed on a wide range of Pressure Management Zones (PMZs). The analysis of more than 50 field tests on different PMZs enabled the achievement of the relationship between N1 values and ILI for flexible pipe material water systems.

METHODS

N1 Tests were performed on a wide range of Pressure Management Zones (PMZs) by reducing inlet pressures in several steps at night, during the period of minimum consumption. For each Test, loggers were installed in order to register: the Flow (Q) entering to the PMZ and the pressure at the Critical Point (CP), Average Zone Pressure (AZP), Upstream Pressure (U/S) and Downstream Pressure (D/S).

How FAVAD N1 value was estimated?

For each PMZ, the FAVAD N1 value was calculated using the following formula:

$$N1 = log_{\left(AZNP_a / AZNP_b\right)} \left[\frac{NL_a}{NL_b}\right] \qquad [2]$$

Where AZNP is the Average Zone Night Pressure and NL is the Night Leakage, “a” and “b” represents the values before and after pressure reduction. AZNP values were obtained from logging data, whereas night leakage rates were obtained by deducting Night Consumption (NC) from the Minimum Night Flow (MNF) (Fantozzi & Lambert, 2012).

How ILI was estimated?

The ILI was calculated as the relationship between Current Annual Real Losses (CARL) and Unavoidable Annual Real Losses (UARL). These values were taken from the Water Balances made for each distribution system. Take into account that a PMZ is just a portion of a distribution system.

$$ILI = \frac{CARL}{UARL} \qquad [3]$$

RESULTS AND DISCUSSIONS

40 PMZs were tested for the analysis, all of them constituted by flexible pipe materials (plastic pipe) on more than the 95% of the total length of mains. As a consequence the results obtained are valid just for flexible water networks. All the PMZs are located on urban areas and have densities of connections (Dc) ranging from 22 to 112 with an average of 55 conn/km. Small and large PMZs were studied, ranging from 30 to 1866 connections and 0.5 up to 48 kilometres of pipelines. The main characteristics of the PMZ are listed in Table 1.

Table 1. *Main characteristics of the Pressure Management Zones (PMZ) analyzed.*

Variable	Minimum	Average	Maximum
Nc [conn]	30	324	1866
Lm [km]	0.5	7.6	48.0
Dc [conn/km]	22	55	112
AZP [bar]	3.8-2.6	7.1-4.3	12.1-7.4
NDF [h]	18.5	23.1	26.7
N1	0.97	1.29	1.79
ILI	3.4	6.1	13.2

The ILI values obtained from the studied water systems range from 3.4 up to 13.2, which are in the range of values suggested by the IWA for developing countries, as South Africa (Ziegler, 2011). On the other hand the FAVAD N1 values range from 0.97 up to 1.79, with an average of 1.29. Usually N1 is assumed to be 1.5 for flexible water networks, which is not far off.
Figure 2 shows N1 values on the ordinates and ILI values on the abscise. Each single blue dot represents a PMZ and the red curve is the logarithmic trendline:

$$N1 = 0.28\,.\ln(ILI) + 1.78 \qquad [4]$$

The formula suggests that the FAVAD N1 value ranges from 1.5 to 1.05 for flexible water systems which have an ILI between 3 and 13. N1 decreases with an increment of the ILI, and this decrement is more pronounced as ILI becomes lower; then, for high ILI values N1 tends to be 1. The results indicate that N1 value for the studied flexible water systems varies between 1.5 and 1.0, tending to be 1.5 for low ILI values (water systems with a good performance), and 1.0 for high ILI values (water systems with a poor performance).

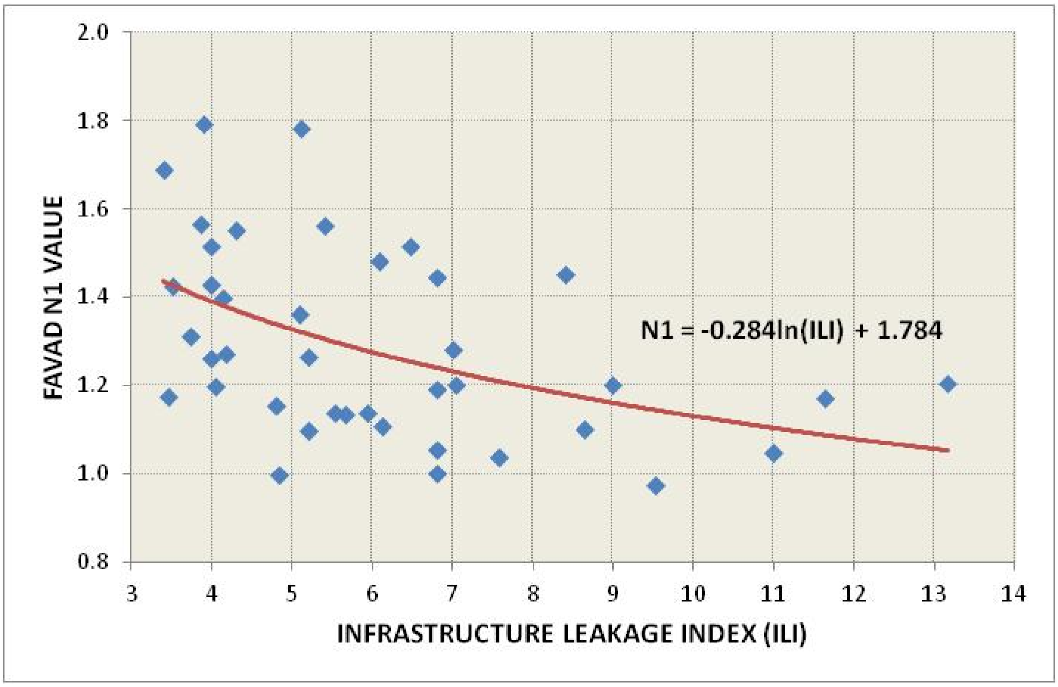

Figure 2. *Predicting the relationship between FAVAD N1 Value and Infrastructure Leakage Index (ILI) for flexible water systems. Blue dots represent the values obtained for the 40 PMZs studied. Red curve is the logarithmic trendline.*

New method to analyze leakage

Leakage is a function of several variables: soil type, number of service connections, network length, system operating pressure, time during which the system is pressurized, between others. The following formula attempts to relate the Leakage (L) to four specific variables: Length of mains (Lm), Number of service connections (Nc) , Night Day Factor (NDF), and Average Zone Pressure (AZP). In this way:

$$L = f(Lm, Nc, NDF, AZP) \quad [5]$$

It would be very complex to find a function "f" that relates these five variables. However it is possible to reduce the number of variables using the "π Buckingham Theorem". The π theorem is a method for reducing a number of dimensional variables into a smaller number of dimensionless groups, also called π numbers. In order to apply the π Theorem a new variable is introduced, the water density ρ [kg/m^3], so dimensionless groups can be created. So there will be a new function "g" that relates the variables mentioned before:

$$L = g(Lm, Nc, NDF, AZP, \rho) \quad [6]$$

Applying the π Theorem it is possible to reduce the six dimensional variables to only two dimensionless groups, which are related by a new function "h":

$$\pi_1 = h(\pi_2) \quad [7]$$

$$\pi_1 = \frac{L.NDF.Nc}{Lm^3} = \frac{L.NDF.Dc}{Lm^2} \quad [8]$$

$$\pi_2 = \frac{AZP.NDF^2}{\rho.Lm^2} \quad [9]$$

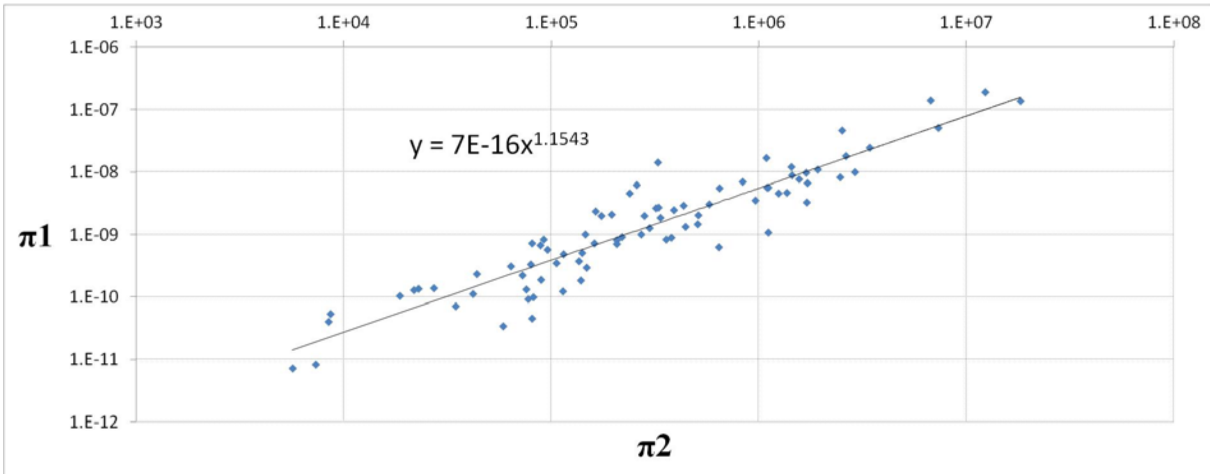

Figure 3. *Values of π_1 y π_2 for each PMZ represented on a log-log chart. The curve relating the two dimensionless groups is a power trendline.*

The "h" function is presented below, which relates π1 and π2. Dimensionless groups π1 and π2 were obtained for each PMZ and are showed in Figure 9, where each point corresponds to a different PMZ. It is notorious that there is a relationship between the two dimensionless groups; this relationship is defined by a power law function:

$$\pi_1 = A.\pi_2{}^B \qquad [10]$$

$$\frac{L.NDF.Nc}{Lm^3} = A.\left(\frac{AZP.NDF}{\rho.Lm^2}\right)^B \qquad [11]$$

Where A and B are constants, and their values are A = 7.10-16 and B = 1.1543. Solving the equation [11] the equation [12] is achieved, which is very practical. According to this new formula Daily Leakage per Connection is proportional to AZP and NDF, and inversely proportional to Dc and Lm:

$$L\left[\frac{litres}{conn.day}\right] = A.\frac{Lm}{Dc}.\left(\frac{AZP}{\rho}\right)^B.\left(\frac{NDF}{Lm}\right)^{2B-1} \qquad [12]$$

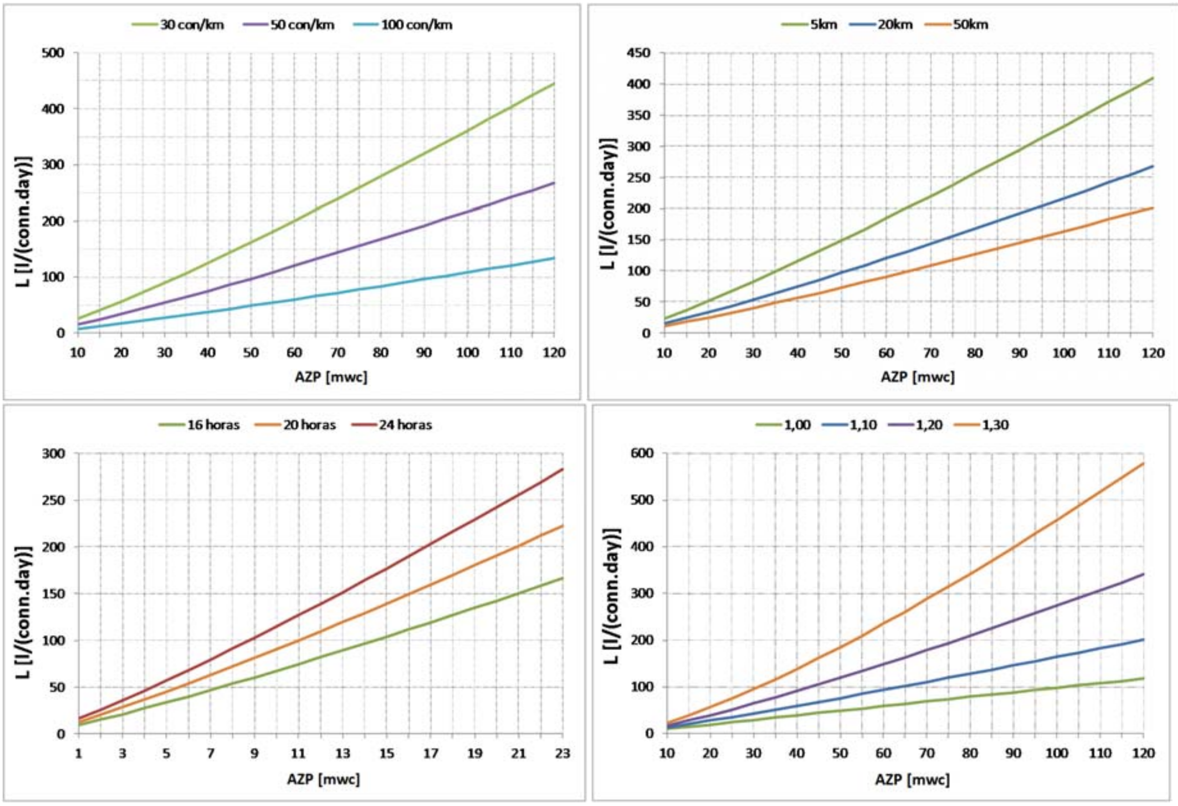

Figure 4. *Relationship between Leakage (L) and Average Zone Pressure (AZP) for a Pressure Management Zone (PMZ) with Dc=20conn/km, Lm=20km, NDF=23hours, A=7.10^{-16} and B=1.15. On each chart one variable is modified. Up-Left: Dc=30-50-100conn/km. Up-Right: Lm=5-20-50km. Bottom-Left: NDF=16-20-24hs. Bottom-Right: B=1.0-1.1-1.2-1.3.*

Figure 4 shows the values of L obtained using the equation [12] for different AZPs, in a PMZ with Dc = 50 conn / km, Lm = 20km, NDF = 23 hours, A = 7.10-16 and B = 1.15. Each graph shows how L varies when some variable is modified. The upper left graph shows that L decreases as the density of connections increase. The upper right graph shows that L decreases with increasing length of the network. The lower left graph shows that L increases with increasing NDF. Finally, the bottom right graph indicates that L is greater the larger the constant B of the network is.

It is also interesting to compare situations before and after pressure variations using the formula [11]. As a first step the constant "A" is cleared from the equation [11]; then the ratio between $\pi 1$ and $\pi 2^B$ will always be constant:

$$A = \frac{\pi_{1,before}}{{\pi_{2,before}}^B} = \frac{\pi_{1,after}}{{\pi_{2,after}}^B} = constant \qquad [13]$$

Usually when a pressure reduction is implemented in a PMZ, it takes no longer than a couple of weeks. In that period Lm, Nc and ρ usually remain constant. Assuming this on equation [13] gives:

$$La = Lb.\left(\frac{AZPa}{AZPb}\right)^B.\left(\frac{NDFa}{NDFb}\right)^{2B-1} \qquad [14]$$

Equation [14] indicates that leakage reduction is proportional to the variation of AZP and NDF of the PMZ. Figure 5 shows the variation of the ratio of leakage after and before, accord to the variation of the ratio of AZP after and before. The graph on the left shows three curves for different ratios of NDF after and before, where B = 1.15. However in the right graph NDF ratio remains constant (24 hours / 20 hours) and represents the variation curves for three different values of B. It follows that for a given change in pressure, the leakage reduction is lower for greater NDF variations. Furthermore L variation for a given variation of AZP will be greater the higher the coefficient B of the network is.

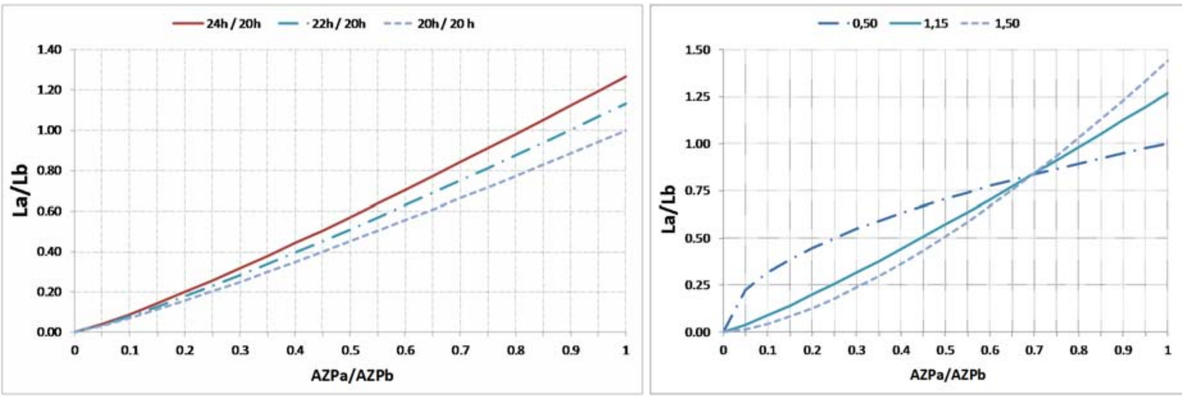

Figure 5. *Relationship between Leakage (L) and Average Zone Pressure (AZP) after and before ratios. On the left graph three curves are presented for different Night Day Factor (NDF) ratios are assuming that B is (B=1.15). On the right graph three curves are presented for different values of B, assuming the same NDF ratio for all the curves (NDFa/NDFb=24hs/20hs).*

If in equation [13] it is assumed that NDF does not change, then an equation equivalent to the traditional power law is obtained:

$$La = Lb.\left(\frac{AZPa}{AZPb}\right)^B \qquad [15]$$

The constant B therefore equals to FAVAD N1. The value B = 1.15 obtained for the analyzed networks equals the coefficient obtained by Ogura in 1979 in various networks in Japan. This way the equivalence between the formulas [14] and [1] can be checked, which further validates the formulas [11], [12], [13] and [14].

CONCLUSIONS

- The FAVAD N1 values obtained for the flexible water systems analyzed range from 0.97 up to 1.79, being 1.29 the average value.

- The FAVAD N1 value decreases with an increment of the ILI, and this decrement is more pronounced as ILI becomes lower. The logarithmic trendline obtained from the PMZs analyzed suggests that N1 varies between 1.5 and 1.0; tending to be 1.5 for systems with low ILI (ILI < 4) and 1.0 for systems with high ILI (ILI > 10).

- Two new dimensionless groups were presented on this paper, which are related by a power law:

$$\pi_1 = h(\pi_2)$$

$$\pi_1 = \frac{L.NDF.Nc}{Lm^3} = \frac{L.NDF.Dc}{Lm^2}$$

$$\pi_2 = \frac{AZP.NDF^2}{\rho.Lm^2}$$

Where A and B are constants and their values for the networks studied on this paper are: A = 7.10-16 and B = 1.1543.

- Daily leakage per connection is proportional to AZP and NDF, and inversely proportional to Dc and Lm:

$$L\left[\frac{litres}{conn.day}\right] = A.\frac{Lm}{Dc}.\left(\frac{AZP}{\rho}\right)^B.\left(\frac{NDF}{Lm}\right)^{2B-1}$$

- For PMZ, leakage reduction after pressure regulation can be estimated with the following formula:

$$La = Lb.\left(\frac{AZPa}{AZPb}\right)^B.\left(\frac{NDFa}{NDFb}\right)^{2B-1}$$

For a given change in pressure, the leakage reduction is lower for greater NDF variations. On the other hand, leakage reduction for a given variation of AZP will be greater the higher the coefficient B of the network is.

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